Computer Assisted Orthopaedic Surgery

5th Annual Meeting of CAOS-International Proceedings
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Introduction

On June 19-22, 2005 the International Society for Computer Assisted Orthopaedic Surgery (CAOS-International) will meet in Helsinki, Finland for its 5th Annual Meeting. The conference will be another gathering of physicians, researchers, developers, and system providers who are interested in all aspects of CAOS technology, its development, and its clinical application and evaluation. The first CAOS Symposium was held ten years ago in Bern, Switzerland with some 40 participants. Today CAOS-International’s annual meetings have established themselves as the most appreciated events in the calendars of the CAOS community. For additional information on CAOS-International and the conference series, please visit the CAOS-International homepage at http://www.CAOS-International.org/

The call for abstracts for this 5th Annual Meeting has once more resulted in a tremendous response: More than 200 abstracts were submitted by authors from 22 different countries, from which an international Program Committee has selected 68 podium presentations, 22 special posters, and 102 posters. We would like to take this opportunity to thank our fellow committee members for their efforts and time spent: Norberto Confalonieri, Florian Gebhard, P.S. John, Leo Joskowicz, Marin Krismer, Lutz-Peter Nolte, and Michael L. Swank. We are also grateful for the support of our sponsors and all organizers who will make this meeting possible. Special thanks go to Karin Nolte, who once again did and is still doing a great job in preparing CAOS2005. Last but not least, Ulla Jakob-Burger needs to be acknowledged, who spent endless hours to get the manuscript of this book into a “printable” shape.

This book contains a collection of those abstracts that have been accepted as podium presentations, special poster presentations, or poster presentations for our 5th Annual Meeting. For reasons of simplicity, the papers are listed alphabetically by first authors. In addition, a full authors listing at the end of the book makes it easy to find a specific abstract.

We would like to point out that the authors alone are fully responsible for the style and content of their contributions.

And now: “Welcome to CAOS2005!”

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Biomechanical and geometrical consequences of femoral resurfacing component placement

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Introduction: Metal-on-metal hip resurfacing arthroplasty has shown excellent results in short-to-medium-term follow-up, offering an attractive although unproven alternative to total hip arthroplasty for people who are young and active [1 – 3]. Placement of the stem within the femoral neck is a key but time-consuming step of the surgery. We are developing a computer-assisted surgery system to achieve this placement accurately and quickly, but the question remains as to what the best placement is. Recommendations to surgeons, ranging from neutral [1] to as valgus as possible [2], lack a clear basis. More varus neck-shaft angles have been associated with higher levels of loosening [2], but neither the biomechanical nor the clinical consequences of varus and valgus placement with respect to the neck itself have been studied to our knowledge. Femoral neck fractures occur clinically at the component-neck junction due to: superolateral notching, exposed cancellous bone, or poor quality bone, including large femoral cysts, necrotic bone or osteopenic bone [1,4]. The purpose of our study was to test the effects of relative varus/valgus and ante/retroverted placement of the femoral component on the static vertical failure load of the surgical construct to determine if a placement other than neutral should be recommended.

Methods: We sequentially resurfaced 15 artificial femurs (Sawbones model 1130.21, Pacific Research, Vashon, WA) using the same size 48 Durom femoral head component (Centerpulse Orthopedics, Winterthur, Switzerland). The goal of using Sawbones was to investigate different parameters using identical geometry and consistent mechanical properties. The component was cemented at one of four varus/valgus angles relative to the neck axis: 10°
varus, neutral, 10\(^\circ\) valgus or 20\(^\circ\) valgus (3 each) with neutral ante/retroversion in all cases, based on the range of angles found clinically for a similar system [5]. The center of rotation was set so as to limit changes in the femoral offset. The remaining three specimens were prepared with the component in neutral varus/valgus, but with different ante/retroversion angles: -10\(^\circ\), 0\(^\circ\) (a repetition), and +10\(^\circ\). Of the sets of three components at the same varus/valgus angle, one specimen was tested in the uncompromised state, another with 5 mm of exposed reamed bone, and the third with notching (where possible). Unfortunately, the exposed reamed bone was still relatively strong due to the thick cortical layer on the artificial femurs. Notching in the neutral position would have required reaming unrealistically far, so we instead repeated the uncompromised case. Trial order was randomized. The femurs were potted just lateral to the trochanter line to reduce unnecessary flexibility of the shaft; they were angled 10\(^\circ\) in the frontal plane and 9\(^\circ\) in the sagittal plane, in accordance with the ISO 7206 hip prosthesis testing standard. The potted femurs were placed on a roller-bearing plate to eliminate horizontal forces, then loaded quasi-statically at 20 mm/min to fracture using an Instron 8874 materials testing machine (Instron, Grove City, PA). After testing, the artificial bone material and cement were removed from the prosthesis to allow for reimplantation of the component. Statistical comparisons were made using a Student’s t-test.

**Results:** All of the femurs broke within the femoral neck. The two femurs with superior notching failed at the notch, with significantly less vertical translation (mean 2.2 mm, range 2.1 – 2.4 mm vs mean 3.3 mm, range 2.8 – 3.7 mm; p<0.05), showing less plastic deformation before failure. Femurs with 20\(^\circ\) valgus placement failed at locations significantly farther from the trochanter line than the other femurs, even without notching (mean 11.0 mm, range 10.3 – 11.6 mm vs. mean 6.9 mm, range 4.4 – 9.9 mm; p<0.05). Failure loads did not differ significantly, but the 20\(^\circ\) valgus unnotched femurs tended to fail at lower loads than the other three angles, approaching significance (mean 1236 N, range 1117 – 1356 N vs. 1664 N, range 1142 – 2113 N). Retroversion had no apparent effect, but the one anteverted component had the largest vertical displacement to failure (4.1 mm) and one of the largest failure loads (1879 N). Notching was easier to achieve in valgus due to the larger superior neck radius.

**Discussion:** Although we were unable to recreate the type of clinical failure at the component-neck junction associated with poor bone quality (due to the relatively thick cortical shell), we were able to recreate failure at the notching location. Failure loads were less repeatable than we expected for the artificial bone model, disguising some trends. The consistent, although non-
significant, reduction in failure load with the largest valgus angle was unexpected yet uncemented pilot testing of 12° varus to 12° valgus showed a similar trend. It would appear from video records of the testing and from simulations with foam models that varus placement leads to more pure cantilever-style deformations, with the deformation increasing with distance from the support; by contrast, 20° valgus placement leads to pivoting of the entire head and neck, with bending occurring about the center of the superior neck. These observations correlate with the location of failure. Notching of the inferomedial neck in varus caused the neck to deform in compression at this location, either having no effect or possibly increasing the maximum load carried.

This is the first study we are aware of to assess the influence of relative varus/valgus placement on the strength of the resurfaced construct. We had anticipated superior results for valgus placement, with the upper limit being determined by the likelihood of notching and by the increase in head size, which forces greater bone resection on the acetabular side. The results of this study suggest that optimal placement may lie closer to the neck axis. We plan to test these hypotheses further using paired cadaveric femurs. A finite element analysis would also be valuable to examine the stresses and deformations under the various conditions.

References
5. Shekhman (2005) Trans. 51st ORS.
Computer assisted preoperative planning and cup positioning in total hip arthroplasty

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Introduction: Computer assisted preoperative planning for total hip arthroplasty is used in our institution since 1990 on the basis of computer assisted designed custom femoral stem¹. Due to the recent developments in computer intraoperative assistance, the logical evolution was to obtain three dimensional data for intraoperative cup positioning during total hip arthroplasty (THA).

The purpose of this study is to evaluate the performance of a dedicated software for cup positioning combined to the computer assisted preoperative planning routinely used in our institution for total hip arthroplasty.

Material and Methods: The hip surgical procedure used an imageless cup positioning computer-based navigation system, Hiplogics Universal Protocol (Praxim Medivision®), in an antero-lateral approach with the patient in supine position. This system is CT-free, based on Bone Morphing.

An Iliac Hard-body was positioned on the acetabular roof trough the conventional exposure, and a temporary femoral hard-body was placed on a Verbrugges retractor. Lewinneck plane was obtained by external palpation with the special palpation device. Then the acetabular bone morphing was realized and the spatial pelvic reconstruction obtained. After reamer navigation the cup impactor navigation was realized in order to control peroperative cup anteversion and abduction angles.

A controlled randomized cross match prospective study was realized including two groups of 20 patients with assessment of French Ethic
Committee. In the first group, cup positioning was assisted by computer-assisted orthopaedics systems (CAOS group). In the control group, we performed a free-hand cup placement (Control group). All the patients were operated by the same surgeon in the same anterolateral approach. The acetabular component was a hemispherical non-cemented socket and the femoral stem was a custom made prosthesis (Symbios®).

Cup positioning was evaluated post-operatively for each patient by an independent observer on CT-scan with a special cup evaluator software. CT-scans were performed one month after surgery for all patients with the same protocol in the same center. Cup anteversion and abduction angles were measured. The accuracy of the navigation system was evaluated by the comparison of the per-operative anteversion and abduction angles and the post-operative angles in the navigated group. Then we compared accuracy and reproducibility of computed assisted cup positioning versus free-hand positioning. Statistical analysis was performed by the hospital statistic department.

**Results:** There were 10 males and 10 females in each group. The mean age was 63 years in the two groups (33 – 80). The mean Body Mass Index was 24. The mean acetabular cup diameter was 52 millimeters. The mean operative plane abduction angle was 30° (25 – 46), the radiological one was 35° (25 – 47) and the anatomic one was 36° (27 – 48). The mean in operative plane anteversion angle was 14° (0 – 25), in the radiological plane 13° (0 – 26), in the anatomic plane 19° (0 – 27). There were no statistical differences between the peroperative angle and the postoperative angle for the CAOS group. There was no statistical difference between the CAOS group and the Control group for the abduction and inclination but the CAOS group had a lesser margin of error.

Mean additional time of the CAOS procedure was 13 minutes (8 – 20). We never needed additional skin incision. Intraoperative subjective agreement of the surgeon with the computer guidance system demonstrated a high correlation in 12 cases, weak correlation in 8 cases and a poor correlation in 0 cases.

**Discussion:** The results of this study are in accordance with the recent ones published on the subject showing less variability for cup positioning when using a navigation system. Whether the definition of correct acetabular orientation is still debated, the effect on hip stability and optimal range of motion is proved. The combination of an optimal cup positioning to a three dimensional designed prosthetic neck may provide the best conditions for adequate range of motion after THA while reducing the risk of potential
This study has shown the reproducibility of the procedure and the accuracy of cup positioning using a navigation system. This intraoperative computer assisted control combined to the computer assisted preoperative planning realized during the process of custom designed stem may offer the correct solution for restoring hip geometry after THA, especially for difficult cases.

It was important to validate the first step of computer assisted cup navigation in order to promote the procedure in combination with standard stem since the system may provide intraoperative assistance for optimal neck orientation in case of modular neck.

The next steps will be the potential for reducing error analysis by using echo-morphing instead of skin reference planes, and the development of computer-assisted guidance of stem introduction, either standard or custom.

References

Computer-assisted hip osteotomy surgery with near real-time biomechanical feedback

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Introduction: The current state of research has shown the advantages and significance of using biomechanics and joint contact pressure calculations in planning a hip osteotomy (Hipp et al., 1999). Intraoperative assessment and visualization of the biomechanical state of the joint during surgery can further enhance results. Improved outcomes can be achieved for the following reasons: 1) Often a modification in final shape of the cut of bone fragment due to individual variation in bone shape and quality and thickness of cortical structures may become necessary, 2) bone and tissue impingement should be checked during surgery and, 3) intraoperative testing of the hip range of motion provides better assessment of joint stability.

In this paper we report a portion of our ongoing effort to develop and test an intraoperative biomechanical guidance system (BGS) that will be interactively used during hip osteotomy surgery. The BGS interacts with the surgeon and reports the biomechanical state of the joint during the operation. It uses information from the preoperative CT data and computer-assisted navigation system and displays the contact pressure distribution in the hip joint as the joint alignment is modified intraoperatively.
Figure 1  Setup for testing the accuracy of the three-screw technique. The Figure shows Faro Arm measuring the coordinates of one of the screws on the bone fragment prior to the osteotomy. Also shown are the Polaris active tools attached to Femur and Pelvis

Availability of accurate kinematic and geometric data (e.g., 3D joint alignment angles during osteotomy) is a prerequisite for the development of a reliable BGS system. The detailed architecture of the BGS is described in the Methods section below. The Results section presents our preliminary analysis of the registration accuracy and its implications for the measurement of realignment angles of the osteotomized bone.

Methods: Presently the BGS uses a Polaris camera to track the femur and the acetabulum and calculates the contact pressure distribution on the acetabular cartilage. The pelvis, proximal femur and its condyles, and the acetabular cartilage surface are segmented from their preoperative CT data. To register the pelvis with the CT data, several points on the surface of the bone near the line of osteotomy are digitized and matched to the segmented pelvis model using a surface matching algorithm. Intraoperatively, three small custom-made screws with alignment grooves cut into each cap are fixed to the bony fragment that will be relocated while the acetabulum is realigned. Prior to osteotomizing the bone, the coordinates of these screws are digitized using a custom-made Polaris tracking probe. At any time during the procedure, the
surgeon can digitize the new coordinates of these screws with respect to the registered pelvis model. The BGS then calculates the new orientation of the fragmented bone with respect to the pelvis and finds the contact pressure distribution and the location and magnitude of the maximum contact pressure for the range of motion. During the procedure, the range of motion of the hip is determined by attaching an active rigid-body tool to the thigh and tracking it with respect to a rigid-body tool attached to the pelvis. The surgeon finds the range of motion of the hip by abducting, flexing, and extending the thigh. Given the orientation of the thigh, the BGS also calculates the contact pressure distribution for the extreme orientations of the thigh. The BGS uses discrete element analysis technique (DEA) to calculate the joint contact pressure distribution. Because DEA is very fast and approximates the pressure distribution with few parameter settings, it is ideal for near real-time application to the surgery.

**Results:** The accuracy of the three-screw technique for registration and tracking of the fragmented bone was tested. Three custom-made screws were attached around the acetabulum of a plastic bone. The coordinates of these screws were measured using a custom-made Polaris tracking probe, and a FARO arm (accuracy 0.005 mm). The transformation between the coordinates of these two systems was calculated by performing point-cloud matching using the screws. Osteotomy was simulated by rotating and translating the acetabulum of the pelvis and measuring the location of the three screws in the Polaris system. The location of the screws in the FARO arm system was then predicted and compared with its actual location.

As the distance between the screws and the registration point was varied over a range of 40 – 280 mm, the prediction error on the location of the screws on the acetabulum remained less than 2 mm. This error roughly corresponds to an error of less than ±3 degrees in the realignment angles of the osteotomy. Furthermore, the prediction error did not increase significantly as the acetabulum was moved away from the registration point, and thus the percentage of the prediction error decreases for the greater realignment angles.

**Discussion:** The validation of DEA for calculating the contact pressure distribution around the hip joint was reported previously (Armand et al., 2002). The results from this paper suggest that DEA can successfully predict the location of the maximum pressure when accuracy better than five degrees is not required. In light of reported prior results, the 2 mm prediction error obtained from the BGS appears to be acceptable. The three-screw registration technique offers a tool to check the orientation in cases with difficult anatomy.
The variability between the predicted error and the distance between the acetabulum and the registration point suggests operator error as a likely cause. Difficulty in touching the tip of the alignment groove in the screw cap with the tip of the designed Polaris probe may contribute to this variability. Further improvement in the design of the screws and the Polaris probe should therefore improve the accuracy of the system.

References

3. This work is supported by grant number R21 EB002881-01 from the National Institute of Biomedical Imaging and Bioengineering (NIH/NIBIB).
Three-dimensional biomechanical analysis of acetabular osteotomy for preoperative planning

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Introduction: During preoperative planning of periacetabular osteotomy, surgeons commonly attempt to reproduce the joint coverage seen in the normal hip. Since the structure of dysplastic hips may vary markedly, such realignments may not necessarily result in optimal planning of surgery. The preoperative planning of periacetabular osteotomy was investigated using three-dimensional contact analysis on six patients based upon pre- and postoperative CT. A contact model was developed using the Discrete Element Analysis (DEA) technique, giving an estimation of the distribution of pressure on the cartilaginous regions of the hip joint including peak pressure and contact area. The computationally-efficient nature of this technique facilitates biomechanically-founded exploration of the repositionable parameters either pre-operatively or intraoperatively.

Methods: The study was performed on the CT data of six patients without a history of femoral head deformation or a radiographically detected deformation of the femoral head. Preoperative radiographs and CT scans were taken at one week prior to surgery and at a minimum of 4 months postoperatively using a standardized technique (Lepistö et al., 1998). In these surgeries, the surgeon aimed to correct multiple characteristic angles in order to reproduce values typical of a normal joint.
The cartilaginous region of the acetabulum was segmented from axial CT (z = 1 mm) on a patient-specific basis. In each case the unique shape was identified by selecting the bounding edges of the cartilage on each slice of the pre-operative scan. These edges were then curve-fit to form a spherical shell. Osseous landmarks were identified on both the pelvis and on the acetabular cup region, which was separated and rotated in the procedure. A point-cloud to point-cloud technique based on least-squares (Arun et al., 1987) was used for registration of the cup with respect to the pelvis. Once the position of the acetabular contact region was quantified in the pre- and post-operative cases, contact analysis was performed to determine the effectiveness of these interventions.

The DEA technique (An et al., 1990) approximates contact pressure and contact area for a system in which non-deformable bodies interact through an elastic substrate. The appropriateness of this method is based on the assumption that under normal physiological loading cases the cartilage deforms significantly compared to the osseous components. A system of linearly compressive springs was distributed uniformly across a contact midsurface corresponding to the cartilage region. Standing loads were approximated by static analysis of the hip joint in the frontal plane including body weight, hip abductor force (at 21 deg), and the hip joint force. Within the analysis, the joint force was applied through the center of the femoral head and system constraints were applied such that the pelvis was rigidly fixed and the femur was free to move within the joint.

A) Pre- and B) post-operative three-dimensional biomechanical analysis of the joint contact pressure for the same patient. Decrease in pressure is a function of reorientation of the load bearing surfaces; the magnitude of the joint force is constant between cases.
**Results:** Total calculation time for each case was under 1 second for the average 4000-element spring system. Peak pressure was reduced by an average factor of 2.1 due to the repositioning and contact area was increased by 57%. While the lateral coverage of the femoral head was increased in all patients, it did not proportionally reduce the maximum contact pressure. In fact, in one case it slightly (by 0.2 MPa) increased it. Both positive and negative rotation of the cup in the transverse plane was observed, however these rotations were not independently correlated to the reduction of the maximum contact pressure. Notable discrepancies were observed between the 2-D versus 3-D analysis results in two cases. In one case the present analysis predicted a reduction in peak contact pressure whereas the former analysis predicted an increase; the dominant rotation of the cup for this case was 50° in the transverse plane. In the other case, over-rotation of the cup in the 2-D analysis resulted in medially developed peak pressures whereas inclusion of the anterior and posterior horns in this study prevented such phenomenon.

**Discussion:** A simple but well-implemented biomechanical model such as Discrete Element Analysis is ideal for exploration of the rotational repositioning parameters of the acetabular region. The rapid computation time brings this biomechanical analysis into the realm of near real-time applications. Results were compared with a previously completed two-dimensional analysis using radiographs of the same subjects (Armand et al., 2005) which suggests that improved results can be obtained using the 3-D method which accurately represents the entire contact region within the hip and includes the effect of multi-dimensional rotations of the acetabular cup. The ratio of pre- to post-operative peak contact pressure observed in the present study was comparable to those published in the two dimensional study. In two cases it was shown that the 3-D model produced significantly different biomechanical results from the 2-D model and this was explained by two facts: 1) In the 2-D model the alignment change in the transverse plane could not be assessed and it seems to contribute to the final contact pressure change seen postoperatively, and 2) The anterior and posterior horns of the contact surface, not seen in the 2-D model, seem to contribute remarkably to the final biomechanical outcome. Improvements to this model will be made to include a wider range of physiological loads beyond the simple standing scenario considered here. These results imply that real time biomechanical assessment during surgery may be beneficial and offer a new tool to assess realignment of osteotomized acetabular fragments with individually varying structure.
References


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Computerized hexapod assisted orthopaedic surgery (CHAOS) in the correction of long bone fracture and deformity

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Introduction: Complex long bone deformities are difficult to correct acutely using conventional osteosynthesis. Gradual postoperative correction often requires the use of an external fixator, which is applied for a period of several months.

We have used the software driven potential of the Taylor Spatial Frame to achieve intra-operative correction of complex deformities prior to internal fixation using conventional techniques.

The Taylor Spatial Frame is an external fixator, which uses the principle of the Stuart-Gough platform to manipulate defined points on a long bone. The established clinical applications include accurate reduction of fractures, gradual correction of chronic deformity and specific indications including bone transport. The fixator consists of two parallel rings, which are connected with adjustable struts in a hexapod configuration. The rings are attached to bone with tensioned fine wires or pins.

The calculations required to alter the configuration of the fixator and therefore the position of the bone fragments are performed using web based software.

Methods: We report the use of this technique in the management of complex deformities of the distal femur in ten patients. The patient group includes neglected fractures and established deformity occurring as a result of pathological conditions including multiple enchondromatosis (Ollier’s disease) and hypophosphataemic rickets.
The components of the deformity were analyzed from orthogonal radiographs using established geometric techniques. The Taylor Spatial Frame was used to effect precise realignment of all components of deformity prior to internal fixation.

The femur was stabilized using a locked intra-medullary nail or a minimally invasive plate osteosynthesis. The fixator was removed in the operating theater after the bone had been stabilized.

**Results**: We report the results of ten consecutive patients that have been managed using this technique.

Seven patients had post-traumatic deformity and three had non-traumatic bone pathology. In all cases, precise reduction was achieved per-operatively and this was confirmed with postoperative radiographs.

The Taylor Spatial frame was used in chronic residual mode and all components of the deformity were corrected simultaneously. Stability was achieved using locked intramedullary nail (seven patients) or LISS plate (three patients). There were no complications associated with this technique and in particular, there was no loss of correction following fixator removal, no neurological injuries and no hardware failure.

Several strategies were developed to allow the insertion of the appropriate internal fixation device. They include careful pre-operative determination of wire and pin position and the use of incomplete or oversized rings to allow unrestricted access to the bone.

We will describe the construct and surgical technique in detail.

**Discussion**: We have found this to be a straightforward method of managing difficult deformity. The technique utilizes the considerable versatility of the Taylor Spatial Frame and the precise control that is associated with software driven correction. It produces anatomical and mechanical correction of the affected bone allowing rigid fixation with conventional devices.

The technique is straightforward, reproducible and associated with a low incidence of complications.

It has added another dimension to the surgical treatment of severe deformity with considerable advantages over alternative techniques in terms of patient experience and technical implementation.
Navigated freehand bone cutting for TKR – More experiments with more detailed 3-d quantitative surface comparison to conventional cuts

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Introduction: Previous studies in Pittsburgh [1] and Nebraska [2] showed feasibility of navigated freehand bone cutting with CAOS. The latter aimed towards minimally invasive TKR surgery with smaller incisions by eliminating the need for cutting jigs altogether. The cutting tool and bones are tracked in real time allowing the computer to guide the surgeon during cutting through meaningful graphical feedback – a form of “virtual” dynamic template. However, the quality of the navigated freehand cuts and their speed should at least match the conventional approach to justify use of this novel concept clinically. The study of [2] evaluated early navigated freehand cuts for TKR and compared them with conventional jigs in a pseudo-3D manner.

This study presents a new, larger, and more controlled set of experimental TKR distal femoral cuts using an improved freehand navigated CAOS system. Conventional jigs were also used as controls for comparison. Two new navigated tools were introduced into the system: A surface probe and an implant trial. The first was used to evaluate the orientation of each planar cut surface during cutting, and the second to assess the fit and positioning of the implant after the bone reshaping was completed. Another addition which makes this study much more comprehensive is the way the cuts were quantitatively assessed. The implant fit/tightness, implant alignment and the errors in 3-dimensional location of individual surfaces carved versus their
Methods: An experimental in-house developed CT image-based CAOS system was used for freehand-navigated cutting. It utilized an NDI Polaris infra-red tracker for navigating a battery-driven oscillating saw, a surface monitor, an implant trial and the bones (Fig. 1). All were fitted with passive
reference frames “registered” as rigid bodies with an algorithm which was tested independently.

Identical physical bone models were cast with a suitable foam material from a mold replicating the distal femur of the female right knee of the Visible Human Project [3]. To provide controls for comparison, the five plateaus for a common TKR femoral component were aligned and cut conventionally with a combination cutting jig. In navigated-freehand cutting, the computer rendered, dynamically in real-time, realistic 3D models of the saw, bone and planes along which the blade should be orientated at any instant. The user navigated the ‘implant trial’ and ‘surface monitor’ to test the fit/looseness of the implant, and refined their cuts accordingly. In a strict protocol, the ‘implant trial’ was later navigated to record all the positions in which the femoral component could plausibly be cemented with this set of cuts without loss of the original registration. This objectively gathered raw data for assessing fit/tightness and alignment/location of the implant for each experiment.

All bone samples were digitized by CT scanning at (0.39x0.39x0.65mm) resolution and reconstructed in 3D. The five cut surfaces were digitally extracted for each bone for further calculation of surface roughness, translational and three rotational deviations from the desired location of that particular surface.

Two experienced arthroplasty surgeons and one modestly trained user performed the experiments. Each cut two bones with jigs and four bones with navigated freehand. The cutting of each whole bone was timed till completion of all surface refinements to adjust for implant fit.

**Results**: The results (detailed in Fig. 1) showed 15% saving in time with navigated freehand compared to using conventional jigs. The freehand cutting produced almost 200% rougher surface (measured by mean Ra) compared with jigs. The Ptm parameter shown in Fig. 1 represents the difference between the means of the highest 10 peaks, and the deepest 10 valleys. Cutting with jigs was again smoother with less severe peaks and valleys. Fit resulted looser with navigated freehand cutting than with jigs, but the best with freehand navigation was slightly better than that with jigs. Implant alignment was examined by its errors (i.e. deviations from ideal at the best possible location assuming perfect cementation technique). The “implant trial” did not have a fixation stem, so there was no constraint on medial-lateral translation, and thus no data in ML errors were applicable. The mean of all errors in AP misalignment with navigated freehand cutting were almost four times less than with jigs. In Flexion-extension, frontal varus-
valgus and internal-external rotation the mean angular errors were all also much lower with navigated freehand. The mean of the flexion-extension alignment errors with jigs reached nearly 4 degrees with jigs, but was lower than 0.25 degree freehand. Fig. 1 shows the superior overall alignment with navigated freehand was not accompanied by any worse outliers compared to jigs.

**Discussion:** Previous experiments [2] showed freehand cutting to be 35% faster than conventional. The previous saving in time was partly expended in these experiments by the users utilizing extra navigated tools to improve the quality of their cuts, and improvements in quality were indeed achieved. The higher surface roughness of the navigated freehand cuts presents a problem, and will direct future work on the technique towards smoother finishes, possibly with hand rests to reduce shaking.

Navigated freehand cutting, as simple as the technique may appear, is still at its infancy and will require a serious research effort with cutting edge software development.

**References**

The Tubes™ for minimally invasive computer-assisted hip resurfacing surgery

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Introduction: Hip resurfacing (HR) has significant potential for younger and more active patients requiring surgery, since it conserves bone, provides more physiological loading, reduces the potential for dislocation and allows for revisions. However, HR is technically demanding with a long learning curve, it requires a large incision to allow instrument alignment, and has a greater risk of failure if the prosthesis is not implanted correctly.

This paper presents a new technology – the Tubes™ System for Minimally Invasive (MI) Hip Resurfacing – which addresses the problems of conventional HR. The system allows HR to be performed in a truly MI manner – conservative on the soft tissue by minimizing the incision and the degree of tissue retraction required, whilst maintaining the conservation of bone in contrast to other MI total hip procedures.

The Tubes™ System is unique amongst computer-assisted navigation systems since it incorporates a small, low cost mechanical digitizing arm to track surgical tools, thus avoiding many of the issues associated with optical tracking systems.

Methods: The current embodiment of the Tubes™ System uses a pre-operative planning software module to plan the operation based upon a CT scan. The scan allows the surgeon to plan the operation accurately and obtain a mental map of the anatomy prior to surgery, while free from the pressure of the intra-operative environment. Use of CT also allows the system to achieve
the greatest accuracy, and is the only available method which can be used to give an accurate assessment of procedure outcome in terms of planned versus achieved implant position [1]. The planning process takes approximately 30 minutes – 25 minutes of radiographer time for segmentation and bone model generation, and 5 minutes of surgeon time to verify and plan component position. The planning software also allows the surgeon to check that the prosthesis position coincides with a good bone interface, and to check the kinematics.

The patient is placed on the operating table in the lateral position. The pelvis is held using a customized non-invasive positioning system which ensures the pelvis remains in a vertical position throughout the procedure, and minimizes motion. A restraint is placed on the patient’s knee to constrain the femur during registration and preparation, but the leg remains free at all other times. The system is draped separately and introduced to the sterile zone once patient draping is finished.

The surgical approach to the joint is through two “mercedes” incisions, an anterior approach through which the acetabulum is prepared, and a posterior incision which allows preparation of the femoral head. This approach allows for minimal tissue trauma in terms of both the size of the incision and the degree of manipulation of the soft tissues. However, the system does not dictate the surgical approach – all conventional approaches may be used. The initial incision is dilated using a series of tubes of increasing diameter up to a size large enough for surgery.

The acetabulum is registered by touching points on the bone surface using a probe connected to the digitizing arm. The probe is removed once the registration is verified and the arm is connected to a reamer. Reaming of the acetabulum is performed using on screen information to guide orientation and depth. The acetabular component is introduced at the correct orientation by following the display.

The femur is registered by collecting points on the femoral head and trochanters. Once the bone is registered and the position verified, the probe is replaced with a drill guide. The surgeon places the drill guide into the planned position using on screen guidance and drills down the femoral neck. The femoral post is inserted into the hole and the flat cut on the top of the femur is made using a tracked cutter. The post and bone flat constrain the remaining cutting tools to finish preparation of the femur. Once the femoral component is inserted, a tracked depth guide is used to ensure that the component is fully seated.
Results: Laboratory tests have shown the accuracy of the digitizing arm fitted with a sterile registration probe is within 0.6mm. This is inside the margin deemed acceptable by [2] for optical tracker-based systems. We have validated this acceptability using computer-based registration simulations which have led to a protocol which restricts registration errors to within 1.5mm translation, 3° anteversion and 1.5° inclination for the femur, and 1.5mm translation, 4° anteversion and 3° inclination for the acetabulum. The protocol requires sets containing 20 points for the femur and 30 points for the acetabulum, to provide registration within the above ranges with a 95% confidence interval. Our error margins are within those described in the literature for acetabular component placement using comparable optical tracker based systems (5° inclination, 6° anteversion) [3]. No data could be found in the literature regarding the accuracy of femoral component during computer-assisted HR. The post-operative method described in [1] will be used to evaluate the clinical performance of the system.

The Tubes™ System is currently undergoing regulatory approval to enable use in clinical studies starting in April 2005. The concept has been proven on plastic bones under laboratory conditions, and cadaver trials have validated the anatomical approach. Results from the clinical validation will be presented.

Discussion: The Tubes™ System provides the potential to perform HR surgery through a minimal incision whilst ensuring the prosthesis is inserted
accurately every time. The system is expected to be in the final stages of commercialization by third quarter 2005.

The Tubes™ System is a collaborative project between The Acrobot Company Limited, Corin Group PLC, University College London Hospitals and Imperial College.

References


Ultrasound guided scaphoid pinning

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Introduction: This abstract describes the results of a feasibility study of a new scaphoid pinning procedure using pre-operative planning and intra-operative ultrasound (US) guidance.

Scaphoid fractures are the most common wrist fractures. Treatment options include casting, percutaneous pinning, and open reduction pinning. However, complications like mal- and nonunions are also common due to the bone's poor blood supply [1]. Percutaneous pinning reduces the risks associated with invasive procedures, but often involves taking many intra-operative fluoroscopic images. Apart from the exposure to the ionizing radiation, another drawback is the two-dimensional nature of X-rays, which limits the three-dimensional (3D) orientation of the surgical tools.

We propose to replace the intra-operative fluoroscopic imaging for this specific application with a combination of pre-operative planning using 3D surface models generated from computed tomography (CT) images and intra-operative US images to guide the surgeon during positioning of the surgical tools.

Methods: To determine whether intra-operative ultrasound guidance during scaphoid pinning is feasible, CT images were taken from an artificial human scaphoid bone (Sawbones Inc.) using a GE LightSpeed scanner at Kingston General Hospital. The in-plane resolution of the images was 0.188 × 0.188 mm and the images were 1.25 mm apart (interpolated to 0.625 mm). Mesh software developed at Queen's University was applied to segment the bone's geometry from the CT images and to generate a three-dimensional surface model using a marching-cubes algorithm. Then the scaphoid phantom was
rigidly mounted on a stainless steel jig equipped with a dynamic reference body (DRB).

After the jig was placed in a tub of room-temperature water, US images were taken using a 12 MHz, one-dimensional array GE Voluson transducer, which was also equipped with a DRB. The DRBs were tracked using a Certus optical tracker (Northern Digital Inc.) with a frequency of 6 Hz. The US images were captured through a frame-grabber, which was synchronized with the Certus camera. Using an in-house developed method the US transducer was calibrated, so its position and orientation with respect to the reference DRB on the jig was known. Semi-automatic registration of the 3D surface model to the segmented US images using an iterative closest point algorithm was applied to position and orient the model with respect to the reference DRB on the jig [2].

A drilling interface that communicated with the Certus camera was developed using VTK 4.2 (Kitware Inc.) and Qt 3.2.1 (Trolltech AS) libraries. Using this interface the tip of a stylus and the drill bit could be calibrated by pivoting and the stylus was used to measure the center of the drill head, which together with the drill tip position determined the direction of the drill bit. The drill entry location and direction were selected on the bone model using the mouse pointer. The drill hole was visualized by means of a line surrounded by a cylinder with a radius of 2 mm. The scaphoid model with drill hole, and a graphical representation of the drill were shown in real-time to facilitate the user aligning the drill with the virtual drill hole.

To investigate the reproducibility of the measurements, a hole was drilled in the jig and repeated measurements of the location of this hole were taken using the stylus as well as the drill. The accuracy of registering the 3D surface model to the US images was investigated by taking measurements on the surface of the scaphoid phantom using the stylus. Finally, three K-wires (diameter: 2 mm) were drilled into the phantom guided by the drill interface.

**Results:** The measurements of the location of the calibration hole in the jig had a standard deviation of 0.13 mm (n=37) using the stylus and 0.25 mm (n=28) using the drill, respectively. The accuracy of the registration of the 3D bone model to the US images was determined by taking measurements on the scaphoid phantom using the stylus. The mean of the distance was 1.347 mm with a standard deviation of 0.82 mm (range: < 0.5 mm – 2.9 mm; n=26).

The three K-wires were drilled through the bone with varying success, primarily due to user interface problems. Placement within 2 mm of the planned position was achieved.
Discussion: Registration between the 3D bone model and the limited view US images requires relatively accurate placement of the images in initialization. This placement is readily facilitated by knowledge of the approximate registration from gross anatomy. With a good initial estimate it is feasible to provide accurate automatic registration and drill guidance from US in real-time.

Further work on the user interface is required to improve reliability and simplify operation. Additional testing will establish performance variation over different human operators.

References


Differences in patellar tracking between intact and replaced knee with and without patellar resurfacing: An in-vitro study

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Introduction: Patellar maltracking after total knee arthroplasty (TKA) introduces complications such as anterior knee pain and patellar subluxation [1,2]. Prosthetic component malalignment in both tibio-femoral (TF) and patello-femoral joints are generally considered the main causes of this maltracking. In particular, it is still debated if it is necessary to resurface the patella, which would better adapt the patellar articular surface to the prosthetic femoral trochlea with prosthesis, but also would result in possible bone fractures [2]. In this study, an in-vitro analysis on three amputated knees is presented in order to identify differences between intact and TKA patellar tracking with and without patellar resurfacing and to show how much the latter is similar to intact knee patellar tracking.

Methods: Three fresh-frozen amputated legs with the knee free from anatomical defects and with intact joint capsule, ligaments and quadriceps tendon were analyzed using the Stryker® knee navigation system (Kalamazoo, MI-USA). Clusters with active markers were pinned on the femur, tibia and patella. The standard pointer was used for system control and landmark digitation. Series of five trials of manually driven TF flexions were performed under conditions of 10 kg on the quadriceps, with intact knee and TKA with patella resurfaced and not. The landmarks were used to define anatomical frames for femur and tibia according to recommended definitions [3]. Medial and lateral patellar prominences and the patellar apex were used to define a patellar anatomical frame with origin in prominence mid point,
anterior-posterior axis as normal to the plane for the apex and the prominences, proximo-distal axis along the vector from the apex to the origin, medio-lateral axis as normal to the previous two axes. TF flex/extension, intra/extra rotation, ad/abduction were calculated according to a standard articular convention [1]. Patellar flex/extension, medial/lateral tilt, rotation and shift were calculated according to the articular convention proposed by Bull et al. [3]. These conventions measure flex/extension about the medio-lateral axis of the proximal bone, intra/extra rotation and medial/lateral tilt about the proximo-distal axis of the distal bone, and ad/abduction and medio-lateral rotation about the floating axis normal to both previous two. For each group of trials, standard deviation and mean value were calculated at each single degree of TF flexion. Patellar shift is the translation of patellar anatomical frame origin along medio-lateral femoral axis.

**Results:** A TF flexion from 0° to nearly 140° was achieved by all specimens. In the figure, and below, the results relative to both TF and PF joints are reported from a single well representative specimen.

![Rotations and patellar shift inside the intact and replaced knee, both with and without patellar resurfacing](image-url)
**TF add/abduction:** A continuous adduction from 0° to 4° is observed in the intact knee throughout the whole TF flexion range. From 0° to 110° TF flexion, the prosthetic knee without patellar resurfacing presents an adduction like in the intact knee. Differently from the intact knee, the prosthetic knee with patellar resurfacing presents a continuous abduction.

**TF intra/extra rotation:** The intact knee rotates internally from –16° to –4° between 0° and 30° TF flexion, reaching almost 10° of external rotation in near full TF flexion. The prosthetic knee both with and without patellar resurfacing presents a continuous intra rotation for –10° to –5° throughout the whole TF flexion range. The manual operator could affect this rotation, thus causing differences in intra/extra rotation between intact and prosthetic knee.

**Patellar flexion:** A linear increase in patellar flexion, from 20° to 110°, is observed throughout the whole TF flexion range. Also in the prosthetic knee, the patella, both with and without resurfacing, flexes in the same way, but, from 0° to 40° TF flexion, the patella without resurfacing flexes like that in the intact knee.

**Patellar rotation:** The Patella in the intact knee rotates medially from 12° to 8° between 0° and 70° TF flexion, and laterally up to 12° from 70° to near full TF flexion. In the prosthetic knee, the patella without resurfacing rotates also medially and laterally as in the intact knee, even if it is rotated more laterally in full TF extension. In case of resurfacing, the patella rotates differently from that in the intact knee.

**Patellar tilt:** In the intact knee, between full TF extension and 70° TF flexion, the patella tilts laterally, from 4° lateral to 4° medial; from 70° to near full TF flexion, the patella tilts medially up to almost 5°. In the prosthetic knee, the patella without resurfacing tilts like that in the intact knee, even if it is tilted more laterally, on average 5°, throughout the whole TF flexion range. In case of resurfacing, the patella tilts differently from that in the intact knee.

**Patellar shift:** In the intact knee, the patella shifts laterally. Likely accounted for the surgical technique for femoral prosthesis implant, in the prosthetic knee, both with and without patellar resurfacing, the patella shifts medially, differently from that in the intact knee.

By not resurfacing, original patellar tracking, at least for flexion, rotation and tilting, seems to be nearly restored in phase of TKA.

**Discussion:** In this in-vitro study on three anatomical specimens, similarities between natural and TKA patellar tracking with not resurfaced patella are shown. The natural patellar tracking seems to be reproduced by not resurfacing the patella. Non-resurfacing shall be preferred where the original
patellar tracking is nearly physiological, thus preserving also the native patella from fracture, likely in case of resurfacing. Resurfacing would be performed selectively, as in case of severe deforming arthritis causing patellar maltracking.

References


Soft tissue tightening in the intact and prosthetic knee: In-vitro analysis with a navigation system

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Introduction: Knee ligament tightening at appropriate flexion angles is one of the surgeon targets for a successful total knee arthroplasty (TKA). Slacken or tighten soft tissues can result in restricted and not natural knee motion. Patellar tendon (PT) also plays an essential role as part of the extensor apparatus, whereas the anterior (ACL), the posterior (PCL) cruciate ligaments, the medial (MCL) and the lateral (LCL) collateral ligaments play the important role of guiding and stabilizing the knee in full tibio-femoral extension and flexion [1,3].

In this study, an in-vitro analysis on three knee specimens, by means of a navigation system, is presented in order to identify differences in tightening patterns, between intact and prosthetic knee, by observing the length change of selected fibers in these soft tissues.

Methods: Three fresh-frozen amputated legs with the knee free from anatomical defects and with intact joint capsule, ligaments, and quadriceps tendon were analyzed using the Stryker® Knee Navigation System (Kalamazoo, MI-USA). Standard clusters with active markers were pinned on the femur and tibia. The standard pointer was used for system control, and digitations of anatomical landmarks and bone-ligament attachments. Bony landmarks were used to define the anatomical frames for the femur and tibia according to standard recommendations [2]. Series of five trials of manually driven flexions were performed and collected under condition of 10 kg on the quadriceps, with intact knee and after TKA.
Soft tissue lengthening
Bone-ligament attachments were digitized after the identification of sub-bundles attachments [1,3]. In the cruciate ligaments and MCL, two sub-bundles were identified: the anteo-medial (AM) and the postero-lateral (PL) in the ACL, the antero-lateral (AL) and the postero-medial (PM) in the PCL, the anterior (AB) and the posterior (PB) bundles in the MCL. Strips of points along ligament fibers in known anatomical positions were collected: along the most anterior and the most posterior fibers in the LCL; along the most anterior and the most posterior fibers of AB in the MCL; along the most medial, central and lateral fibers in the PT.

The centroids of the attachments are considered as origins and insertions of single fibers that are representative of the whole ligament or sub-bundles. For the LCL, MCL and PT, extremities of the collected strips relative to anatomical fibers were also considered. For each trial group, mean value and standard deviation of fiber length were calculated at each single degree of flexion by linear interpolation. The length of each fiber was calculated as the distance between the femoral origin and tibial, or fibular, insertion. Moreover, also the attachments and the lengths of the most isometric fiber for all ligaments and PT were also considered.

**Results:** A flexion from 0° to nearly 140° was achieved by all specimens. In the Figure, the results are reported from a single well representative specimen. In the left and right columns, the results respectively in the intact and replaced knee are presented, whereas each row refers to a ligament. In all plots, the legend labels indicate the length between the centroids of the sub-bundles, between the extremities of the digitized strips, and the length of the most isometric fiber.

ACL. In the intact knee, both sub-bundles are tight around 0° flexion in full extension. Further, both of them begin to slacken, but from 30° up to near full flexion, only PL tightens, whereas AM remain slack. The most isometric fiber, inside AM bundle, lengthens almost like AM. Since resected during TKA, ACL is absent in the prosthetic knee.

PCL. Both in the intact and prosthetic knee, AL and PM play opposite roles during flexion. In near full flexion, AL is slack and only PM is tight, whereas in full flexion it is the contrary. The resection of the ACL in TKA delays AL tightening and anticipates PM slackening. The most isometric fiber, inside PM bundle, lengthens in part like PM.

LCL. Both in the intact and prosthetic knee, the degree of tightening is higher in the first 30° of flexion. The high length variability of the most isometric fiber suggests that among the knee ligaments, all LCL fibers are subjected to the highest length variability.
MCL. In this ligament, the fiber lengthening is not affected appreciably by the TKA. All fibers are tight in near full extension, whereas only AB fibers are tight in near full flexion. The isometric fiber, inside AB, lengthens like AB central bundle fibers.

PT. Whereas in the intact knee, fiber tightening occurs in the first 60° of flexion, in the prosthetic knee this occurs in the first 30° of flexion. This could be due to the bottom of the resurfaced patella, which was implanted more proximally than the original.

Discussion: As observed, the several fiber bundles play different roles during flexion [1], and these are modified by the implant. In order to restore the natural knee motion, an appropriate knee soft tissue tightening is essential during a TKA. In this sense, a navigation system is very useful. By frequently monitoring the state of soft tissue tightening, those factors, altering the flexor/extensor mechanism and the effectiveness of the stabilizing effect of knee ligaments, can be recognized and corrected. This is true not only during a TKA, but also during knee ligament reconstruction. Moreover, by simply digitizing bony-ligament attachments, it is possible to identify the origins and insertions of the most isometric fibers. These, especially in the cruciate ligaments, seem to control passive knee flexion, and their bone-ligament attachments are frequently used to locate the grafts in case of ligament reconstruction [1,3].

References

Tunnel placement in computer assisted anterior cruciate ligament surgery

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Anterior cruciate ligament (ACL) reconstruction is a widely accepted treatment of choice for functionally unstable knees due to ACL knee injury. The aim of reconstruction of ACL injuries is to prevent progressive symptomatic knee joint instability which can further damage and injure the structures of the knee joint and progress to osteoarthrosis.

Commonly, two types of graft material are being used for the reconstruction of ACL, an autogenous bone-ligament-bone graft that involves one-third of the patellar ligament and an autogenous graft involving the hamstring tendons.

The procedure involves either open or arthroscopic techniques.

Less invasive techniques of ACL reconstruction have evolved over time with minimal trauma to the extensor mechanisms and scarring in the knee.

Intra-operative placement of graft is the main source of error that could lead to early failure of Anterior cruciate ligament (ACL) reconstructive surgery [1]. Anatomical variation of the notch geometry is an added burden. To minimize this source of error we used computer assisted tunnel placement [2] in open method of ACL reconstruction using bone patellar tendon as an autogenous graft.

Aim: To illustrate our clinical experience from January 2003 to December 2004.

Materials: We studied 18 patients, all male, 8 patients with right knee injuries and 10 with left knee injuries. Their mean age was 31.15 years (range 18 to 50 years) presented to our senior author with clinically and radiologically [MRI] confirmed ACL injury. Only 13 had arthroscopic
confirmation before we carried out biological repair. We have excluded multiple ligamentous injuries of the knee and revision of ACL surgery. 70% of the study population group had sustained some kind of sports injury. 12 of these 18 patients had meniscal tear which had been treated during arthroscopy. 6 of these patients had articular changes but none required any intervention.

**Methods:** Lateral incisions were made and Graft median diameter 10mm prepared from the lateral third of the patella, including quadriceps aponeurosis, part of the patella and ligament leaving a distal attachment with the proximal tibia.

Using orthopilot navigation system extraarticular and intraarticular anatomical data as well as knee kinematic data were obtained.

The tibial tunnel exit point on the tibial plateau was 5 mm anterior to anterior margin of posterior cruciate ligament with knee joint 90 deg flexion and 44% of the coronary width of the tibial plateau beginning with the medial position.

The femoral tunnel was placed 5mm from the posterior margin of the fossa.

The graft then passed through the trans-osseous tunnel so that the bony part of the graft stays within the femoral tunnel. The remaining part was sutured with the ilio-tibial tract.

The patients began immediate knee exercises with continuous-passive-motion devices in the recovery room. With 100 degrees of knee motion, they allowed to bear full weight on the operatively treated limb with the knee in a brace in full extension

**Results:** 3 patients had superficial wound infection and 2 had haemarthrosis. None had any laxity or flexion contracture; the mean flexion was 135 (130 – 145).

**Conclusion:** We had no graft failure in the early post-operative rehabilitative phase. None required notch plasty.

**References**

The role of navigation-supported minimally-invasive total hip replacement in daily practice by means of the SAL-device

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Introduction: Minimal Invasive Total Hip Replacement is rapidly gaining importance. Faster rehabilitation, thus shortening of hospital stay and increased patient comfort promote the use of this type of procedure. For patients with BMI > 28 or heavy muscular patients, MIS procedures are not recommended. Limited view and the necessary, modified patient position to get access to the acetabulum and the femur create difficulties, particularly when broaching the femur. Surgical Navigation is proposed as a tool to securely perform MIS THR. The criteria for the selection of an MIS approach are the possibility of extending the incision, if necessary, as well as the learning curve, the potential of additional risks and the possibility to support the procedures by navigation.

Methods: 50 consecutive patients were operated by a single surgeon using an MIS antero-lateral approach: 8 – 9 cm skin incision, splitting of the tensor fasciae latae tendon, approach to the hip joint between M. gluteus medius and M. tensor without muscle dissection.

No preoperative patient selection was done. All patients were operated under spinal anesthesia. Surgery was performed in supine position using a special positioning device – the SAL-device – that allows free mobility of the operated leg. All patients were operated with support of a navigation-system (PIGalileo, PLUS Orthopedics, Aarau, Switzerland) for acetabular reaming, positioning of the acetabular component, broaching of the stem and stem positioning. An uncemented press-fit cup (EP-FIT) and an uncemented straight-stem (SL) were implanted in all cases. OP time, complications and hospital discharge were recorded.
**Results**: Based on the evaluation of plain X-rays, all cups were positioned within the desired angulation. Body Mass Index was not a contraindication for the chosen MIS approach in our patient population. With one female patient, navigated surgery could not be performed due to insufficient fixation of the skeleton-fixed navigation markers, because of osteoporotic bone quality. This patient was operated using the same procedure but not navigated. In one case an evacuation of a haematoma was necessary two days after operation. OP time was 1h 10 min +/- 7.5 min. Due to early mobility, the hospital stay of the MIS patients was shortened by 3 – 5 days compared to patients that got standard THR.

**Discussion**: The learning curve involved with starting an MIS Total Hip procedure is easier to pass if the change can be done in steps. The anterior-lateral approach in combination with the chosen patient positioning enables the surgeon, used to supine positioning, to pass this learning curve in secure steps. Navigation is a valuable tool to compensate for the missing visibility due to the MIS procedure. The positioning of the cup and the stem in correct angulation and seating depth can be securely done due to navigation support. Proper leg-length and correct joint-offset within narrow tolerances can be achieved by navigation.

Compared to standard procedures, the difference in early outcome was primarily the possibility of early mobilization and thus, early hospital discharge of our MIS patients. In our opinion, the additional effort for the use of navigation is highly justified in MIS procedures, due to the contribution in security of bone preparation and implant positioning. The described procedure enables faster rehabilitation, which is an economic benefit and a significant advantage to the patient.

**References**

2. Th. Sculco, Minimally Invasive Total Hip Arthroplasty. The Journal of Arthroplasty Vol 19, No 4, Suppl. 1 2004
A new optical system for measuring fracture healing at external fixators

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Introduction: In the case of complex fractures of bones, the external fixator is often used for the stabilization. When the patient applies a mechanical load to the extremity treated in such a way, the external forces applied to the broken bone are taken over by the fixator and the bone. In an early phase of the fracture healing, the fixator will have to take almost 100% of the forces whereas in a later phase of the healing process the increasing rigidity of the bone healing tissue leads to a partial transfer of forces via the healing bone. Therefore, the distribution of forces between fixator and healing bone represents an indirect indicator of the progress of bone fracture healing. Using a standardized and well defined introduction of forces into the bone, a deformation of the fixator body and the bone screws can be measured which depends on the force introduced and the healing progress of the bone.

Systems that were used up to now measured the deformation between the bone screws or used strain gauges glued to the fixator body in order to electronically measure the deformation of the fixator.

These systems were used by several groups [1 – 4]; however they did not reach clinical relevance as they were too complicated to use, too complex from the technical point of view or too expensive.

Methods: A system for measuring the deformation of an external fixator body has been developed. An optical measurement system using a differential photodiode and an IR light emitting diode was used for measuring the tiny deformations of the fixator body. A first version of a measuring electronics was developed, tested and calibrated. In contrast to previously used systems,
the proposed new measuring system can be easily fixed and removed from the fixator body of various manufacturers by using special magnetic adaptor pieces. The system is able to measure reliably the very small deformations of the fixator. Due to the short rise time of the photo current of 500 ns of the detector used, dynamic load measurements at the fixator body can be performed.

**Results**: The optical measuring system was calibrated against a strain gauge applied to the external fixator body. Applying repeatedly a load of 250 N to the fixator screwed to a fractured artificial bone resulted in a deformation of the fixator body of 250 microstrain with a standard deviation of 0.8%. Using the optical system, a signal of 906 mV with a standard deviation of 7.7% a load of 250 N could be measured which corresponds to a fixator body
deformation of 187.8 microstrain. A simulated fracture healing using no material, soft material with a stiffness $k=0.3^6$ N/m and a hard material with $k=2.3^6$ N/m in the bone fractures zone showed that the developed system has sufficient resolution to monitor the healing process of fractured bones. Hereby, the stiffness of the fixator with screws fixed to the bone was $k=1.36^6$ N/m. Figure 1 compares the measured optical deflection signal for different materials used in the fracture gap. At a load of 150 N, a clear difference between the measured load curves can be discerned which allows the surgeon to evaluate the state of the healing process.

Discussion: The difference between the strain gauge measurement and the optical measurement of 25% can be explained by the fact that the strain gauge locally measures strain whereas the optical measurement averages the strain over the whole length of the detection system of 48 mm. The elasticity of the fixator body is increased at the two fixation points where the length of the fixator body can be varied. The strain gauge however was glued far away from these fixation points which explains that the strain gauge measurement is 25% increased compared to the optical measurement. However this is no disadvantage compared to a strain gauge measurement as the degree of fracture healing is not measured as an absolute value but as the reduction of the fixator deformations compared to an initial state with open fracture zone. The signal obtained is therefore independent of the mechanical properties of the fixator body.

The measured standard deviation of 6% – 8% in the optical measurements of the fixator deformation can be further reduced by an improved mechanical guiding of the optical components reducing the influence of lateral forces on the optical measurement system.

References
TKR and ligament balance by CAS

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Introduction: To obtain a good outcome in TKA it is mandatory to reach a balanced flexion-extension gap. That requires, during surgery, to choose the amount of bone resection and the position of the prosthetic component, mainly the femoral one. These choices are based upon some bone landmarks, but overall could be based upon a proper ligament’s tension, as a preview of ideal kinematics.

About this topic several authors published in the last decade, but the determination of a value of ligament’s tension still remains a big issue.

In our last three years C.A.S. experience we thought about a device useful to measure, to evaluate and to record the ligament’s tension.

So we made an hydraulic knee analyzer (HKA®) computer integrated and we tested and validated by a cadaveric study.

Aims of this study are to validate the reproducibility, in vivo, of the results of the cadaveric study, and subsequently to evaluate the outcome between two groups of patients who underwent surgery, one by conventional technique and the other by C.A.S.

Methods: Twenty patients were operated by C.A.S. (Navitrack® Centerpulse-Zimmer) and HKA®, twenty patients were operated conventionally, by the same surgeon and utilizing the same prosthesis (Innex® Centerpulse-Zimmer).

Pre-operative and post-operative study was performed by: Lower limb X-ray, IKSS score and SF 36 score.

Intraoperative evaluation, through ROM, of the actual pressures measured by the device (HKA®) was performed on the trial implant in both groups; to check the correspondence between the planned tension and balance and the achieved ones.
Postoperatively all patients were tested by a fluoroscopic joint stability test.

**Results:** In all the C.A.S. patients the result was an aligned and balanced knee, both in flexion and extension, connecting the obtained gap and the measured applied tension by HKA®.

In all patients who underwent either C.A.S. or conventional technique, a subjective stress testing was performed by the surgeon using spacer blocks.

The comparison between two groups of patients has underlined less outliers in the C.A.S. group than in the conventional one. The poorest outcomes are in those patients in which the subjective stress testing by the surgeon did not detect a subclinical compartment abnormality while the HKA® recorded an intraoperative compartment pressure imbalance on trial implant; most of these imbalances were recorded in flexion than in extension.

At the time of the meeting it will be presented the functional result of the surgery including a fluoroscopic joint stability evaluation test, the average follow-up being 21 months (min 18 – max 24).

**Discussion:** The CAS with HKA® and its intraoperative outputs provide the surgeon with quantitative feedback on gap balance and ligament tension, being more sensitive than surgeon feel especially in flexion where variables including tourniquet placement, patient leg size, and ability to stabilize the knee during testing can make qualitative assessment of ligament balance difficult.

Of course the measurements made by device are likely to be different from those experienced with weight bearing and other activities of daily living. Therefore it functions more appropriately as a relative, rather than an absolute, measure of compartment pressure.

The future could be an improvement of the sensor device and a new ability of CAS to evaluate and to integrate all the variables influencing knee kinematics.

**References**


3D visualization using fluoroscopic images acquired in virtual fluoroscopy

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Introduction: Fracture reduction and precise localization of targeted areas in the bone in 3D space are important applications for CAOS with potential for reducing radiation. However, virtual fluoroscopy systems typically project planned locations on a number of 2D images. Thus, surgeons must infer 3D position and structure from these projections. Any visualization in 3D is currently achieved either by pre-operative CT scan [1] or recently through intraoperative Iso-C3D (Siemens) [2]. Both methods need significant X-ray exposure to reconstruct a precise 3D volume. However, such detailed 3D images are not always needed during surgery, where alignment of the bone or only the exact location of the target is needed. In many cases, regularly updated real-time information is more important than a detailed 3D model of the bone. A good example is long bone fracture reduction. In such cases, the numerous X-ray exposures that are needed to reconstruct the precise 3D shape can not be justified.

The aim of this study is to provide 3D reconstructions of the bone, without additional X-ray exposure or preoperative images, and using the ordinary image intensifier. The detail of the reconstructions must be of sufficient quality to perform most tasks in operative fracture fixation, and should be easier to comprehend than the equivalent 2D projections.

Methods: The virtual fluoroscopy equipment comprises of a computer workstation and an optical tracking system. Optical tracking targets are attached to the surgical instrument, bone and a registration phantom. A minimum of two sets of images in the C-arm AP and lateral positions are acquired by an ordinary image intensifier. Calibration of fluoroscopy images is obtained preoperatively (typically once a month) by using a calibration plate containing a grid of radio-opaque balls attached to the X-ray reception
tube. A distortion-undistortion map is created and used to correct the deformation in images obtained intraoperatively. The registration phantom [3] when placed in the fluoroscopic imaging space permits the position of the X-ray source and image plane to be accurately determined and displayed.

An additional view is reconstructed by visualization of both images in their respective planes in 3D space. In this view, a 3D reconstruction of the bone is also created based on the available X-ray images, and displayed as a shaded surface model. This is achieved by outlining an area of interest in the bone in the fluoroscopic images, and then back-projecting this outline towards the X-ray source for each image. The intersection of the resulting volumes is used to compute a 3D bounding volume which encloses the area of interest. For example, in the case of long bone fracture treatment, the whole bone is outlined in both views. The reconstructed bone surface is then immediately visible in the 3D view. The tracked instruments are also visualized in real-time on the same 3D view.

The surgeon currently marks the outline in the images, and the areas of interest can be chosen arbitrarily. They could include bones, fragments, nails, screws and other features. Additional fluoroscopic images can be taken if needed, to improve the detail of the 3D reconstruction.

**Results:** Using the virtual fluoroscopy system, we have reconstructed 3D models of a displaced subtrochanteric femoral fracture on a plastic bone from two 2D fluoroscopic images. This reconstruction clearly shows the degree of displacement and angulation of the fracture in 3D space. It also clearly
included a reconstruction of the fracture line, the position, the alignment of the medullary canal and the piriformis fossa position in 3D space. This provides sufficient information to establish the direction of the maneuver needed for fracture reduction, insertion of guide wires in the direction of the medullary canal and nail insertion for fracture fixation. This information is displayed in 3D space, instead of projective 2D images, to ease comprehension. Extended in vitro studies are being planned. First results will be available at the time of the conference.

**Discussion:** Current virtual fluoroscopy systems provide planar projections of 3D reality, completely missing the depth information of the third dimension [4], however, it is often important to verify the correct tool or bone alignment in all three dimensions. Accordingly, the current recommendation is to use multi-image features, or to use an expensive new volumetric fluoroscope which increases imaging time and requires numerous X-ray exposures to generate the image. Our new system, which builds on the existing Hull University Computer Assisted Orthopaedics Surgery System – CAOSS [5] bridges the gap between the two systems, and provides a modular system that allows the surgeon to rationalize the radiation exposure and tailor it to the needs of different operations.

Another benefit of this system is that the tracked instruments, for which 3D information is already available, can be displayed in 3D instead of as a projection. The image planes are displayed in their correct relative position, and the mechanism of virtual fluoroscopy is clearly demonstrated. This is likely to help in better understanding of the system on the part of the user, with consequent benefits in terms of system safety.

**References**

A comparative study of minimally invasive computer assisted total knee replacement (MICA TKR) and conventional open computer assisted total knee replacement (CATKR)

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Introduction: Total knee arthroplasty has become one of the most successful procedures in orthopaedic practice since its introduction in the early 1970’s. Since its development it has undergone many refinements, leading to good 10 – 15 year follow up studies. The orthopaedic community is now faced with two new advancements. Firstly the introduction of surgeon controlled computer navigation systems and secondly the increasing use of minimally invasive surgery. The aim of this study was to assess the safety and effectiveness of Computer Assisted TKR through minimally invasive incisions versus open computer navigated TKR.

Method: Forty patients underwent MICA TKR surgery over a five-month period, using the Stryker Knee Navigation system and Specialist navigation instruments developed for this technique. They were compared to forty patients having conventional open CATKR during a similar time period. The minimally invasive surgery involved a mini mid vastus approach whilst the conventional surgery utilized a medial parapatellar approach. All surgery, in both groups, involved the use of the standard Scorpio Knee implants.

The surgical technique for the MICA TKA group utilizes the principles of freehand cutting block placement, minimal soft tissue retraction, no patella eversion, limited patella subluxation and in-situ bone cutting techniques. Freehand block placement allows the surgeon to place the navigated resection
block on any exposed surface of the femur/tibia whilst being guided by the computer navigation system. Thus when using the mini mid-vastus approach, the cutting block was first placed on the medial aspect of the femur, allowing the surgeon to cut in a medial to lateral direction resulting in minimal movement of the patella and quadriceps mechanism. The proximal tibial surface was next resected thus increasing the space within the knee. The distal femur was then resected, after sizing, using smaller 4 in 1 cutting blocks. The navigation system allowed each bone resection to be checked for accuracy prior to progressing with the next step.

After trialling, the components were cemented in situ using simplex cement. The computer navigation system allowed dynamic balancing throughout the range of flexion.

The length of time to achieve straight leg raise, length of stay in hospital and pain scores were recorded. Component alignment was assessed using pre-operative and post-operative long leg standing radiographs. Knee Society Scores were measured pre-operatively, at 6 weeks, 6 months and at 1 year.

**Results:** The mean age of patients was 68 years of age in the MICA TKR group and 65 years of age in the CATKR group. The time for a patient to straight leg raise ranged from day 0 (Operation day) to day 2 for the MICA TKR group and from day 1 to day 5 for the CATKR group. The mean length of stay was 3.3 days (range 2 – 5 days) in the MICA TKA group and 5.7 days (range 3 – 9 days) in the CATKR group. The mean pain score for the first seven days post operatively was 3.4 in the MICA TKR group and 6.8 in the CATKR group. The coronal alignment of both the femoral and tibial components was determined from long leg standing radiographs. The mean alignment of the femoral component was 90.7 degrees (range 89 – 94) for the MICA TKA group and 90.2 (range 89 – 92) for the CATKR group. The mean alignment for the tibial component was 89.7 degrees (range 87 – 92) in the MICA TKA group and 89.7 degrees (range 87 – 91) in the CATKR group.

The pre-operative knee society scores were 55 for the MICA TKA group and 58 for the CATKR. The scores at 6 weeks were 77 (MICA TKA) and 65 (CATKR), at 6 weeks were 89 (MICA TKA) and 72 (CATKR), at 6 months 92 (MICA TKA) and 85 (CATKR) and at 1 year 94 (MICA TKA) and 91 (CATKR).

**Discussion:** This early series included the learning curve for MICA TKA and the development of the technique, whereas the senior author had a significant experience of conventional computer assisted TKA. The results show no difference in the mean alignment of components or the range of component alignment. The ability to reproducibly produce good alignment of femoral
and tibial components in a coronal plane whilst employing minimal soft tissue dissection and ‘in situ’ bone cutting has clearly produced a dramatic improvement in the recovery of not just quadriceps function, as shown in the recovery of SLR but a general improvement in function that has lead to less pain and quicker rehabilitation ultimately resulting in more rapid discharge from hospital. All patients involved were discharged home with the same Intermediate Care service (Hospital at Home). The improved function is further seen in the improvement in Knee Society Scores at 3, 6 weeks and 6 months, although the difference between the two groups is certainly smaller at the 6 month stage.

Whilst the aims of all minimally invasive surgery is to reduce soft tissue trauma, post-operative pain and hospital stays, it is clear that this must not be at the cost of poor surgical positioning of components that will ultimately lead to early failures and revisions. The potential for surgical inaccuracies when operating through small incisions is real and errors can be frequent, as the surgeons’ normal visual landmarks are not always clearly visible. The use of computer navigation has provided many advantages as well as challenges. The use of entirely extramedullary devices means that the medullary canal of either the femur or the tibia is not violated, reducing the risk of cognitive impairment from fat embolism. The ability to cut accurately from the side, checking each resection after it has been performed, leave the joint “in-situ”, too avoid repetitive joint dislocation and produce minimal trauma to the entire soft tissue envelope of the knee, is clearly producing dramatic results, as shown in our short early series.

Whilst this study has limitations of size, it has clearly shown that minimally invasive total knee arthroplasty can be performed reproducibly and safely and that whilst in its infancy MICA TKA may well produce a dramatic leap forward in both surgical technique and patient recovery.
A system for ultrasound-guided computer-assisted orthopaedic surgery

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Introduction: Current image-guided orthopaedic surgery systems typically use preoperative computed tomography (CT) and intraoperative fluoroscopy as their imaging modalities. Because these imaging tools use X-rays, both patients and surgeons are exposed to ionizing radiation that may cause long-term health damage. To register the patient with the pre-operative surgical plan, these techniques also require tracking the targeted anatomy by invasively mounting a tracking device onto the patient, which results in extra pain and may prolong recovery time. The mounting procedure also leads to one major difficulty of using these approaches to track small bones or mobile fractures. Furthermore, it is practically impossible to mount a heavy tracking device to a small bone which restricts the use of image-guided techniques.

This paper presents a novel image-guided method that employs 2D ultrasound as the imaging modality. Medical ultrasound is non-ionizing and real-time, and our proposed method does not require any invasive mounting procedures. Furthermore, the method enables us to image small and mobile bone structures and to accurately register the pre-operative datasets to the patient for real-time surgical guidance – a procedure that has only been possible for large bone structures (e.g., pelvis or femur) in current approaches. The method also differs from previously reported techniques in the literature (see [1, 2, 3]) in that it does not require segmentation of ultrasound images. Therefore, segmentation errors will not be propagated to the registration process.
Methods: Preoperatively, a set of 2D ultrasound images is acquired with the corresponding positional information of the ultrasound probe provided by a tracking system. Using ultrasound calibration parameters, the position of every pixel in the images is transformed into the world coordinate frame to construct a 3D volume of the targeted anatomy for surgical planning. Intraoperatively, the surgeon takes live ultrasound images from the patient with the position of the ultrasound probe tracked in real-time. A mutual-information-based registration algorithm [4] is then used to find the closest match to the live image in the preoperative images. Because the position of the preoperative image inside the ultrasound volume is known, we are able to register the preoperative volume to the patient’s anatomy.

Results: Preliminary laboratory experiments were conducted on both a radius phantom and human subjects. To validate the registration results, a marker was rigidly mounted on the subjects and tracked by the optical tracking system. This allowed the positions to be accurately determined for both the live image and the best matching image. By measuring the difference between transforms (which transform the live and best matching images to the marker frame) we could calculate the registration error. On average, there is a translation error of 0.71 millimeters (in the frame origin) and an averaged
rotation error of 0.13 degrees (in Euler-ZYX angles) for the phantom. For human subjects (on distal radius), two types of experiments were conducted. In the first setup, the live image was taken from within the pre-captured image database, and yielded an average error of 0.49 millimeters in translation and 0.03 degrees in rotation. This result indicated that the registration algorithm itself has sub-millimeter accuracy in localizing the best match between the intra-operative and pre-operative datasets as long as these two closest matches exist. Figure 1 shows the registration result for the radius phantom. In the second setup, the live image was captured at a different time then searched in the pre-captured database, which gave an averaged error of 2.6 millimeters in translation and 1.1 degrees in rotation. In all, these preliminary results are significant and have shown that the registration algorithm and the methodology are capable of satisfying the majority of image-guided applications with the acceptable error range of 2 millimeters.

**Conclusion:** An ultrasound-guided computer-assisted orthopaedic surgery system has been presented. We proposed a novel technique to register live intra-operative ultrasound images with the pre-operative 3D ultrasound data. Laboratory experiments on both a radius phantom and human subjects have shown that mutual information based registration is promising and demonstrate the potential of the presented approach. Further laboratory and clinical studies are on the way to validate the performance of the algorithm under different surgical situations.

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**References**


Single- vs. multi-fiber ligament model: An in vivo kinematics analysis

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**Introduction:** A forward-kinematics knee (FKK) model was previously introduced. Given a joint angle, the precise knowledge of the articular geometry plus the mechanical properties of knee ligaments, the FKK model predicts where the femoro-tibial contacts are based on the principle of ligament energy-minimization. We now introduce a validation protocol: A graphical contact-determination algorithm was developed and independently validated with Fuji-film contact study. The contact-determination algorithm produced a set of in vivo contacts that was contrasted to the set of in vitro contact locations predicted by the FKK model. Once the FKK model was validated, different hypotheses of ligament model were tested. In particular, simulation suggested that a single-fiber ligament model could produce knee kinematics that were very similar to those produced by a multi-fiber (3) ligament model on the Sigma Knee.

**Methods:** Surfaces of a Total Knee Replacement (TKR) were laser-scanned at 0.25 mm resolution and computer models of the surfaces, in the form of point cloud with point normal, were reconstructed. TKR components were mounted to a knee jig where they were held in contact with each other by tensile forces of 6 springs: 3 mimicking MCL, 3 mimicking LCL. The mechanical properties of each of the 6 springs, including spring constant, unloaded length, and insertion locations relative to TKR components, were measured. The entire knee jig was duplicated/simulated using the FKK model.

A Dynamic Reference Body (DRB) was attached to each of the TKR components. TKR components were moved to various orientations, while keeping in contact with each other, and their poses were recorded with a 3D...
optical tracker (OPTOTRAK). Between each recording, pause was given to allow TKR components to rest to a neutral position. The recorded joint angle was used in the FKK to produce a set of in vitro contact locations.

A near-real-time contact-determination algorithm was developed. This algorithm determines the contact between two point clouds by matching points that are in close proximity and having point-normal in the opposite directions. The implementation was facilitated with a generalized-binary-search tree (KD-tree), making it extremely fast. To validate the contact determined by this algorithm, the laser-scanned TKR components were mounted to a FORCE5 manipulator that applied 100 lb of downward force to produce imprints on Fuji-film. Contacts produced by the Fuji-film and by our algorithm were graphically compared (see attached Figure). Once the contact-determination algorithm was validated, joint poses from the recorded knee motion were used in the contact-determination algorithm to produce a set of in vivo contact.

Results: A size-3 Sigma Knee (Johnson & Johnson), represented by approximately 31,000/19,000 points for each of the femoral/tibial components, respectively, was used for this study. On a 2GHz PC, the contact-determination algorithm determines the contact between two surfaces under 1 second. To validate the contact-determination algorithm, the contact imprints of the Fuji-film were digitized and superimposed to those found by the algorithm (see Figure 1). They showed a high degree of conformity.

![Figure 1](image)

*Figure 1  In vitro contact (FKK model) vs. in vivo contact (contact-determination algorithm)*
The knee jig was moved to a total of 171 different poses and two sets of contact location were produced: one predicted in vitro contact from the FKK model, the other observed in vivo contact from the contact-determination algorithm. The average difference of the translations found by these two methods was about 1 mm. Once the FKK model was validated, different ligament models were experimented in attempt to reproduce the same kinematics (i.e. contact locations) as those resulted from the 6-springs model. In particular, a single-fiber ligament model, constructed by averaging the ligament insertion location of the 3-fiber model with an increased spring constant, was found to produce in vitro contact locations that were very similar to the original knee-jig setup.

**Discussion:** A validation protocol, based on graphical contact-determination algorithm, is introduced for a forward-kinematics knee model. The contact-determination algorithm is independently validated using Fuji-films and it computes contacts between two surfaces in near-real-time. The modular design of the FKK model allows each part of the computation model to be tested and experimented separately. It is demonstrated that, in a semi-congruent knee such as the Sigma Knee, a single-fiber ligament model can produce knee kinematics that is similar to a multi-fiber ligament model.

**References**

A modified new reference clamp for minimal invasive navigated operations

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Introduction: During the last years, navigation systems were used increasingly for traumatological indications, especially in the field of spine-pelvic- and foot surgery. Particularly in spine surgery the CT based navigation could prove higher accuracy compared to conventional placement. The stable rigid fixation of the dynamic reference clamp (DRC) in different anatomic regions is an essential step for successful navigation procedures. The dynamic reference clamp has to be fixed rigid close to the region of interest before the data acquisition during ISO C or fluoroscopy based navigation can be done. However, a minimal shift of the DRC can cause remarkable consequences for the registration and the surgery. So far rigid fixation was either achieved with two single Schanz screws of each 4 mm diameter or one larger pin system including a large 8 mm diameter screw. Both pin systems are invasive and can cause artifacts especially in the ISO-C3D navigation system. Their use especially in smaller anatomic regions like the foot is often limited and large surgical exposures are necessary for a rigid fixation. The aim of our study was to develop a new minimally invasive DRC which can easily be fixed and additionally has a high rotational stability.

Methods: We developed a new screw with a diameter of 4 mm, which incorporated an expanding clamp at one end. This enables a fixation of the screw in a 4 mm monocortical drill hole and further fixation by simply mechanical spreading of the clamp monocortically. Thus a stable fixation using a minimally invasive incision becomes possible. After the navigated
operation, the screw can be removed easily by turning the head of the screw backwards, unlocking the fixation mechanism.

First testings were done at cadavers studies. Furthermore, during 5 intraoperative navigated procedures the clamp was used. Three times the use was performed at the foot and angle region and twice during drilling procedures at the femoral head. Artifacts between the conventional 1 pin DRC and the new DRC were compared additionally.

**Results:** All cases did not show any dislocation of the new DRC. Stable fixation was achieved in all cases. The artifacts identified in the Iso-C3D images were significantly less than observed with conventional 1-pin fixation systems. Adequate navigation procedures were possible in all cadaver and clinical cases. There was no evidence of wound infection at the DRC insertion site. Uneventful wound healing was found in every case. Maximum size of the incision was 1 cm.

**Discussion:** Using a minimal invasive DRC, a simple fixation with only one 4 mm pin becomes possible. The appropriate handling allows fast fixation and sufficient navigation procedures also in smaller anatomic regions, without large exposures for a conventional DRC fixation. The compact design shows most advantages in foot and hip surgery and causes significantly less artifacts than conventional fixation systems. Also the use in tibial osteotomies would be favorable, allowing the fixation at the proximal tibial fragment through minimal incisions. At present, comparative biomechanical analysis of the minimal invasive DRC with conventional fixation systems has already been started.
Possible effects of artifacts on the Iso C-3D navigation

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Introduction: It was shown in the past that Iso-C 3D navigation could be very precise in experiments as well as under optimal conditions in clinical treatment. Beside the source of error of the hardware, the calibration of the Iso-C is a decisive step as the acquisition of data is the foundation of the navigation. The fixation of the reference base too far from the isocenter can lead to significant mistakes in the registration progress. The fixation too close to the path of ray or metallic implants can lead to significant artifacts. These artifacts can aggravate the localization of lesions in the operation field. This study evaluates the effect of artifacts caused by different metals as titanium and steel particularly with regard to the verification.

Methods: A T-piece was manufactured of synthetic bone material (Synbone, Switzerland) with the size of 92 x 50 mm (cube 1, Region of Interest, ROI) and 335 mm x 50 mm (cube 2, for the fixation of the reference base). On cube 1, 12 PVC markers (2 mm diameter) were fixed. On cube 2 the reference base was fixed 100 mm from the isocenter. 5 scans were taken for each metal, i.e. a Schanz screw of titanium (4 mm diameter), a Schanz screw of steel, a 5-hole plate and without any metal. The Iso-C-3D Siremobil® was used. For the scanning the T-piece was placed on a carbon table and with the help of a laser placed in the isocenter. This data set was transferred via NaviLink-interface (Siemens) to the navigation system in the mode of Iso-C-3D navigation. As navigation system the Surgigate® (Medivision, Oberdorf, Switzerland), including an Ultra 10 Workstation (SUN Microsystems, Palo Alto, CA) and an Optotrack 3020 optoelectronic localizer (Northern Digital Inc, Waterloo, Ontario, Canada) was used. The precision of the optoelectronic camera is declared with 0.1 mm in translation and 0.1º rotation. The camera was placed in 2 m distance from the isocenter in each experiment. The registration was analyzed by “reverse verification” with a pointer in a purpose-built manipulateable three-dimensional holder. The mean error was calculated from the average of the 12 markers and 5 scans for each metal.
Results: The more metal was placed in the scan area the larger the mean error got. The metal screws that are fixed too close to the isocenter lead to considerable artifacts in the Iso-C 3D scan and to significant mistakes in the verification. The achieved error values lay between 0.05 and 0.7 mm. The titanium screw was not significantly better compared to the steel screw as seen in the Figure below.

Failure of registration in relation to artefacts due to metal

Discussion: The registration is a decisive process of navigation. As a source of error anatomical pair-point registration was several times mentioned in literature among incomplete resp. deficient acquisition of data, segmentation and drill bending. With the help of a training curve, a couple of them could be reduced in most instances. The self-acting registration of Iso-C 3D navigation at the moment of data acquisition reduces the incidence of errors within the complete process of navigation. But implants and dynamic reference bases that are fixed too close to the isocenter lead to considerable artifacts in the Iso-C 3D scan. The results indicate that the registration is getting worse with more metal in the scan area. The achieved error values lay between 0.05 and 0.7 mm. It can be arrived at the conclusion that a lot of metal could have an influence in clinical treatment with Iso-C 3D navigation. It could be helpful to develop new reference clamps that contain less metal or are made of radiolucent materials (polyetheretherketone) to produce relief and to minimize this source of error.
Influence of navigated soft tissue balancing on the height of the so called “joint line”

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Introduction: One unsolved problem of the TKA-instrumentation is the definition of the optimal tibial and femoral resection height in order to rebuild the natural joint line. Most of the instrumentation advice concerning that point is inaccurate. With the classical resection we remove more bone on the lateral than on the medial tibial side and vice versa on the femoral side. Additionally we have the dorsal slop of the tibia. The orientation should be on the healthy or on the damaged side? There is no concrete advice in manual and navigated instrumentation. In order to reach perfect balanced gaps the distal femoral cut sometimes must be changed. Does this necessity lead to a relevant change of the joint line?

Methods: 50 consecutive patients with a navigated TKA-implantation are examined. The OrthoPilot System Version 4.0 including gap-balancing and the e.motion knee system was used. In all cases a classical resection was done. The natural joint line was defined perpendicular to the mechanical axis. The height is half of the difference between the most distal parts of the medial and lateral femoral condyle. This height is compared with the height of the most distal part of the implanted femoral component.

Results: The median of the height of the medial and lateral resected bone on the femoral side was built and compared with the thickness of the implanted femoral component. The biggest difference between medial and lateral resection was 10.9 mm, the average difference was 3.1 mm. There was no femur with more resection on the lateral side than on the medial side. 44 cases show a change of the joint line in a range of ± 3 mm. In 6 cases the joint line was changed to a larger extent. The maximum change was 4.5 mm.
proximalisation. 30 cases show a proximalization, 20 cases a distalization. The average change is a distalization of 0.2 mm.

**Discussion:** Today we have no perfect tool to restore the joint line. It is still a question of the definition of the so called joint line. Depending on this definition we have to look for good points or areas to give a navigation-system a relevant input with respect to the slopes. A lot of basic science has to be done. Even this study shows only data from deformed knees. Which amount of proximalization or distalization is tolerable? What tells biomechanical science about the resulting forces? How relevant is a patella bacha? What is more important, the restoration of the natural joint line or the perfect balancing between flexion and extension-gap? Is classical resection in times of navigation still useful or is a natural resection the best way out?

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Introduction: Joint replacement is now accepted as a safe and reliable procedure with a significant impact on quality of life. While awaiting surgery, patients’ health deteriorates, yet access to such treatment worldwide is limited by the cost of the procedure, the physical resources of theatre time and hospital beds, and by the human resource of surgical skill. There is a significant re-operation rate that is principally attributable to implantation error [1].

Computer-assistance devices have been developed to improve reliability using navigation, and fully active robots [2, 3]. Surgical navigation has reduced the number of outliers as defined by radiographic criteria, but improvement in outcome has been hard to document. Fully active robots have also had problems preventing their acceptance. We report a prospective, randomized, controlled trial of minimally-invasive unicompartmental knee arthroplasty using a hands-on robotic assistant, the Acrobot® System.

Methods: Recruitment

31 patients on the waiting list for unicompartmental knee replacement were invited to participate in the study. All accepted the invitation. Randomization
was performed blind, using numbers concealed in envelopes prepared by an independent party. Post-operative assessment was also blind.

Test device

The Acrobot® System used is a hands-on robotic device for orthopaedic surgery. It is the most recent in a series of devices which share the same essential characteristics. It consists of a high speed drill that is mounted on a robotic device which the surgeon holds and directs. The Acrobot® System actively prevents the surgeon from cutting bone away outside the area defined in the pre-operative plan, but servo-assists the surgeon when the drill is within the area of bone to be milled away.

Outcome measures

The primary outcome measurement was the difference between planned and achieved joint lines for both tibia and femur in the coronal plane. The post-operative CT scan was co-registered with the pre-operative plan. The resulting change in varus-valgus alignment was calculated from the proximal/distal translation error (achieved vs. planned), obtained in millimeters, for both the femoral and the tibial components. Other variables were also measured but, since they have not been described by other authors, comparison is not possible.

Secondary outcome parameters studied included the American Knee Society (AKS) Score [4] and Western Ontario and McMaster Universities Osteoarthritis (WOMAC) [5] index, pre-operatively and at 6 weeks, all adverse events and specifically device-related and procedure-related complications, and the operating times.

Statistical methodology

The study hypothesis was that the Acrobot® System achieves angles of tibio-femoral alignment on the coronal plane within ±2° in >99.9% of UKR patients, versus a predicted (from the literature) percentage of 48% with conventional surgery.

Results: Treatment details

27 analyzed subjects (28 knees) were treated over a 6 month period in 2004. Operating time (skin to skin) has a mean of 95 ± 18.1 minutes and it is higher in Acrobot treated subjects (104 ± 16.6 vs. 88 ± 16.3 minutes). The difference in operating time between the two types of surgery does not reach significance.
Primary outcome parameter
Tibio-femoral angles were transformed into dichotomous data (angles ±2° or > ±2°). All (13 out of 13) of the Acrobat cases were ± 2°, while 9 out of 15 (60%) of the control group were outside this limit. Both Pearson chi-square and Fisher's exact test were calculated and results are statistically significant (p=0.001).

Secondary outcome parameters
- AKS score
- The difference between type of surgery is statistically significant (p=0.004) at the non parametric test.
- Proximal/ distal translation error
- Femoral and tibial post-surgery proximal/ distal translation error (achieved vs. planned) was analyzed.

Compound Errors
All 6 degrees of freedom (3 degrees of translation, and 3 degrees of rotation) were measured. A plot depicting improvement in AKS scores versus translational accuracy is presented (Figure 1).

![Figure 1  Compound translational accuracy against difference between pre-op and post-op AKS scores](image-url)
Discussion: Accuracy in arthroplasty

Improving the accuracy with which arthroplasty is performed has been shown to improve function. The use of CT scans in the assessment of implant accuracy has enabled a much more detailed inspection of the impact of surgical technique to be undertaken. While the relationship between accuracy and arthroplasty has been suspected, it has been difficult to prove radiographically. Without a way of ensuring accuracy, there has been a reluctance on behalf of surgeons to address the issue: measuring the inaccuracy of an implantation is pointless unless there is something which can be done to prevent it. The post-operative CT scan protocol we have developed allows the precise position of any implant to be determined. It is our suggestion that this precision of post-operative measurement will allow detailed explanation of the previously inexplicable variation in outcome of outliers in knee arthroplasty.

Future Prospects: By permitting the creation of bone surfaces that can be machined by means other than an oscillating saw, the Acrobot® System paves the way for novel implant designs to be developed. These should facilitate bone conserving arthroplasty in the knee, hip and spine and even less invasive but more reliable procedures.

Conclusions: The accuracy of prosthesis implantation affects the success of the operation, as measured by the function of the joint in the early post-operative period. By enabling accurate and complex bone sculpting, the Acrobot® System has been shown to enable the surgeon to perform knee surgery precisely and reliably with repeatable superior outcomes.

References
Anterior cruciate ligament reconstruction using knee joint laxity measurements and a bendable ligament model

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Introduction: Injury to the anterior cruciate ligament (ACL) is the most common ligament injury in the knee, resulting in over 50,000 reconstructions per year in the United States [1]. Ligament reconstruction can be a technically challenging procedure, however, and recent studies show that a significant number of ACL reconstructions are being improperly positioned in surgery. The knee joint complex is indeed interconnected with several structural ligaments and surrounding tissues, which may or may not be functioning normally at the time of surgery. Trauma related injuries which cause ACL rupture can often entail damage to these other surrounding structures which are also critical for insuring adequate knee function, rotatory stability, and normal kinematics.

Although various clinical tests exist for assessing the integrity and function of the ligaments in the knee, objectively incorporating clinical test results into the surgical plan can be illusive. We have therefore been working to effectively integrate knee instability measurements into a kinematic based image-free system for guiding both intra-articular and extra-articular ligament reconstructions. In addition, we have integrated a new “bendable” ligament model that is capable of “wrapping around” curved bone surfaces, for simulating impingement and anisometry as a function of the patient specific 3D joint kinematics and morphology, and the planned placement.

Methods: Upon review of the various clinical tests for assessing knee injuries and instability, we selected four protocols for intraoperative evaluation [2]:
Each test can be performed at various stages in the procedure, for pre- and post-reconstruction comparisons, for example. For each test, various key landmark points are selected on the bone surface and are used to calculate and display the corresponding laxity values (for example, the internal and external tibial glenoids). The system then guides the surgeon in performing each test by displaying in real time the 3D BoneMorph models, along with the flexion angle, the landmark point trajectories and their maximum displacements in the relevant planes/directions. Upon reviewing the reported kinematic trajectories and maximum displacements, the surgeon can then decide to alter the plan accordingly, by for example, adding an external stabilizing ligament on medial side of the knee.

Table 1 Maximum laxity values before and after graft fixation for the anterior drawer, varus-valgus stability, Lachman’s tests and pivot shift test

<table>
<thead>
<tr>
<th></th>
<th>Anterior Drawer Test</th>
<th>Varus-Valgus Stability Test</th>
<th>Lachman’s Test</th>
<th>Pivot Shift Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medial</td>
<td>Lateral</td>
<td>Medial</td>
<td>Lateral</td>
</tr>
<tr>
<td>PreOp</td>
<td>9.7 ± 2.4</td>
<td>13.5 ± 2.3</td>
<td>15.6 ± 4.2</td>
<td>19.4 ± 4.6</td>
</tr>
<tr>
<td>PostOp</td>
<td>1.9 ± 0.9</td>
<td>5.8 ± 1.1</td>
<td>2.4 ± 1.2</td>
<td>3.4 ± 1.4</td>
</tr>
</tbody>
</table>

The system passively guides the placement of both intra-articular and extra-articular ligaments using isometry and impingement maps superimposed on the bone surface models. In addition, the predicted ligament length variation curve is displayed as a function of the flexion angle and insertion sites. The bendable ligament model is calculated and displayed in real time as a function of the position and shape of the bones and the planned fixation points. The graft simulation is based on a non-linear energy criterion that monitors collisions with the 3D bone surface during the kinematic measurements. The application has been integrated into the open platform Surgetics Station (PRAXIM-medivision, La Tronche, France) [3].

Results: Over 50 ACL reconstructions have been performed with the system to date. Postoperative knee stability was markedly improved with respect to
the preoperative laxity measurements in all cases. Table 1 summarizes the
mean (± standard deviation, SD) of the maximum displacement values
before and after graft fixation for the medial and lateral tibial condyles
relative to the femur during the anterior drawer, varus-valgus stability, and
Lachlan’s tests. In addition, the pivot shift test, which measures the anterior
subluxation and reduction of the tibia within the 10 – 40° window of flexion,
is represented by the characteristic parameter d (Table 1). In computing d, the
trajectory of the midpoint of the anterior inter-meniscal ligament during the
pivot shift test is compared with the initial neutral knee flexion acquisition.

Discussion: Quantitative laxity measurements are extremely useful for
intraoperative guidance and planning of knee ligament reconstructions. The
instability caused by traumatic injury to the ACL and other structures
surrounding the knee can be objectively characterized and interpreted with
the abovementioned kinematic tests. In particular, fixation of extra-articular
grafts, to stabilize an injured medial collateral ligament for example, can be
diagnosed, planned, and navigated with such a system. The bendable graft
model, in combination with the displayed impingement and isometric data,
prove particularly useful for guiding placements in these types of
reconstructions, where the curved outer surfaces of the femur and tibia can
significantly interfere with the graft trajectory during flexion. The renderings
aid the visualization of the ligament trajectory, by depicting how the “virtual”
ligament glides overtop of the 3D bone surface models as the knee is flexed
and extended.

References

[1] Frank CB, Jackson DW, The Science of reconstruction of the anterior cruciate
[2] Scuderi GR Scott NW: Classification of Knee Ligament Injuries. In Insall and
Scott (Eds) Surgery of the Knee, Chapter 29, pp. 585-599. Churchill Livingstone
2001
into a system for computer-assisted anterior cruciate ligament surgery. Med Image
Is computer-assisted surgery worthwhile in high demanding knee replacement?
A matched paired study

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Introduction: Computer assisted surgery has been developed to help surgeons in reconstructive procedures in improving implants alignment and performances. In literature different authors have already demonstrated its efficacy in traditional knee replacement surgery despite different alignment systems. Nevertheless no study has analyzed its results in high demanding replacements such as in significant limb and articular deformity with bone loss and multiple ligaments instability. The authors assessed their experience in high demanding computer assisted knee replacement matching every patient with traditional implants performed by the same authors.

Material and Methods: Among 353 computer assisted knee replacements performed since 1999, 14 cases were selected according to limb deformity and bone loss (Group A). Criteria of inclusion were a limb deformity of at least 15 degrees or an articular bone loss type 2 according to the Anderson Orthopaedic Research Institute Classification. Two cases were following complex intra-articular knee fractures and 2 cases following failed high tibial osteotomy. In all the cases a computer-based CT-less alignment system (Orthopilot, 2.0 and 4.0 versions, Aesculap, Tuttlingen, Germany) was used. Different surgical solutions have been adopted. In 4 cases a bi-unicompartmental knee prosthesis (UC-Plus Solution Plus, Rotkreuz, Switzerland) was implanted, in 5 cases a PCL sparing prosthesis (Search and Evolution, Aesculap, Tuttlingen, Germany) was implanted and in 6 cases a PCL sacrificing or constrained implant (Nexgen PS and CCK, Zimmer, Warsaw, Indiana, USA) was implanted. Every patient was matched to another case treated using conventional knee alignment systems (Group B) according to sex, age, bone
mass index, pre-operative limb deformity, ligaments stability and bone loss. Surgical time, type of the implant, bone resections and augmentations/wedges used, limb alignment Knee Society clinical score at the last follow-up were considered in the study for both groups.

**Results:** The surgical time was significantly longer in the computer assisted group. In the traditional group despite similar deformity/bone loss a constrained implant was used more frequently associated to a high number of wedges. Computer assisted prostheses were significantly better aligned than implants performed with traditional guides which includes 2 cases of “patella baha” because of major tibial bone resection. The mean post operative flexion was 120° in group A and 100° in group B. The Knee Society clinical score was statistically higher in group A. At the latest follow-up in Group A no case has been revised compared to 1 case in the group performed using traditional alignment systems because of a septic loosening of the tibial component.

**Discussion:** Even if this matched paired study has some evident limitations, the results according to the author’s experience reveals different advantages of computer assisted surgery in high demanding knee replacements. Despite a longer surgical time less invasive implants, bone sparing associated to better alignments produce better results compared to traditional systems. Improved results can overcome higher costs because of surgery time and systems purchasing.

**References**

In-situ evaluation of a force-measuring device for assistance in ligament balancing during knee arthroplasty

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Introduction: Total Knee Arthroplasty (TKA) is nowadays routinely performed with a satisfactory success rate. However, postoperative complications such as instability, component loosening and premature wear limit the lifetime of the prosthetic implants. Tibio-femoral misalignment and ligament imbalance are the surgically controllable factors that influence these problems. While current navigation systems help achieve an optimal tibio-femoral alignment, the soft-tissue imbalance is only assessed qualitatively through manual movements of the limb. A few systems aim at measuring the forces or pressure within the knee joint: the Tekscan array pressure transducers; the Fuji pressure-sensitive films; a mechanical tensor/balancer [1]; a robotic distraction device [2]; an instrumented tibial implant [3]. However, they show various drawbacks such as low accuracy, need for patella dislocation, lack of robustness or measurements at a late stage of the surgery. A force-sensing device that intraoperatively measures the ligament forces and moments was developed to overcome the above disadvantages.

Methods: The device is inserted into the knee joint following the tibial cut, but before any femoral cut (see Figure). Consequently, the joint stability can
be assessed at the beginning of the surgery, offering the possibility to make a better plan for the femoral cuts and the femoral component rotation. Thanks to its small size and thickness, the device entirely fits into the knee joint and measurements can be performed with the patella in its anatomical place, thus avoiding undesirable forces that a patellar eversion may induce. The device bilaterally measures the amplitude and location of the condylar compressive forces with respective accuracies of 1.4 N and 0.6 mm [4]. Based on these measurements, the net varus-valgus moment, which is considered as the biomechanical parameter characterizing the ligament balance, can be computed.

In order to evaluate its in-situ functioning, the device was tested with a cadaver specimen mounted on a knee joint loading apparatus previously described by Dürsel et al. [5]. This machine allows the monitoring of the relative angular position of the femur and tibia as well as the application of varus-valgus moments on the tibial side with the help of weights and pulleys. It was therefore possible to mechanically reproduce the current surgical approach of ligament balancing. Intraoperatively the surgeon determines and manually compares the varus and valgus forces that must be applied at the ankle to create a lateral or medial condyle lift-off. With the knee joint loading apparatus, we determined the varus and valgus weights required to compensate the lateral and medial contact compressive forces. In order to validate the device’s diagnosis, the ratio of these weights, which intraoperatively characterizes the knee stability, was then compared to the ratio of the measured forces and moments. In a second step, the effect of collateral ligament release was quantitatively evaluated. Following an initial medial imbalance created by the insertion of spacers pulling away the femur and tibia, a standard medial collateral ligament release was performed. The
internal joint forces and moments were measured and compared in both situations.

**Results:** During the comparison of the apparatus-monitored and device-assisted ligament balancing assessment, a varus weight of 610 g compensated the initial 32.2 N lateral force and 750 Nmm moment, whereas a valgus weight of 460 g compensated the 27.6 N medial force and 690 Nmm moment. The weights ratio was therefore 1.3, the compressive forces ratio 1.2 and the varus-valgus moments ratio 1.1. All ratios indicated a lateral imbalance, thus showing the consistency between the approaches. The 15% deviation of the varus-valgus moments ratio from the weights ratio was due to the measurement error as well as to tibio-femoral relative motions. At the points of condyle lift-off, we observed a 1.1° varus and 1.3° valgus angular deviation from the unloaded position. As ligaments are relatively stiff structures, this 2.4° total deviation could have a significant influence on the measurements.

With spacers applying stress to the ligaments, the medial and lateral forces were 47.7 N and 41.6 N whereas the varus and valgus moments were 1250 Nmm and 980 Nmm respectively. After a standard medial collateral ligament release, the medial and lateral forces were 39.7 N and 42.4 N whereas the varus and valgus moments were 1060 Nmm and 1010 Nmm respectively. As expected, the medial ligament release was almost exclusively effective on the medial side with a relative change of 16% in the moment and force, which allowed bringing the unbalanced knee in a quasi-balanced condition. However, the small force amplitude variation of 8 N demonstrated that a collateral ligament release cannot correct strong imbalance. Consequently, the initial stability assessment on which the femoral cuts are planned is crucial.

**Discussion:** A novel surgical instrumentation that can intraoperatively measure knee joint forces and moments to assist ligament balancing during TKA has been presented. The consistency between the information provided by the device and the current surgical approach of the varus-valgus stability assessment was demonstrated using a knee joint loading apparatus. Finally, the quantification of the biomechanical effect of a collateral ligament release thereby illustrated its benefits and limitations, thus showing the importance of a precise stability assessment at the beginning of the surgery. During the planning of the femoral cuts, the alignment and the ligament balance must be simultaneously evaluated to avoid the difficulty of large corrections at a later stage of the surgery.
References


A practical reference coordinate system for planning hip resurfacing arthroplasty

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Introductions: In order to achieve optimal acetabular placement in hip arthroplasty, the abduction and anteversion angles of the acetabular cup have to be planned and executed carefully. These angles are measured in relation to the anterior pelvic plane (APP), first described by Cunningham in 1922. The APP is based on the two anterior superior iliac spines and the two pubic tubercles. Jamarez et al. have introduced the concept of the APP to computer assisted cup placement in hip arthroplasty, and it has proved to be an invaluable tool (1).

There has been no universally accepted reference coordinate system available for studying femoral geometry and biomechanics. The so-called condylar plane used by many as a reference plane for measuring femoral anteversion has no uniform points that have been universally adhered to (2). Zheng et al. have recently introduced a femoral coordinate system that is based on the femoral head center, the tangential line of the posterior femoral condyles, and the medullary canal axis of the proximal femur (3). Although the former two can be determined with reasonable accuracy, the proximal femoral axis may prove to be difficult to reproduce, as the two end points that define it are not based on fixed landmarks.

We propose the concepts of the Posterior and the Sagittal Femoral Planes, together forming a femoral reference system which will enable reliable and reproducible documentation of femoral implant positioning. The idea of the

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posterior femoral plane stems from observations that there are three reasonably uniform points that come into contact with a flat surface when the femur is placed on it. This concept was first put into use by Kingsley and Olmsted when they reported their direct method of measuring femoral anteversion on dry specimens in 1948 (4). The sagittal femoral plane however is a novel concept that involves a further point and its projection onto the posterior femoral plane.

Methods: The posterior femoral plane (PFP) is based on Kingsley and Olmsted’s points. These points are namely the most posterior points on the femoral condyles (points A and B) and the most posterior point on the intertrochanteric crest (the quadrate tubercle, point C) (see Fig. 1). On the other hand, the sagittal femoral plane (SFP) is defined by point C and two other points; those are the lowest and most proximal points on the patellar groove of the femur anteriorly (point F) and its orthogonal projection onto the PFP (point G).

Ten unpaired dry cadaveric femora, five right and five left, were studied to determine their anteversion, offset and neck/shaft angles. All ten bones rested on points A, B and C when placed on a flat horizontal table. The CT scanning protocol involved imaging the femoral head and neck, as well as the shaft to a level just distal to the lesser trochanter. Sections through the femoral condyles were also obtained. Using custom reconstruction software, 3D models of the bones were created and landmark acquisition was done. The
center of the head was obtained by fitting the best sphere to a collection of points on the surface of the head and then determining the center of the sphere. The axis of the femoral neck was determined by joining the head center to the centroid of the neck at its base.

**Results:** Each of the ten femora was measured in this manner. The characteristics were tabulated and are summarized as follows: the anteversion angle ranged from 6° to 21° (mean 14°; SD 6°); the offset measured from 24 to 52 mm (mean 37 mm; SD 9 mm); and the neck/shaft angle ranged from 117° to 137° (mean 127°; SD 7°).

**Discussion:** With the advent of computerized tomography and software for reconstruction, it is now possible to define the posterior femoral plane accurately and reproducibly.

The sagittal plane is derived from the addition of one further point distally. It has the merit of using landmarks that are simply acquirable and does not rely on the definition of any axis at the knee. As such it is simpler and more easily interpretable than others.

The femoral coordinate system proposed here has a great potential in serving as a reference system for preoperative planning in hip and femoral surgery. We have used it to validate the coordinate systems for hip resurfacing arthroplasty and we plan to apply it on a larger scale and study its interobserver variability.

**References**

Biomechanical analysis of strength of fixation of tracker devices to bone in computer navigated joint replacement arthroplasty

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Introduction: Computer aided joint replacement surgery has become very popular during recent years and is being done in increasing numbers all over the world. The available literature published shows there is increased accuracy of the component placement. The accuracy depends to a major extent, on accurate point registration and immobility of the tracker attachment devices to the bone. If during the procedure the bone and bone tracker position changes due to any reason, this can greatly affect the accuracy of the procedure. This study was designed to assess the forces needed to displace the tracker attachment devices in the bone simulators.

Methods: Bone simulators (the bicortical sawbone models with the porosity of cancellous bone approaching a comparatively osteoporotic bone, 1522-192 Block: 7.5* cellular laminated on both sides) were used to maintain the uniformity of the bone structure in the study. The fixation devices tested were 3 mm diameter self drilling, self tapping threaded pin, 4 mm diameter self tapping cortical threaded pin, 5 mm diameter self tapping cancellous threaded pin and a tripod fixable with three 3 mm pins. All the devices were tested for pull out and translational forces in unicortical and bicortical fixation modes. Also tested was the normal bang strength and forces generated by leaning on the devices.
**Results:** The forces required to produce translation increased with the increasing diameter of the pins. These were 105 N, 185 N, and 225 N for the unicortical fixations and 130 N, 200 N, 225 N for the bicortical fixations for 3 mm, 4 mm and 5 mm diameter pins respectively. The forces required to pull out the pins were 1475 N, 1650 N, 2050 N for the unicortical, 1020 N, 3044 N and 3042 N for the bicortical fixated 3 mm, 4 mm and 5 mm diameter pins. The tripod junction of the central post failed at 450 N and 800 N for pullout and translational forces. Rotatory forces required to displace the tracker on pins was to the magnitude of 30 N. The manual leaning forces and the sudden bang forces generated were of the magnitude of 210 N and 150 N respectively.

**Discussion:** The strength of the fixation pins increases with increasing diameter from 3 to 5 mm for the translational forces. There is no significant difference in pull out forces of 4 mm and 5 mm diameter pins though it is more than the 3mm diameter pins. This is because of the failure of material at that stage rather than the fixation device. The rotatory forces required to displace are very small and much less than that can be produced by the accidental leaning or bang produced by the surgeon or assistants. One has to be very careful not to put any forces during the operation on the tracker devices to ensure the accuracy of the procedure.

The details of the tests and the recommendations will be presented in details in the paper.

**References:** No study was found in the literature on tracker fixation biomechanical strength.
Zero-dose C-arm navigation reducing intraoperative radiation

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Introduction: One major issue in orthopaedic surgery is the minimization of X-ray radiation. With the introduction of fluoroscopic navigation systems, radiation dose could be widely reduced. Thereby, the minimal number of X-ray images is given by the required number of different views as needed for the planning system.

However, a common practice to achieve an optimal visibility of the relevant structure is to acquire several “pilot-shots” or even to reposition the C-arm under continuous radiation. In cases where just standard views are necessary, an experienced user will have no problems imaging the desired structure. But if for example the dimension of the target comes close to the diameter of the image intensifier, it becomes more difficult. Also, when the CAS planning system requires X-ray images from special predefined views, a successful imaging without iterative X-ray imaging for the approximation of the desired view, could be a challenging task.

In fluoroscopy based revision total hip replacement, e.g. the three dimensional surface of the bone cement has to be reconstructed [1]. Therefore, a number of about 5 X-ray images from predefined views of the femur have to be acquired including the most distal part of the cement as well as the proximal approach. To achieve all required views, the C-arm as well as the leg have to be repositioned. Apart from spatial orientation, the limited workspace of the C-arm induces major problems.

Methods: We propose a new concept and approach for the navigation of the C-arm without additional radiation. To enable an online preview X-ray imaging during the C-arm repositioning, the target as well as the X-ray image intensifier and any other equipment (such as e.g. radio-opaque elements of
the operating table) have to be tracked. Similar to the conventional X-ray navigation, a virtual view is created representing the expected X-ray image.

To realize the navigated zero-dose preview X-ray imaging, the system has to be calibrated regarding distortions and the projection geometry. As the distortion correction has to be done without making an X-ray image, a magnetic field sensor based calibration is the preferred solution [2]. This has the additional advantage of avoiding the use of an intraoperative calibration cage that would limit the positioning abilities of the C-arm. The projection geometry can be calibrated using standard camera calibration algorithms as used in many fluoroscopic navigation systems.

With a calibrated imaging chain the X-ray preview can be easily realized by showing semi-opaque objects such as parts of the operating table, bone models or other relevant objects superimposed to each other. These models, that have to be referenced to the anatomy, can either be statistical bone models, or, if accuracy is not an issue, a more abstract modeling could be sufficient.

**Results:** The first prototype of the zero-dose C-arm navigation has shown that X-ray images, that are just used to find an optimal view of the desired structures, can completely be avoided. Besides the reduction of radiation dose the time to find the target structure could be significantly reduced.

**Discussion:** The overall system accuracy depends on the used modeling of the target structures. For most applications accuracy requirements of C-arm positioning are not very high. Therefore, the use of an abstract bone model should be sufficient. This also reduces the complexity of registration of the model to the anatomy.

The actual system will be expanded to the navigated alignment of the C-arm to any navigated instrument in the field of view as well as the OR-table, which could partially occlude the anatomy.

**References**


An alternative method for calculation of femoral rotation using image guided surgery

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Introduction: Image guided surgery has proven to be accurate in reproducing coronal and sagittal alignment of both femoral and tibial components in total knee arthroplasty. Femoral rotation however is less accurate to determine. Femoral rotation can be decided from the transepicondylar axis (TEA), the posterior condylar axis, the Whiteside line or from a balanced flexion gap. No method is entirely accurate and is subject to inter and intra observer error (Ref. 1). The intra observer error in determining the TEA has been shown in a previous paper presented to the Society last year to result in a maximal 11 degree error in rotation if incorrect points were chosen at the time of registration. We describe an alternative method to determine the center of femoral rotation using a current software available for image guided knee replacement.

Methods: Twenty patients underwent total knee replacement (TKR) using an image guided computer system (BrainLab v1.5). All implants were of the same type (Nex Gen, cruciate retaining, Zimmer) and were fixed with antibiotic containing cement. The femoral rotation was set using the transepicondylar axis to determine rotation intraoperatively. All points used to map the femoral condyles were then exported and a filter applied to outline all the distal points of both lateral and medial femoral condyles. The distances between each of these points and the epicondylar point was then calculated for both lateral and medial femoral condyles. All points anterior to the mechanical axis were removed as these do not contribute to flexion. The average distance and the standard deviation was calculated and the axis obtained compared to the TEA.
Results: The isocenter point co-ordinates were calculated for each patient. This was then compared to the co-ordinates for the TEA. The co-ordinates were similar to the TEA (range 0.5 to 4.9 degrees rotation). The standard deviation however was much smaller than previously reported data on reproducibility of finding the TEA.

Discussion: There has been recent interest in the true morphology of the distal femur and whether the posterior condyles form a true cylinder with different radii (Ref. 2). This does have implications for the best rotational position of the femoral component in total knee arthroplasty and long term may influence kinematics of the knee and wear of the bearing surface. This method of determining femoral rotation deserves further study as it is potentially more accurate to select a rotation axis than identifying the epicondylar points. It also has benefits with the increasing use of minimally
invasive knee replacement using IGS. It is always possible to map the femoral condyles but extremely difficult to accurately identify the transepicondylar axis. This program may be incorporated into an algorithm for the placement of the femoral component with image guided surgery.

References

2. Eckhoff DG et. al, Three dimensional morphology and kinematics of the distal part of the femur viewed in virtual reality. JBJS, vol 85A supp 4 2003, p 97 – 104
A hand-held computer-controlled tool for total knee replacement

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Introduction: The objective of this project is to develop a servo-controlled hand-held tool for total knee replacement (cf [1], [2]). The expected benefits of the system are:

- To get rid of the cutting guides while providing the same accuracy in bone resection
- A shorter overall time of operation in removing all the cutting guides step manipulations
- A less invasive procedure.

The idea with such a tool is to let the surgeon do most of the motion, and to assist him for accuracy only in the last few millimeters/degrees.

Methods: From an engineering point of view, bone resection in TKR boils down to milling predefined planes in bone: at all time the cutting device (usually an oscillating saw) must remain in the desired plane, which is achieved thanks to mechanical guides rigidly fixed to the bones. These cutting guides provide a good accuracy but need time to place and trim, and add to the ancillary. To help the surgeon to achieve the same precision without any guides, we propose an “intelligent” tool working as an “accuracy augmentation system”. The tool has the general “look and feel” of a conventional saw, but with joints actuated by computer-controlled motors. Sensors give the position and orientation of the cutting device relative to the plane to be resected (the markers and camera of a CT-free navigation system can be used for that purpose). The computer uses this information to calculate at a very fast pace the corrections required by the motors to accurately keep
the cutting device in the desired resection plane, provided the surgeon has approximately positioned the tool (up to a few millimeters/degrees).

To have a simpler mechanical design, we use instead of a saw a cutting device with a symmetry of revolution (such as a drill): in this case only two degrees of freedom are needed to ensure the cutting device is the desired plane (a similar device with a three-degree-of-freedom structure carrying a conventional saw is possible, but more complex).

**Results:** In a preliminary stage, we are developing a prototype capable of cutting only soft material, which simplifies the electromechanical design. Indeed, since bones can be quite hard, the surgeon often applies an important force on the tool. The motors must be powerful enough to resist this force while correcting the position/orientation error as fast as possible.

**Discussion:** One important issue is that the bandwidth of the localization system must be high enough and its latency time small, so that the servo system is very fast compared to the surgeon reaction time. It is not clear that the performance of the localization systems usually used in CT-free navigation (such as Polaris by NDI, Waterloo, Canada) is high enough for this closed-loop use.

**References**

What can go wrong in CAOS

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Introduction: Use of computer navigation in surgery can improve outcomes by increasing accuracy, reducing outliers, and enabling more complex procedures and less-invasive approaches. However, in order to achieve these goals, developers and clinicians must always keep in mind that navigation systems are not foolproof, and that they must work to minimize the effects of potential errors. Despite the ability of these systems to improve the accuracy of surgeries, their improper use can over-complicate surgery and can lead to poor outcomes.

The main sources of inaccuracy and difficulty stem from problems involving three-dimensional (3D) tracking systems, the introduction of new mechanical devices, and errors in data collection and registration. Providing a periodic verifiable feedback on the system’s accuracy during surgery is a great way to gain the trust of the user and ensure that the information provided is accurate.

Methods: This article analyzes the authors’ experience gained from developing and implementing the HipNav1 and KneeNav2 systems over a period of several years, as well as developing and testing new tools and software to make the systems more accurate and user-friendly. This experience was with both image-guided and image-free applications.

Results: The main issues one must keep in mind regarding any 3D tracking system are ease of use, tracking accuracy, and how best to attach the tracking targets. For an optical tracking system, there are several ways to generate inaccurate position data. Ambient light presents a potential problem for accurate tracking data. The light from certain kinds of electrical lighting and, in operating rooms with windows, sunlight can cause an optical tracking system to report the position of a tracking target incorrectly, or in some cases to be unable to report its position at all. Reflective surfaces can also cause an optical system to have difficulty tracking accurately, when they reflect the image of a target to the tracker, or when they reflect infrared emitted by the
tracker in passive systems. The proximity of two tracking targets can also introduce errors into an optical tracking system. If the infrared-emitting diodes of one active target occlude those of another, or if the reflective sphere of a passive target occludes another sphere from the tracker's perspective, significant inaccuracies may result in the tracking data, or the tracking system may not be able to resolve the positions of either target. In the case of reflective sphere occlusion for passive trackers, errors in excess of 7 mm and 6 degrees have been noted.

Tracking systems that use changes in an induced magnetic field to track targets may also have problems, such as potentially large errors created by the introduction of ferrous materials, and electrically operated devices into the field.

Signs of inaccurate tracking data include poor registrations or the inability to register, the inability to achieve an accurate calibration for various tools, and inaccurate reporting of the position or orientation of the implant or cut being guided. If the tracking system is not providing accurate data and there is no way for a user to determine that, implant malposition may result, despite what the system is reporting.

Other difficulties resulting from 3D tracking relate more to the practical use of a navigation system in an operating room environment. The introduction of tracking targets into the surgical field can be cumbersome, and care must be taken to balance their ease of use and accuracy. For example, a large tracker very near the region of interest, while more accurate, can get in the way of the surgery, but a small tracker far from the region of interest can compound the innate tracking inaccuracy. Errors can also come from an inadequate method of fixation of the tracking targets. If the targets move relative to the host bone after the bone is registered, that registration is no longer accurate. Insufficient fixation, pressure of soft tissue against the tracker, accidental knocking of the tracker, and the use of vibrating tools, can all result in the relative tracker motion. Care must be taken to provide as rigid fixation as possible while keeping sure to minimize the invasiveness and intrusiveness of the fixation devices. Also, systems should provide some way to determine if a tracking target moved relative to what it is tracking.

User error can also lead a system to provide inaccurate information and can result in a poor outcome. In a non-image-based system, for example, where digitized landmark points are used to determine the reference for navigation, small errors in point collection can lead to significant errors in registration. The difficulty collecting some points also presents a problem. A user must keep in mind the system can not provide feedback on how accurate the
registration is. In image-based systems, tracking errors, poor registration methods, inaccurate images, and poor data collection can all lead to registration errors. Using the registration method in the HipNav system, a user can decrease a registration’s accuracy by as much as 2 degrees by collecting points too close to each other. In order to minimize these sorts of errors, a user must take care when collecting data to ensure that he or she is touching the desired point.

Discussion: In order to reap the full benefits that navigation systems offer, a user must keep in mind the possible pitfalls the systems present, and take care to minimize their effects. A user should be familiar with how a system works, what can go wrong, and how to mitigate potential errors. A system should provide as much feedback as possible so that a user can determine if something went wrong. Failure to address these issues can result in implant malalignment, poor outcomes, and a distrust of navigation systems by surgeons.

References


Software requirements evolution in CAOS applications: A case study

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Introduction: Because computer-assisted orthopaedic surgery (CAOS) systems can be very similar and offer many common features we envision the integration of programming techniques, called generative programming, in the domain [3]. We aim to enable the reuse and customization of already implemented functionalities as well as the automation of the application development process. Generative programming relies on the design of a software architecture common to an applications family and the implementation of a collection of reusable assets (software components) from which an application can be composed. In order to allow for the composition of a wide variety of applications within the family, software components should be easily modifiable and extendible to new applications and environments. In other words, the architecture from which they derived must be flexible enough to enable an easy adaptation and customization of the components.

Consequently, in order to assess the flexibility and modifiability of our designed architecture we decided to apply an architecture evaluation method that consists in confronting the architecture with a set of change and adaptation scenarios [2]. For this evaluation to be pertinent, however, the selected set of scenarios needs to be representative of changes and adaptations that a CAOS application is most likely to face. This leads us to perform an empirical investigation on the evolution of software requirements in the CAOS domain.

Methods: The case study consisted of a system for preoperative planning of spinal image-guided surgery treatments named iPlan (BrainLAB AG,
The system is divided into modules and sub-modules following a hierarchical scheme. We collected the system specifications of the two first levels of the system decomposition. This resulted in a total of 325 requirements for 3 releases of the system. To better understand requirements evolution, we categorized them into 16 types that belong to three different groups (functional, non-functional, and platform). Then, we computed for each group and for each type their requirement stability index (RSI). Considering the total number of requirements in a release as well as the cumulative number of changes over the releases, RSI evaluates the overall stability of the set of requirements [1].

**Results:** Requirements come in three groups: functional requirements that address what the system must do; non-functional requirements, which are those properties that the subsystem must have such as safety or performance; and platform requirements that define a standard around which the system can be developed. Of the total 325 requirements, 186 (57%) are functional, 57 (18%) are non-functional, and 82 (25%) concern the platform. While the number of non-functional and platform requirements remains rather constant, functional requirements are constantly increasing over releases. The computation of RSI for each of the previously-mentioned category reveals that the requirements of the three categories remain quite stable for the second release (RSI > 0.6). However, in the third release the RSI value falls down to a value below 0.15 for the functional and the platform requirements.

It is then more interesting to concentrate on the RSI value achieved in the last release by each requirement type belonging to these groups. We obtained no significant difference between the four types (feature, process, data, user interface) of the functional requirements group; each of them has as well quite a low RSI (−0.1 < RSI < 0.2). However, for four types (hard disk, operating system, processor, RAM) of the platform group, we obtained a value inferior or equal to 0 while it remains superior or equal to 0.7 for the three others (display, peripheral device, other).

**Discussion:** As one could suspect, the specifications of CAOS systems are heavily functional with a constantly increasing number of requirements, reflecting the constant improvement and refinement of the system. The specific variation points revealed by the analysis of the platform requirements group confirms that CAOS systems as computer-based systems are driven by the constantly evolving computer market. Typically, we evaluated that the least stable of the platform requirements type is the one related to operating systems. On the other hand, the fact that our investigation on the fluctuation of functional requirements did not provide so obvious and
significant variation points can be explained by the fact that the gathered data
does not cover the entire module decomposition of the system. Indeed the
system module which contains the essentials of the functional requirements
has a deeper decomposition than the others, which implies that the
requirements collected at the second level decomposition are not detailed
enough to enable the detection of critical points of variation. We argue,
however, that getting too deep into the system decomposition could have
revealed a set of variations more specific to our industrial partner’s software
architecture than to the general domain of CAOS applications.

Although certain requirements constraining industrial CAOS application
development are not always applicable to academic systems development,
this industrial investigation on the evolution of system requirements enables
us to get a better understanding of the dynamic of CAOS system contexts.
Completing this study with a deeper investigation on functional software
requirements will allow us then to perform a realistic evaluation of our
generic CAOS software architecture.

References

In Proceedings of the 26th Annual International Conference on Computer
Software and Applications Conference, COMPSAC 2002 (pp. 27-32). Oxford,
England

modifiability analysis (ALMA). Journal of Systems and Software, 69(1-2), 129-
147 .

implementation of customized CAOS applications In Proceedings of the 4th
annual meeting of CAOS international (pp.139-140), Chicago, Illinois, USA
CT-Fluoro merge using Vectorvision and Stealth Station compared to fluoroscopy for insertion of pedicle screws using minimal invasive percutaneous techniques. Is the accuracy adequate?

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**Introduction**: The present navigation systems for spinal surgery incorporates pre-operative planning (preoperative CT-scanning), intraoperative tracking of patient and instrument (using LED markers) and a registration procedure. The latter either uses the matched points method (the surgeon points out a number of strategically chosen surface points on bony landmarks) or the surface matching technique or a combination of both methods. The registration is often lengthy and the two before mentioned methods do not allow the surgical procedure to be carried out as a minimally invasive procedure. X-ray fluoroscopy has become an essential tool for the orthopaedic surgeon helping him to place the different bone implants accurately. Today a C-arm fluoroscope is present at every orthopaedic operation room. The fusion of intraoperative fluoroscopic images and preoperative CT-scanning images for registration are very useful for minimally invasive spinal surgery. The purpose of the present study was to evaluate the accuracy of BrainLAB’s Fluoro to CT registration module and Medtronic’s Stealth Station CT-fluoro merge module for minimal invasive (percutaneous) insertion of pedicle screws and to compare the accuracy of these computer guided systems to the conventional fluoroscopy technique.

**Methods**: Simulated surgeries were performed on 8 sawbones in each of the three groups. Only L3, L4 and L5 vertebra were used for insertion of cannulated pedicle screws using a minimally invasive “percutaneous”
A total of 48 screws were inserted in each of the 3 groups: BrainLAB, Medtronic and conventional fluoroscopy. The intention was to place the screws in the center of the pedicle and to avoid perforations. The times per screw were registered and fluoroscopy time was registered. Macroscopic inspection of the sawbones and CT-scanning was used to assess the accuracy of the three methods.

The conventional fluoroscopy technique performed better than the computer-guided techniques with less time per screw and with fewer perforations. All perforations were lateral. In the Brainlab group 4 lateral perforations were registered while only 1 lateral perforation was registered in the Medtronic and 1 lateral perforation was observed in the conventional group. The conventional group deviated less from the center of the pedicle than the two computer guided systems (statistically significant). The fluoroscopy time was significantly less for the 2 computer guided systems.

Discussion: The 2-D to 3-D registration process is not fought without problems. The images must be transformed. Often the 3-D pictures are converted to virtual X-rays. Next, the matching has to be accurate and fast. Often the quality of matching is quantified with respect to a similarity measure of the overlapping voxels of the two images. To cut down on the time used for the registration some of the information in the pictures must be left out. These problems are probably the reason why the computer guided techniques were less accurate than the conventional fluoroscopy method. However, the two computer guided systems can both be safely used for minimal invasive insertion of pedicle screws even though the accuracy is less than for the conventional fluoroscopy technique. The time per screw is also significantly higher for the two computer guided systems but the fluoroscopy time is significantly lower.
Accuracy measurement of current TKR instrumentation with navigation

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**Introduction**: Mechanical total knee replacement with femoral and tibial component alignment, using conventional alignment systems, is sometimes not very accurate. These errors are due to the limited accuracy of the pre-operative X-ray planning, to the difficulty to determine the correct location of crucial alignment landmarks, as the center of the femoral head, the center of the ankle, etc. Moreover, the standard alignment guides presume a bone geometry which is sometimes not right for every patient. Finally, the control of the bone osteotomies and the alignment of the lower limb is executed by a visual inspection. Navigation systems have recently been developed in TKR in order to improve the alignment of the femoral and tibial components. The aim of this study was to assess the accuracy of a current femoral intramedullary and tibial extramedullary guide using a Stryker navigation system.

**Methods**: Twenty-five primary TKRs were done using the current instrumentation for the Scorpio Posterior Stabilized (PS) System. Intramedullary alignment was used for the distal femoral osteotomy and extramedullary alignment was used for the proximal tibial osteotomy. The femoral intramedullary alignment was set at 6° or 7° in the varus knee, and at 4° in the valgus knee with respect to the anatomic alignment of the distal femur. The rotational alignment of the femoral component was made with respect to the epicondylar axis, recognized through the manual palpation of the medial and lateral epicondyne. The tibial cutting block was positioned on the extramedullary alignment guide trying to align perpendicular to the mechanical axis of the tibia, and respecting the original pre-operative tibial slope measured by a lateral X-ray of the knee. The accuracy of each femoral osteotomy in the frontal, in the sagittal, and in the transversal plane, and of the proximal tibial osteotomy in the frontal and in the sagittal plane was measured using the Stryker image-free computer assisted navigation system.
**Results:** The alignment of the femoral and tibial osteotomies, and the final coronal lower limb alignment, measured with Stryker navigation system, according to the navigated mechanical axis, are shown in Table 1. A negative correlation was found between the difference in the setting of the intramedullary femoral guide with respect to the X-ray anatomical axis of the distal femur and the frontal alignment of distal femoral cut. The average alignment of the femoral cuts in the transversal plane was $0.9\pm 1.7^\circ$ of internal rotation, whereas the rotation of the femoral cutting block with respect to the posterior condylar axis was $3.3\pm 1.6^\circ$ of external rotation.

Table 1  *Cuts and limb alignment measured with Computer Navigation System*

<table>
<thead>
<tr>
<th></th>
<th>mean±SD</th>
<th>min ÷ max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-operative mechanical axis</td>
<td>3.7°±7.2° of varus</td>
<td>16° of varus ÷ 14° of valgus</td>
</tr>
<tr>
<td>Post-operative mechanical axis</td>
<td>1.1°±2.2° of valgus</td>
<td>3.5° of varus ÷ 5.5° of valgus</td>
</tr>
<tr>
<td>Femoral cut – Frontal plane</td>
<td>0.7°±1.6° of valgus</td>
<td>3° of varus ÷ 4° of valgus</td>
</tr>
<tr>
<td>Femoral cut – Sagittal plane</td>
<td>2.8°±2.0° of flexion</td>
<td>1° of extension ÷ 7° of flexion</td>
</tr>
<tr>
<td>Femoral cut – Transversal plane</td>
<td>0.9°±1.7° of int. rotation</td>
<td>3.5° of int. rot. ÷ 3.5° of ext. rot.</td>
</tr>
<tr>
<td>Tibial cut – Frontal plane</td>
<td>0.2°±1.3° of valgus</td>
<td>2° of varus ÷ 2.5° of valgus</td>
</tr>
<tr>
<td>Tibial cut – Sagittal plane</td>
<td>4.5°±3.1° posterior</td>
<td>1° anterior ÷ 10° posterior</td>
</tr>
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</table>

**Discussion:** Good alignment of the tibial cut in the coronal plane is achieved using the extramedullary guide with respect to the femoral cut obtained using an intramedullary guide. Thin intramedullary rods in large femoral canals can
determine large errors, in particular in the sagittal plane. Moreover probably the simple visual control of the alignment for the tibial osteotomy is more effective than for the femoral osteotomies. It is very important to follow a careful pre-operative planning with an AP long radiograph, because to set the femoral guide with 6° or 7° in the varus knee, and 4° in the valgus knee, is not always right, above all in severe deformities.

The tendency to give 1° of internal rotation to the femoral component could be due to the not easy alignment of the guide to the epicondylar axis. The external rotation of 3.3° of the femoral cutting block with respect to the posterior condylar axis sometime is not enough to obtain a perfect alignment with respect to the epicondylar axis.

References

Computer-assisted arthroplasty versus conventional jig-based/hand-guided techniques: A systemic review

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Introduction: Knee arthroplasty has been found to be a safe and cost-effective treatment for relieving pain and restoring physical function in patients with osteoarthritis unresponsive to non-surgical therapy. Although the results of knee arthroplasty are usually good, complications can and do occur. The success of knee arthroplasty is dependent on several factors, chief among which is correct component alignment. Mal-alignment can lead to abnormal patellar tracking, increased polyethylene wear, early loosening and poor functional outcome. The development of extra- and intra-medullary guidance systems has improved the accuracy of implant alignment. However obtaining correct implant alignment remains difficult. Recently, computer-assisted surgery systems have been developed to help surgeons improve component alignment during surgery. The proposed advantage is intra-operative, real-time computer feedback on component alignment, facilitating the surgeon in making accurate bone cuts, ligament balancing and fine adjustments to ensure correct component alignment.

The aim of this systemic review is to evaluate the effectiveness of computer assistance in improving knee arthroplasty results.

Methods: We searched electronic databases, MEDLINE (1966 – November 2004), EMBASE (1974 – November 2004) and Cochrane Central Register of Controlled Trials, Issue 3, 2004 for all potential randomized controlled trials comparing either image-guided or image-free computer-assisted knee arthroplasty versus conventional jig-based or hand-guided techniques. The search strategy was combined with all phases of the optimal trial search
strategy and modified for uses in other databases. The search terms used were arthroplasty [MeSH], knee replacement [MeSH] and surgery computer assistance [MeSH], computer, computerized, computerised, computer aided, computer-aided, computer assisted, computer-assisted, computer guidance, computer guided, computer-guided, computer directed, computer-directed, computer-guidance, computer-guided, navigation and navigational.

Two reviewers independently selected the trials based on titles and abstracts, assessing whether the studies met diagnosis, design and intervention inclusion criteria. Those selected had the full articles retrieved for final assessment. All non-English articles were translated in full to English.

An independent final selection of the trials to be included in the review was performed using a pre-tested standardized form. Disagreements were resolved by discussion, and if necessary through arbitration by a third reviewer. The methodological quality of the studies was evaluated by two reviewers. Any disagreements were resolved at a consensus meeting. When disagreements persisted a third reviewer made the final decision.

The data was extracted independently by two reviewers for meta-analysis using a pre-determined standardized form. The primary outcome was radiological assessment of implant alignment, while the secondary outcomes were total operating time and post-operative blood loss. Overall treatment effects were calculated as relative risk (95% confidence intervals) for binary outcomes and weighted mean difference (95% confidence intervals) for continuous outcomes using Review Manager (computer program) Version 4. The results were pooled using fixed effects model and if there was heterogeneity between studies, a random effects model was used.

**Results:** 28 articles in MEDLINE and 15 articles in EMBASE were found, of which only 6 articles met our inclusion criteria. 3 studies were published in English and 1 each in French, German and Spanish languages. The sample size of these studies ranged from 25 to 240. All 6 of them were single-blinded, randomized controlled trials with intention to treat. Concealment of allocation was described in 3 of them.

Meta-analysis was performed, analyzing the results of post-operative long leg radiographic measurements of the standing femoro-tibial angle, varus/valgus alignment of both femoral and tibial components, total operating time and post-operative blood loss.

The pooled estimate showed that the risk of having a post-operative standing femoro-tibial angle of +/-4, +/-5, +/-6 degrees was less in the computer-assisted knee arthroplasty group compared to the conventional jig-based/hand guided technique group (RR 0.17, 95% CI 0.01, 2.46). However the results were not statistically significant. The risk benefit of a post-operative standing femoro-tibial angle of 0, +/-3 degrees, which is considered clinically and
functionally acceptable, was also higher in the computer-assisted knee arthroplasty group compared to the jig-based/hand guided technique group (RR 1.14, 95% CI 0.90, 1.45). Significant result heterogeneity was however noted between the studies for both groups of analysis.

Similar results were found for post-operative varus/valgus alignments of femoral and tibial components (RR 1.09, 95% CI 1.01, 1.17 and RR 0.19, 95% CI 0.04, 0.85 respectively). The computer-assisted knee arthroplasty group showed a better alignment compared to the jig-based/hand guided technique group, and results were statistically significant with valgus alignment. More patients in the conventional jig-based/hand-guided technique group had shorter total operating times (minutes) compared to the computer-assisted knee arthroplasty group (WMD 19.75, 95% CI 2.57, 36.94), and results were statistically significant. Blood loss (millimeters) at 24 hours was less with computer-assisted knee arthroplasty group (WMD 104.67, 95% CI -384.68, 175.34), but the results were not statistically significant.

Discussion: This systemic review reveals that radiologically computer-assisted knee arthroplasties appear to have better implant alignment than conventional jig-based or hand-guided techniques, although computer-assisted knee arthroplasties generally took longer in terms of total operating time. Larger randomized controlled clinical trials are needed to validate the above findings. It is recommended that future trials include other outcomes, especially functional knee scores. In addition there is a need to standardize reporting of results among the various research groups to facilitate pooling of data, as well as to allow structured evaluation of their study designs and results.

Cochrane Musculo-skeletal Group: This topic is registered by the authors with the Cochrane Musculo-skeletal Group under the title of “Computer assisted knee arthroplasty for osteoarthritis and other non-traumatic diseases”.

References

Navigated pedicle instrumentation in the thoracic spine with the ISO C 3D. Is the precision satisfactory?

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Introduction: The 3-D navigation, with the help of the ISO C 3D (ISO-C 3D, Siemens Medical Systems, Erlangen, Germany) is used in operating theaters since approximately 3 years. One of the first applications for the 3 D navigation in the BG Unfallklinik Ludwigshafen was the pedicle instrumentation in the lumbar and thoracic spine. Concerning the precision, measured by the misplacement ratio, the superiority of the ISO C 3D navigation, compared to previously known methods, the conventional pedicle instrumentation with a fluoroscopic control, the 2-D navigation and the CT-based method, together with a significant reduction of the fluoroscopy time has already been proven. Yet it is still unknown, whether the precision of the navigated instrumentation in the thoracic spine, using the ISO C 3D in combination with the SurgiGATE system (Praxim/Medivision) is satisfactory, compared to the application in the lumbar spine.

Methods: Since February 2002 we have registered patients with an instable fracture of the lumbar or the thoracic spine, where the pedicle instrumentation was navigated, in a prospective study. Among other parameters, the time from incision to suture and the fluoroscopy time were registered intraoperatively. The position of the screws was evaluated by an independent radiologist on the basis of axial CT images. A misplacement was defined, medially as a perforation of the pedicle wall and laterally as a perforation of more than 2 mm. The thoracic and lumbar positioning were compared statistically.
Results: 372 pedicle screws (188 in the thoracic spine and 184 in the lumbar spine) were implanted in 82 patients (32 thoracic spine and 50 lumbar spine). The average fluoroscopy time was 1.51 min (1.61 min thoracic spine and 1.44 min lumbar spine), the incision to suture time was 96 min (113 thoracic spine and 84 min lumbar spine). All screws were placed accurately, except for 5 in the thoracic spine. Thus the misplacement ratio was 1.34% (2.66% thoracic spine and 0% lumbar spine). In a single patient 4 misplacements were caused by a loosening of the dynamic reference base, thus a symmetric misplacement with 2 medial malpositions and 2 lateral malpositions could be observed. An application error with a lateral malpositioning occurred once, a correct positioning of the pedicle screw according to the planned trajectory could not be achieved. Neurological complications were not observed.

Discussion: Besides a smaller diameter of the pedicle and a reduced quality of the images in the area of the thorax the precision of the ISO C 3D navigation in the thoracic spine is, as in the case of the lumbar spine, sufficient for an accurate instrumentation, especially if you compare the misplacement ratios to the ratios of the other methods presented in literature. However the cause for the misplacements can be seen in the region of the thoracic spine. The main explanation for this is the reduced pedicle diameter, especially in the upper thoracic region. Already very small deviations from the plan can lead to a misplacement in this area, even if screws with a small diameter are used. The normally greater diameter of the lumbar spine allows a certain deviation, without causing a perforation of the wall. The time from incision to suture of each patient was increased by nearly 30 minutes in the area of the thoracic spine, however, in average, two additional pedicle screws were placed during the instrumentation. This fact also increases the fluoroscopy time, which is thoracically still significantly lower, compared to the other methods available.
Computer assisted high tibial osteotomy

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Introduction: After a few years of minor concern the corrective therapy of long bone misalignment has gathered more attention than ever before. Young and active patients can obtain the therapy they need to postpone joint replacement.

Today computer aided surgery delivers the chance to improve existing techniques with an traceable planning and a higher degree of accuracy. Intraoperative use of fluoroscopy can be reduced and the results regarding leg axis can be improved.

Method: In our department 10 patients received HTO using the open wedge technique in combination with the VV osteotomy 1.0 software (BrainLAB AG, Munich, GER). In this workflow the patient anatomy is registered intraoperatively; the alignment of the tibia cut and the amount of corrective spreading is planned; the resection is done and the correction is performed under continuous tracking of the patient’s leg geometry. The geometry can be controlled until the tibia is stabilized again. Stabilization was achieved using a plate with headlocking screws (Tomofix, Synthes).

The correction amount was planned intraoperatively with the navigation system and compared with pre- and postoperative radiographs and clinical parameters.

The primary outcome parameter was defined as the intersection alignment (FUJISAWA) set during the intraoperative planning. This parameter was compared to the radiographs.

Secondary outcome parameters were the amount of correction angle, the postoperative varus/valgus alignment, the medial proximal tibial angle
(MPTA) and the radiation time. The postoperative leg axis was analyzed using 2.5 D ultrasound.

**Results:** In all cases the intraoperative analysis was possible using the HTO module. The intraoperative displayed deformed leg axis was +/- 2° different from the preop planning. There were no surgical problems due to computer guidance noted. Fluoroscopy was used in all cases to verify the implant position as well as the resection plane after inserting the k-wires for saw blade guidance. The postoperative 2.5 D ultrasound leg axis analysis showed again +/- 2° difference to the intraoperatively displayed values.

**Discussion:** The chance to track the patient’s leg geometry through the complete procedure until bone fixation is the main benefit of the computer assistance. The chance of failure during reduction and fixation can so be minimized; potential misalignment can be improved immediately. In addition, like in navigated joint replacement, the result of the surgical treatment can be simulated and judged before any action, values can be influenced showing the consequence right away. But the final result regarding the leg axis is not only determined by the computer guidance, but by the primary stability of the implant as well. The chosen Tomofix plate is supposed to provide highest initial stability.

This first results show a promising increase of accuracy while radiation can be reduced. All leg geometry parameters are predictable, even slope correction and the thickness of the bone bridge, serving as a hinge. The eventuality to achieve misalignment becomes less prominent. The long term results will show the clinical outcome, the actual values show that the main goal to increase the intraoperative accuracy in corrective osteotomies has been achieved.

**References**

Computer assisted minimal invasive IS joint arthrodesis

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Purpose: Arthrodesis of the Iliosacral (IS) joint usually requires a large surgical access. Computer assisted technology enables minimal access for arthrodesis of the IS joint.

Methods: A 48 yrs old female patient suffered from IS joint pain following pelvic injury. Local infiltration with lidocaine resulted in pain relieve. The stabilization was done using minimal invasive technique. Computer guidance (BrainLab) and 3D intraoperative C-arm imaging (Siemens) provided placement of 2 screws. A minimal invasive bone harvesting system (Synthes) was used to receive a bone cylinder out of the Sacrum and to replace it into the joint.

Results: Postop CT control showed a correct placement of the screws as well as bone cylinder bridging the IS joint.

Conclusion: Computer guidance and 3D C- arm imaging provides perfect guidance in minimal invasive posterior pelvic ring surgery. Both techniques give additional safety to standard surgical techniques and may influence surgery in the future.
Comparison of two different navigation systems for spinal instrumentation –
An experimental study

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Introduction: During the last two decades transpedicular fixation systems became standard for stabilization in thoracic and lumbar spine surgery. Following the promising results in the laboratories the navigation systems were released for the use at the patient and to be used in clinical routine. Several studies were able to show the benefit of navigated pedicle screw placement due to a decreasing number of misplacements [1,2]. With conventional techniques misplacement rates are described with up to 40 % while in contrast the misplacement rate with computer assisted surgery is below 10 %.

However, within all studies only one navigation system was used. There has been no comparison of navigation systems for pedicle screw placement yet.

Methods: In this experimental study two commercially available navigation systems were analyzed. We were able to include the Surgigate System (Medivision, Oberdorf, Switzerland) and the Stealth Station (Medtronic, Düsseldorf, Germany). With both systems CT-based navigation and fluoroscopy based navigation were possible. The main difference between these systems is the different camera system. The Optotrac camera (Medivision) uses infrared light with active LED’s at the instruments and the Polaris camera (Medtronic) uses reflecting markers at the instruments.

With both modalities pedicle screw placement was performed at level T2 down to T8. A thoracical spine model (Synbone, Switzerland) was used. With each system and one modality four models were used.
Using the CT based navigation (Medivision: Surgigate spine 2.1; Medtronic: Spine3DTM) a CT scan of the whole model was performed. For placing the screws the reference base was placed to the spinal process and the matching was performed as the system required. Trajectories were planned within the pedicle and performed with the navigated spine tools.

Within the fluoroscopic based navigation (Medivision: Surgigate C-Arm Navigator 0.9; Medtronic: FluoroNavTM2.2) the reference base was also placed to the spinal process of the vertebra and an ap and a lateral view was taken. The procedure was performed in real-time within these images.

All pedicle screw placements were performed by one person.

For analyzing the accuracy of the drills an ISO-C-3D scan of the model was performed. Within this dataset the hole was adjusted in the axial slices directly on the monitor of the system. The pedicle screw was scored following a newly developed scoring system [3,4].

**Results**: In total 256 pedicle screws were placed. With each system 64 pedicle screws were placed per modality.

Including both systems (128 pedicles) with CT based navigation 114 (89%) of the drills were scored grade 1a, 2 (1.5%) grade 1b, 2 (1.5%) grade 2a, 9 (7%) grade 2b, 1 (1%) grade 3a and none 3b.

*Classification of the pedicle screws*
With fluoroscopy based navigation 126 (98.5%) of the pedicle screw placement were placed according to grade 1a and 2 (1.5%) grade 2b, none grade 3 a or b.

Comparing the systems with another the Surgigate System came to 56 (87.5%) screw placements grade 1a, 2 (3%) grade 1b, 2 (3%) grade 2a and 4 (6.5%) grade 2b with CT based navigation. Fluoroscopy based the scoring was 62 grade 1a and 2 grade 2b.

The Medtronic system came to the result of 58 grade 1a, 5 grade 2b and 1 grade 3a in the CT based modus. Fluoroscopy based the scoring was 64 (100%) times grade 1a.

Discussion: An influence of the different camera systems could not be assessed. It has to be mentioned that this was an experimental setup. Influences from a real operation like blood on the reference bases or the specific intraoperative setup with an assistant or nurses could not be simulated. Furthermore the impaired image quality especially in the area of the upper thoracic spine in vivo has to be considered.

However, comparing the overall accuracy of both tested systems our study showed that CT based registration might be inaccurate and there is still the need for intraoperative fluoroscopy control.

Fluoroscopy based navigation is more accurate than CT based navigation. The reason therefore might be that no registration is needed. One disadvantage might be the limited image quality.

References

Correction of posttraumatic ankle and hind foot deformities with computer assisted surgery (CAS)

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Introduction: After complex trauma of the ankle and hind foot posttraumatic deformities are not uncommon. The biomechanical consequences of these deformities frequently lead to clinical symptoms like pain and gait disturbances. The correction of the deformities is challenging [2]. The preoperative diagnostic with radiographs and CT allows accurate planning of the correction [1]. However, during the operative procedure the realization of the planned correction is difficult, because the correction process is performed by the surgeon without guidance. However, there is no commercially available tool for navigated foot surgery. A Computer Assisted Surgery Based (CAS) guided correction was developed using a commercially available navigation system for reduction of fractures. In this study, the clinical experiences were analyzed.

Methods: Patients with posttraumatic deformities of the ankle or subtalar joint with deformity (malalignment) were included. C-arm based CAS guided arthrodeses with correction of the deformity were performed. Time spent, accuracy, problems, surgeons’ rating (Visual Analogue Scale [VAS], 0-10 points) were recorded and analyzed. The accuracy of the corrections was assessed by ISO-C 3D. Technical background: A navigation system with wireless Dynamic Reference Bases (DRB) was used (VectorVision™, BrainLAB Inc., Kirchheim-Heimstetten, Germany). The system was connected with a modified c-arm (Exposcope™, Instrumentarium Imaging Ziehm Inc., Nuernberg, Germany). One DRB was fixed to each of the two bones or fragments that had been planned for correction in relation to each other. With the c-arm, standard radiographic images were obtained, and the data were transferred to the navigation device. During the correction, the angle motion and translational motion between the bones or fragments in all degrees of freedom and virtual bones/fragments were displayed on the screen of the navigation system.
**Results**: Patients. 10 patients could be included in this clinical study. Three patients had an ankle correction arthrodesis, six a subtalar correction arthrodesis, and one patient a Lisfranc correction arthrodesis.

**Time spent.** The time needed for the procedure was 500 s (400–900). This includes the time for preparation, including the placement of the two reference bases, time for generating fluoroscopic images and preparation on the screen for the correction. Time for the correction process was 45 s (30 – 60).

**Accuracy.** The postoperative evaluation was performed with the Iso-C-3D. The scans revealed that all angles and translations were exactly achieved as planned before. The screw positioning were accurate and achieved as planned and showed no misplacement.

**Problems.** During the navigated operation no problem occurred.

**Surgeons' rating.** Within the ten procedures three surgeons were involved. They rated the feasibility, VAS 9.5 (9 – 10), the accuracy 9.8 (9.5 – 10) and the clinical benefit for this correction operations 9 (8 – 10).

**Discussion:** CAS guided correction of posttraumatic deformities of the ankle and hind foot region is feasible and provides very high accuracy and a fast correction process. The time spent is less than 15 minutes. The correction process is very fast and extremely accurate, especially regarding the problems with the conventional c-arm based correction. In our experience, the correction without CAS guidance needs more time because of the necessary frequent c-arm controlling. Furthermore, it is much more difficult, not only because of the difficult visualization but also because the very demanding correction process with three-dimensional motion of two different fragments in relation to each other. This is one reason that during ankle fusion high X-ray exposure is common. With CAS based fusion operation X-ray exposure will decrease due to virtual correction. In our study just two fluoroscope images were needed for the correction process and two for judgment of the accuracy afterwards. In conclusion CAS guided correction of posttraumatic deformities of the ankle and hind foot region is feasible and provides very high accuracy and a faster correction process. The significance of the introduced method is high in those cases, because the improved accuracy may lead to an improved clinical outcome. Further studies will show if CAS will improve the clinical outcome and if the patient will profit from this novel method.

**References**

Intraoperative use of the ISO-C-3D in foot and ankle trauma care – Preliminary results of the first 101 cases

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Introduction: During the operative treatment of fractures in foot and ankle trauma care, the correct retention and implant placement is problematic. One of the reasons is the identification and interpretation of articular steps and hardware misplacement. Two-dimensional intraoperative imaging modalities, as the c-arm, are not sufficient as three-dimensional image modalities and usually limited in analyzing complex anatomic shapes. The exact analysis of intraarticular steps and hardware placement is often limited although standardized fluoroscopic images are used. Therefore often postoperative CT became a standard method for decision making and postoperative analysis of complex intraarticular fractures at different anatomic regions. Correctional reoperations are necessary if significant articular steps or hardware misplacements are finally identified.

Due to the possibility of the intraoperative use of the new ISO-C-3D there is the advantage of direct intraoperative three-dimensional imaging.

The aim of the study was to assess the feasibility and benefit of the intraoperative use of a new C-arm based three-dimensional imaging device (ISO-C-3D) in foot and ankle trauma care.

Methods: The ISO-C-3D (Siemens, Erlangen, Germany) is a motorized fluoroscope providing multiplanar reconstructions like CT imaging from two-dimensional images.

In a prospective consecutive clinical study in a level I trauma center, the ISO-C-3D was used for intraoperative visualization in foot and ankle trauma care.
Before the use of the device, the reduction and implant position were judged to be correct using a conventional C-arm. Positioning of all patients or extremities was done on full carbon tables. An additional sterile draping of the whole situs was performed in all cases. Surgeons were able to analyze the joint reconstruction and screw misplacement. They also had the decision of necessary corrections based on the multiplanar reconstructions, compared to the conventional c-arm images. For this study the time spent, changes after use of the ISO-C-3D and surgeons’ ratings (visual analogue scale, VAS, 0 – 10 points) were recorded.

Results: Between January 1st, 2003 and December 31st, 2004, the ISO-C-3D was used in 101 cases within the operative treatment of foot and ankle trauma (Fractures: pilon, n=15; Weber-C ankles, n=12; isolated dorsal Volkmann, n=3; talus, n=7; calcaneus, n=32; navicular, n=2; cuboid, n=2; Lisfranc-fracture-dislocation, n=8; ankle/hind foot arthrodesis with or without correction, n=4/16).

The operation was interrupted for 430 seconds on average (range, 300 – 700). Preparation time including the sterile draping process took 167 seconds (s) (132 – 423). The scanning procedure time itself takes 120 s in every case during the slow scanning modus of the system. 210 seconds on average (129 – 450) for evaluation of the images by the surgeon were recorded. In 39% (39 of 101) of the cases, the reduction and/or implant position was corrected after ISO-C-3D-scan at the same procedure.

Eight surgeons were involved in the 101 procedures. Their rating was 9.2 (5.2-10) for feasibility, 9.5 (6.1-10) for accuracy and 8.2 (4.5-10) for clinical benefit.

Discussion: Two-dimensional intraoperative imaging does not allow precise identification of all articular joint steps and hardware misplacements. Multiplanar imaging is more accurate in judgment of articular fractures [2]. Intraoperative visualization remains problematic and conventional c-arm images are not always sufficient. The ISO-C 3D provides three dimensional intraoperative images regarding the detection of remaining intraarticular steps and implant misplacements. Direct intraoperative decisions and corrections become possible. Potentially in postoperative CTs identified articular steps and hardware misplacements can be avoided. Besides the ISO-C 3D remains a regular mobile c-arm and can be used as this additionally in all cases. The ISO-C 3D is more accurate than two-dimensional imaging and the quality even to conventional CT scans [1,3].

In conclusion, the intraoperative three-dimensional visualization with the ISO-C-3D can provide useful information in foot and ankle trauma care that
cannot be obtained from C-arm alone. In this study, in almost 40% of cases the reduction and/or implant position was corrected after ISO-C-3D-scan at the same procedure and after the reduction and implant position were judged to be correct by using a conventional C-arm. The ISO-C-3D appears useful in evaluating reduction and implant position intraoperatively, while not unnecessarily prolonging the operation.

References


Decreasing of the torsion difference in femur fractures with the use of fluoroscopy based navigation – A preliminary study

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Introduction: One problem during closed reduction and internal fixation during intramedullary nailing in femoral shaft fractures is the control of torsion because it is difficult to assess intraoperatively. The torsion angle can only be observed in a postoperative CT scan. Within the literature malrotation of more than 10° are described in up to more than 40 percent [1,2]. Revision operations due to a difference in torsion in comparison to the healthy side are frequent because this malreduction leads to unphysiological conditions [2,3]. The goal of this study was to evaluate if the use of fluoroscopy based navigation is able to reduce the revision rate in such circumstances.

Methods: For the experiments seven human donors were used. The control of the torsion was performed with the Vector Vision System (BrainLab, Heimstetten, Germany). Within the trauma 2.5 module (group 1) the measurement of the antetorsion is possible. Before the reduction maneuver the antetorsion angle can be measured on the non fractured healthy side, intraoperatively.

The intact femur was measured with a specially developed software for this experiment to receive the angles and length of the intact femur. Afterwards 11 fractures were performed while bending the femur. The other five femora could not be used due to prior operations, e.g. total hip prosthesis.

For the reposition with the trauma module 2.5 an ap and a lateral view of the femoral neck and a lateral view of the femoral condyle is necessary beneath
the ap and lateral view of the fracture. Within these images and the calculated angles and length the reposition is possible. Afterwards the difference between the values of the non fractured and the fractured femur after reposition were calculated.

As comparison group the same repositions were performed under fluoroscopic control alone (group 2) and with the use of a navigated reposition module without the possibility of determining the antetorsion angel (group 3). The three groups were evaluated with 1way ANOVA, statistical significance was set p=0.05.

**Results:** The new trauma 2.5 module showed the lowest rotational difference with 2.5° in average. This was significant different to group 3 with a difference of 6.6 in average (p=0.01). In contrast to group 2 there was a tendency of significance (5.3°, p=0.07). However, a rotational difference higher than 5° was found in one case in group 1 (5.7°). In group 2 and 3 each, there was five times a difference greater than 5° with a maximum deviation of 17.4° in group 2 and 18.7° in group 3.

Navigation time for fluoroscopy, however, was significantly higher in group 1 with 71 s in average in contrast to group 2 with 42 s (p=0.02) and to group 3 with 10 s (p<0.01).

**Discussion:** Within the experimental setup the newly developed trauma 2.5 module for fracture reduction was able to decrease the torsion difference at closed reduction of femoral fractures. However, this module leads to an increased fluoroscopy time within this study. But it has to be mentioned that in group 2 and 3 no further X-rays were performed as from the fracture zone. Furthermore the system was tested experimentally for the first time so a learning curve while collecting the right images for navigation has to be supposed. Further clinical studies have to prove if the revision rate will decrease with the intraoperative use of the new system.

**References**

Surface-matching can predict dislocation parameters of fracture fragments and might improve alignment in fractures of the femoral shaft.

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Surface-matching can predict dislocation parameters of fracture fragments and might improve alignment in fractures of the femoral shaft.

Introduction: Control of fracture reduction is sometimes problematic with minimal invasive surgery of the femur. Until today fluoroscopy is the standard technique to check for intraoperative alignment. The radiation exposure of the operating staff and the patient is quite high, especially for the process of reduction. Average image intensifier usages between 158 and 316 seconds are recorded in the literature [3;6]. Significant malalignment in the sagittal and frontal plane differs between 2 and 18 percent [1;7;8]. Rotation around the shaft axis is difficult to assess intraoperatively. Today postoperative CT scan is the most reliable diagnostic method. Differences of more than 10° of rotation are recorded with an incidence of more than 40 percent [4;5]. Malreduction leads to unphysiological conditions with consecutive reoperations in several cases [5;9]. Fluoroscopy based navigation was introduced to ease the reduction and to reduce the amount of radiation [2]. Nevertheless, only a small part of the whole femur is imaged, so exact alignment in the coronal and sagittal plane can be difficult to assess. Additionally, rotation deformity can not directly be visualized with this two-dimensional imaging technique. We started a completely new approach to improve fracture alignment. As reduction is the reversion of the dislocation, the knowledge of the dislocation parameters between the two main fragments
might be of importance. With these parameters reversion of the dislocation to an anatomical alignment should be possible.

**Material and Methods:** Three-dimensional CT data of femoral shaft fractures were used. We developed a software that can recompose even multifragmentary fractures similar to a jigsaw. As a result the software outputs the relative three-dimensional transformation parameters between the segments. The retrieval is divided in three steps. First an adapted Hough-Transformation is used to estimate the shaft axis of each fragment. The exact alignment is acquired in a second and third step. A Z-buffer matches the surface of the fracture fragments. This matching is optimized with an ICP-(Iterative Closest Point) algorithm.

9 donor femora were used for the tests. A reference base was fixed to the proximal and distal part. The intact femora were scanned with a multislice CT-scan. Three-point bending was performed and the fractured femora were scanned again. A refer calculates an exact surface matching between the fragments.

**Results:** Our results show that nearly 99% of all fracture surfaces could be recognized accurately. With simple fractures the malalignment is less than one degree. Even in complex fractures we found the malalignment to be less than four degrees.

**Conclusion:** The developed software is able to predict precisely the relative dislocation parameters of the fragments of femoral shaft fractures which are visualized by 3D-CT data. These parameters could be used by a navigation system and/or robot system to achieve anatomic alignment of shaft fractures without any intraoperative fluoroscopy.

**References**

Purpose: Closed fracture reduction is sometimes hard to achieve with minimal invasive techniques. High counteracting forces and torques like in the femur or pelvis make fine manipulations often difficult. Further, retention of the reduction until secure fixation is still problematic. Malalignment and high intraoperative radiation doses are associated with reduction problems in the literature [1-4]. A robot system may allow these fine adjustments as long as the robot’s maximal load is above the counteracting forces and torques of the soft-tissues. Our hypothesis is that robot assisted fracture reduction is feasible and might improve the quality of reduction while reducing the amount of radiation exposure.

Method: 7 human donors were used for the study. Their intact femurs were used for the study. The donors were posed supine on a regular fracture table. 11 femoral shaft fractures were made by three-point bending. A robot system based on an industrial robot was developed which could be used as a telemanipulator for fracture reduction. The proximal fragment was fixed with two Schanz screws to the operating table. A special invented holding tool, which requires 3 lcm incisions, was attached to the distal fragment and to the robot. Calibration of the robot was done using a commercial optoelectronic navigation system. A load cell was attached to the robot to provide force and torque values. These values were translated into haptic impulses which could be felt by the surgeon while moving the input device. The navigation system was further used to measure the alignment of the femur with the unbroken femur as reference.

Robot assisted fracture reduction was performed in all 11 femora. Manual reduction with one proximal and one distal Schanz screw was used as control group. Reduction control was performed by fluoroscopy. Our hypothesis was
that both groups do not differ in post reduction alignment (1way ANOVA, p<0.05).

**Results:** Robot assisted fracture reduction was feasible in all 11 femora without any intraoperative complication. There were no statistical differences in alignment (see Table) or image-intensifier time (Robot: 31s, Manual: 48s; p=0.14).

<table>
<thead>
<tr>
<th></th>
<th>Robot</th>
<th>Manual</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varus/ Valgus</td>
<td>2.5° (0.9-5.2)</td>
<td>1.9° (0.1-5.3)</td>
<td>0.46</td>
</tr>
<tr>
<td>Ante-/ Revurvature</td>
<td>3.2° (1.0-5.5)</td>
<td>2.1° (0.6-6.3)</td>
<td>0.16</td>
</tr>
<tr>
<td>External-/ Internal</td>
<td>5.0° (1.2-14.4)</td>
<td>5.2° (0.2-17.4)</td>
<td>0.93</td>
</tr>
<tr>
<td>rotation</td>
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**Conclusion:** This cadaver study did not show any superiority of robot-assisted fracture reduction compared to manual reduction. The limiting factor might be the intraoperative reduction control by fluoroscopy. Novel intraoperative control mechanisms have to be invented to increase the precision of the reduction. Nevertheless, in our opinion robot assistance will be of importance for the reduction of fractures in the future.

**References**


Femoral rotation and balanced flexion gap using navigation system and hydraulic knee analyzer

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Introduction: To obtain a good outcome in TKA, it is mandatory to reach a balanced flexion gap [1-3]. That requires, during surgery, to choose the position of the prosthetic component, mainly the femoral one [3]. These choices are based upon some bone landmarks (e.g. the transepicondylar axis (TEA)) and ligament tension.

Several authors published in the last decade about this topic, but the determination of a value for the femoral rotation still remains a big issue.

The aim of this study is using a navigation system, to quantify the necessary femoral rotation between the TEA and the posterior condylar line to obtain a rectangular gap in flexion.

Material and Method: We have identified the radiological TEA preoperatively using computed tomography (CT-High Speed General Electric Medical Systems), we have applied equal ligament tension intraoperatively using the Hydraulic Knee Analyzer tensor (HKA™, Zimmer GmbH) and fixed the femoral rotation using a navigation system (Navitrack™ Imageless 1.1 NKII® Orthosoft Inc.). The group of patients (60) was only varus or normal knees (no valgus knees), all with a subvastus approach, all retaining the posterior cruciate ligament. After a tibial cut at 90 degrees to mechanical axis, we applied the HKA™ tensor. The navigated NKII® positioning block was applied on the posterior condyles and rotated to get a rectangular gap. The obtained screen data was recorded.
Preoperatively we have stored TEA (clinical epicondylar axis according to Yoshino [4]), HKA angle, and posterior condylar line (PCL) and the resulting posterior condylar twist (PCT).

During surgery, we stored the rotation of the navigated Positioning Block (PB) in relation to the PCL.

Postoperatively, we searched for a correlation between PB rotation and HKA and compared the TEA and the balanced flexion gap tension line (TL) by using the posterior condyle line as the common reference.

**Results:** Preoperative PCT range is from 0° to 9° with a mean of 5.3. They are correlated to HKA. We collected peroperative PB rotation with results from 3.7° internal to 6° external rotation with mean of 0.7° and SD of 2.1°. We found no clear correlation to HKA.

This way we were able to compare TEA and TL with results from 0.3 to 9.5 (mean 4.6° and SD 2.4°).

The results did not show a homogeneous distribution without correlation between rotations and HKA or PCT.

Finally we compared necessary rotations to obtain rectangular gaps with HKA tensor and Posterior reference line (PCL) usually used in recommended NK total knee technique. Only 80% are in a range of ±2° to the PCL (estimated compatible with posterior reference technique). In 20% of cases, gap and tensor technique seemed necessary to determine the right femoral implant rotation.

**Discussion:** It is now well recognized that rotational alignment of components in TKA is an important factor for the outcome affecting both femoro-tibial and femoro-patellar joint kinematics.

Different solutions have been proposed: Subjective methods using arbitrary 3° of external rotation, recommending a tibial cut in slight varus or objective methods using bone landmarks either preoperative or peroperative with computed images.

Finally instrumentation systems using ligament tensor devices may offer superior reliability being independent of uncertain bone landmarks.

So far as we know, no study using similar rectangular gaps in extension and in flexion, evaluated the final rotation obtained according to the deformity in varus and the amount of this deformity.
Computer enhanced surgery associated to a ligament balancer allows to control precise cuts (tibial cut strictly orthogonal) and rectangular gaps applying the same pressure in both knee compartments. Moreover, computer control gave us final precise femoral rotation obtained.

With the aim of obtaining homogeneous data, we assessed only varus knees and evaluated the final rotation of the femoral cut in relation to the posterior reference which seems the more reliable landmark to digitalize.

Final results compared to the amount of varus don’t allow to find any relationship with the deformity despite the homogeneity of patients (deformations in varus, same approach, PCL retained).

The specific collected data cannot suggest any guide line if any individual knee ligaments status needs specific implant rotation. In a significant number of cases gap balanced technique seems to set the right femoral implant rotation.

Possible errors due to the surgical technique will be discussed: Digitization of posterior reference and possible posterior cartilage wear, influence of the approach and ligament release [8] done in extension, preoperative ligament status (laxity in the convexity), quality of the retained posterior cruciate ligament.

References

Highlightening of navigation of the pelvic tilt through an “in vitro study”

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Introduction: As noted a navigation of the hip presents some important aims which bring into effect on a clinical plan as improved control of the leg length discrepancy and the articular stability after the arthroplasty with methodical progress that lends a helping hand in the attainment of these aims, particularly in relation to the mini-invasive technique where poor visualization of bone traces can effect the correct positioning of the prosthetic components. Nevertheless, since our first experience that started in June 2000 with the navigation system Navitrack CT based we have been able, in some cases to observe, and above all in regard to the antiversion some important differences in respect to the inclination degree and antversion planning.

With reference, for example, a limited case was followed and explored with average simulation. Clinical experience suggests a position in which attribute navigator 62.9° of inclination and 47.1° in antversion, on average this information was signed 58.3° inclination and 36.4° antversion to under-estimate the functioning position of the subject that in a horizontal position, presented a marked tilt of the pelvic bone verified by follow up lateral X-ray in a standing position. Correcting the tilt, that assigns the navigator to a system of co-ordination that reflects the live functional result and not simply the anatomic plain that passes the pubic bone and the iliac spines. We were able to verify, to our surprise, that the marked degrees based on surgical experience, were read as 44° inclination and 29° of antversion. Therefore, the aim of the study was to demostrate and rationalize the influence of the pelvic tilt in the position of acetabular components.

Method: An experimental device was built. This model included a bracked shaped form that rotated the pelvis just around the acetabulum rotating centers, through which a 3.2 mm pin was inserted. In this way it was possible
to mime the tilt functionality as in live. Above all precisely measuring the entity. Exclusively the results of the antversion, the impactor tracker (gun) was fixed onto the set up with an inclination of 46°, where as the antversion was assigned, for every cycle of measurement, respectively at 5°, 10°, 15° and 20°. For an antversion data the positioning of the pelvis was assigned to a zero tilt therefore this varied step by step at 5° starting from -25° to +25° exploring the pelvic retroversion with the tilt ahead and every cycle of measurement calculated the variation of the antversion itself.

**Result:** Repeated measuring was carried out to find out the minimal accidental variations that could happen by means of registration. From the average data it was possible to extract and graph the correlation between the tilt and the antversion, that synthetically expressed and demonstrated a variation of 50° in an explored tilt variation of 37° with respect to 10° antversion “base-line” (that is considering a natural position tilt), and a minimum of 32° for the 20° “base-line”. The average discrepancy of the antversion was considered for every 5° of tilt and was 4° in the case of front rotation (positive tilt) and 4,7° for the inverted pelvis (negative tilt).

**Discussion:** This simple study allowed us to enrich the navigation of the correcting parameter which is very important for the positioning of the acetabulum components that explain the meaning of a “nominal” antversion (that is referred to an anatomic plain that corresponds to a 0° tilt) that for example at 13° in a subject in which the pelvic bone tilt is at 15° would take on a functional position to the same value of about 25°. This invites us to comprehend better the meaning of anatomic orientation and reduce the discrepancy with live studies about functional antversion. With the radiographic antversion, the supine patient is justified to discard between the navigated antversion and “surgery” in the lateral position. This takes away the problem to calculate the tilt live subject.

**References**

A simple method to determine the pelvic tilt through a radiographically linear misuration to enhance the navigation

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Introduction: Firstly, we have five years of experience in the Navigation CT based, and then followed by CT less, using the NAVITRACK ORTHOSOFT System which has enriched us with notable information on the subject of biomechanics of the hip. In particular according to our experience with the navigation of the hip CT less which turned out to be a trustworthy method that is sufficiently slim-line to be used almost routinely. All this down to the fact that the maximum advantage in navigation, which is still necessary to progress in some aspects and that research in correlation with conventional radiology on which pre-operation planning is based.

Thanks to navigation the limits of bidimensionality of conventional planning are integrated. Just bring to mind the pre-operative registration of the central rotation and its direct comparison with the reconstructed acetabulum where it is not possible to compare the cranial-caudalis and later-medialis positioning in function to the pre-operative plane, as well as checking the side and back positioning of the center of rotation itself.

The accuracy in which the central rotation can be defined is reflected on a clinical plan with precise checking of the leg length discrepancy even in complex cases. Another advantage that navigation offers is the relative check control of the inclination and anteverision of the acetabular components which in complex cases may be misinterpreted.

This work underlines the fact that in these situations where anteverision and/or retropulsion of the pelvic bone (positive and negative tilt) differentiate the norm, therefore leaving the anatomic plane that passes the pubic bone and the
iliac spines suggesting the X-ray method for complex cases or the analysis would be widened in all treated cases.

**Method:** Thirty treated cases were examined and compared with insight to the positioning of the central rotation in respect to the data supplied from the navigator. Measurements were taken and also the inclination and antversion conventional radiography of the pelvic bone in antero-posterior and then compared with data registered by the navigator.

**Result:** While the correspondence relative to the central rotation was excellently presented. As already observed in many cases, radiographic antversion, even with corrective facts, discrepancy in respect to the carried out registrations.

From the moment that this problem was highlighted with the navigation CT based was attributed to the tilt functionality of the pelvic bone and we noted the measurements from the radiography in a laying down position and an upright position revealing a higher adhesioning data.
Discussion: the results gathered indicate the necessity to determine the “functional positioning” of the pelvic bone in respect to the anatomical one. Through time this winning problem is on the table, today’s modern methods using the CT based systems where direct measurements in the described perpendicular angle to the body and the passing plane for the pubic bone and iliac spines as evidenced in a lateral radiographic clique of an erect patient in this way the method was directly adopted through a device which perpendicularly touched the points that needed to be reached on the standing patient revealing that the anatomic plan in respect to the lead thread. In the end radiographic relief in the antero-posterior in the standing patient have suggested to correlate the two X-rays (in the lying position) with a 0° tilt and in the up-right functional position and the through the linear measurements of distance between the passing line in the central rotation (perpendicular) to the extreme point of the ischiatic tuberosity, therefore supposing that the tilt comes around the central rotation correlating with a simple trigonometric calculation the two distances taken in two different radiograms are supposedly the radius of the circle passing a perpendicular for the central rotation.

References
MIS meets CAOS – Early experiences and results in MIS TKJR

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Introduction: The concept of Minimally Invasive Total Knee Replacement has been strongly promoted by the Orthopaedic Implant Industry. Some centers have arrived at the minimally invasive and reduced tissue trauma surgical technique by parallel independent development. Our center has been involved in this technique for three years as a development from the minimally invasive Oxford Unicompartmental arthroplasty. The concepts, terminology and technique are discussed and elucidated. The potential benefits and complications are explored and discussed.

Methods: Analysis of the first 27 Minimally Invasive Total Knee Joint Replacements using the Search Evolution and Columbus Knee systems (BBraun Aesculap) with respect to parameters of accuracy of implantation, cementation and in hospital parameters are presented. The study population covered use of both standard jigs and specifically designed minimally invasive surgical jigs. All knees implants were implanted using computer assisted navigation (Orthopilot, BBraun Aesculap. All minimally invasive total knee arthroplasties were performed by a single surgeon.

Results: Incision length is related to patient build and height and associated musculature, rather than absolute values. 10 cm incisions are practicable with patient selection and appropriate instruments. Specifically, true quadriceps sparing incisions preserving the vastus medialis obliquus are practicable with specifically designed instruments and careful patient selection. In our series there is no discernible difference between VMO preservation and VMO Snip.

Straight leg raising and 90 degree bend are easily achievable in the recovery room. Cross over studies relate this benefit to a change in anesthetic technique and post operative pain relief methods rather than solely the operative technique.
Early discharge in our patient population was feasible on third post operative day. The pattern of early discharge relates to patient expectation and age and preoperative mobility. A system of early discharge support with domiciliary nursing and physiotherapy care can achieve significant but lesser gains in conventional TKJR. The accuracy of minimal invasive TKJR with navigation was assessed and no loss of alignment accuracy was noted. Clinically it was evident that alignment without navigation was difficult to achieve consistently due to loss of conventional visual clues.

Implantation and cementation were blindly assessed by an independent reviewer. In all measures these parameters matched conventional TKJR performed during the same period, though there was no control as to particular surgeons.

Operative times were marginally less for MIS TKJR than for standard TKJR though this was felt to strongly represent patient selection for MIS surgery (little deformity, lower body mass, full range of movement.)

Complications noted in this series included one pulmonary embolus. Proximal wound bruising was noted in the early patients but there was no delay to healing. A difficult learning curve despite significant experience of knee surgery was noted.

At six months there was little objective difference between conventional TKJR and MIS TKJR as the observed improved flexion range was not significant in such a small group. There was clear evidence that this also reflected poor sensitivity of present Knee scores as proprioceptive function seemed to be better as subjectively assessed by physiotherapists in a dedicated knee class.

**Discussion**: Progress in scientifically assessing the MIS/CAOS TKR technique against either conventional or navigated conventional TKJR and non navigated MIS TKJR will depend on agreeing definitions, elucidating the anatomy of the extensor mechanism and developing more sensitive knee scoring systems.

The rapid improvement attributed to the specific technique of MIS TKJR may be significantly related to the institution of a MIS rapid rehab protocol associated with changes in peroperative management. Gains in rehabilitation of conventional TKJR patients can be expected by applying the MIS protocols uniformly to all TKJR patients.
Standardized evaluation of accuracy of conventional and navigated cup placement

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The goal of the current study was to determine the accuracy of conventional and computer-assisted cup placement using a cinematic navigation system (OrthoPilot). Since there are only a few studies concerning the postoperative results of ct-based navigated cups there are no really acceptable results available about the accuracy of cup placement using image-free navigation systems. To determine postoperative cup position we developed a special tool to create standardized postoperative X-ray controls without additional radiation for the patients.

We analyzed the cup positions after 50 conventionally inserted THAs and compared it with the positions of 50 navigated cups. The operations were done between October 2002 and November 2004. To determine the accuracy of the cup position, the authors developed a special tool to make sure that the pelvic entrance plane most navigation systems are based on was in a horizontal plane while creating the postoperative X-rays. Therefore the central beam was focused directly on the head of the implanted hip. With special markers in the tool we could determine the inclination angle directly from the X-ray-print. The ante-version was calculated using the well known principles.

With regard to the inclination we found very nice results in both groups. In the conventional group we found 40.3° on average (range 20 to 58°). In the navigated group we found 40.1° on average (range 30 to 54°). Concerning the anteversion angles we found 16.0° in the conventional group on average (range 0° to 29°) and 16.3° on average in the navigated group (range 18 to 25°).

Particularly the anteversion angles variety of the cup position was significantly higher in the freehand implanted group. In the navigated group...
we found no outliers. The standard deviation for the anteversion in the navigated group was 5.0 and for inclination angles 2.8°. In the conventionally implanted group the standard deviation was 7.4° for inclination and 6.9° for anteversion. It must be pointed out, that the standard deviation for the anteversion without navigation help was more than 2.5 times higher than with navigation. Also the confidence areas were more narrow for the OrthoPilot technology.

Particularly the anteversion cannot be exactly calculated without a navigation tool since the individual position of the patient’s pelvic bone cannot be assessed by the surgeon without aids. We didn’t see any luxations in the computer navigated collective till now. Two luxations could be recorded in the conventionally operated group. In addition, the bone stock of the pelvis was perforated in two cases, when reaming without help. We have been able to control accuracy of cup placement in both groups with a simple and reliable method without additional radiation for the patients. Clinical long-term studies for the clarification of a higher standing time of the computer navigated cups are necessary.

References
Comparison between conventional and navigated inserted cups using the OrthoPilot in standardized evaluation X-rays

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The goal of the current study was to determine the accuracy of freehand and computer assisted cup placement. The problem of determination of the postoperative cup position was obvious in several other studies. So by now apart from some ct-based evaluations there is no real result about the usefulness of cinematic navigation systems available. To solve this problem a special tool for collecting standardized X-rays right after operation without additional radiation for the patients was developed. This tool allowed us to take X-rays of the hip postoperatively using the same pelvic entrance plain the most navigation systems are based on (superior iliac spines both and Tubercula pubica).

We analyzed the cup position of 50 conventionally inserted THAs and compared it with the position of 50 navigated cups. The operations were done between October 2002 and November 2004. To determine the accuracy of the cup placement, the author developed a special measurement tool. It was made sure, by the help of this tool, that the radiographs central beam reached the pelvis in a horizontal position. The central beam was focussed directly on the head of the implanted hip. We calculated the anteversion and inclination.

First of all we have to point out that there have been very good results for the inclination angles of 40.1° (range 22 to 56°) on average in the navigated group and 40.3° (range 30 to 54°) on average in the conventional group. The anteversion was 16.0° (range 0 to 37°) in the conventional group and 16.3° (range 11 to 23°) in the navigated group.

With regard to the inclination and particularly to the anteversion angels, variety of the cup position was significantly higher in the freehand implanted
In the navigated group we found no outliers. The standard deviation for anteversion in the navigated group was 5.0 and for the inclination angles 2.8. In the conventionally implanted group the standard deviation was 7.4 for inclination and 6.9 for anteversion. It must be pointed out that the standard deviation for the anteversion without computer assisted help, was more than 2.5 times higher than with navigation. Also the confidence areas have been more narrow in the navigated cases.

Particularly the anteversion cannot be exactly calculated without a navigation tool since the individual position of the patient’s pelvis cannot be assessed by the surgeon without aids. We didn’t see any luxations in the computer navigated collective till now. Two luxations could be recorded in the conventional group. In addition, the bone stock of the pelvis was perforated in two conventional cases. We were able to use a simple and reliable method to determine the postoperative accuracy of cup placement by the use of standardized X-rays. Further clinical long-term studies for clarification of a higher standing time of computer navigated cups are necessary.

References

Development of a new miniaturized robotic device for the removal of femoral bone cement

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Introduction: In Revision Total Hip Replacement (RTHR), the removal of the distal femoral bone cement can be a time consuming and risky operation due to the weakened cortical wall and the difficulty in determining the 3D boundary of the cement. In conventional RTHR the position and orientation of the instruments are being observed using iterative multiplanar X-ray imaging resulting in a high radiation dose for the patient as well as for the OR staff. Within the MINARO project (Minimal Invasive Navigation and Robotics), funded by the German Research Foundation (DFG), we developed a new approach for computer assisted removal of the bone cement.

The shape of the cement volume can be reconstructed on the basis of a three dimensional cement model. Reconstruction is realized by a back projection of two dimensional segmented contours out of multiplanar X-ray projections of the femur. Applying adequate interpolation algorithms the cement volume can be reconstructed with a resulting error of 0.5 mm (RMS) using 5 X-ray images from different views [1].

It is proposed to remove the femoral bone cement by a hand-navigated milling device or an active robotic device, depending on the intraoperatively assessed situation and the preference of the surgeon. Studies concerning the hand-navigated milling showed the feasibility of this approach [2]. Following the modular concept of MINARO a robotic device with 3 DOF has been developed. The design is based on initial studies on the anatomic situation, workspace considerations, fixation of the robot at the femur and on the process of cutting the bone cement with optimization of the milling tool [3].
The objective of the work reported in this paper has been the verification of the suitability of this robotic system for the given application.

**Methods**: The design of the robot is based on workspace considerations with regard to the usual shape and dimensions of the femoral bone cement volume. Preliminary tests yielded information about useful milling parameters such as feed rate and infeed. Furthermore, limits for the resulting forces to be applied by the robot could be determined. A parallel structure with 3 DOF has been chosen due to reasons of stiffness and compactness. Link dimensions were calculated to realize the desired workspace. The mechanical design with brushless motors and special gears reflects the requirements concerning torque and resolution. For the milling itself a pneumatic high speed motor was integrated in conjunction with specially designed extension shafts and milling tools.

**Results**: First trials with the compact robotic device (95x113x210 mm³) used on anatomic bone models with bone cement showed its suitability for the task. The fixation between femur and robotic device seems stiff enough to allow a precise removal of the bone cement. Numerical evaluation of the achieved precision is currently subject of research. Neither excessive heat generation at the tool nor disturbing vibrations have been observed so far. Detailed results of the ongoing tests will be presented.

**Discussion**: The MINARO compact robot device is a promising addition to the modular concept of MINARO. It allows a more time efficient and precise removal of the bone cement. Further investigations are undertaken to improve the concept for revision total hip surgery.

**References**


Basic experiments on milling of bone cement in RTHR

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Introduction: Removal of femoral bone cement during revisional hip arthroplasty is a major problem, often leading to complications due to the additional time needed and possible damage of the remaining bone stock. The most common method for cement removal is still the classic technique with hammer and chisels, optionally under endoscopic control. Alternative methods based on e.g. ultrasound or laser are evolving. In conventional RTHR the position and orientation of the instruments are being observed using iterative multiplanar X-ray imaging resulting in a high radiation dose for the patient as well as for the OR staff. Within the MINARO project (Minimal Invasive Navigation and Robotics), funded by the German Research Foundation (DFG), we developed a new approach for computer assisted removal of the bone cement. The shape of the cement volume can be reconstructed on the basis of a three dimensional cement model. Reconstruction is realized by a back projection of two dimensional segmented contours out of multiplanar X-ray projections of the femur. Applying adequate interpolation algorithms the cement volume can be reconstructed with a resulting error of 0.5 mm (RMS) using 5 X-ray images from different views [1].

For purposes of navigation-assisted or even robotic cement removal milling seems desirable also due to the direct correlation between tool path and cement removed. It is proposed to remove the femoral bone cement by a hand-navigated milling device or an active robotic device, depending on the intraoperatively assessed situation and the preference of the surgeon. Problems herewith subsist because of heat generation [2] and the cutting forces jeopardizing the accuracy of the process. Therefore experiments have been carried out to identify key factors influencing induced forces and heat generation.
Methods: A variety of available surgical milling tools along with the appropriate motors as well as an industrial style pneumatic spindle with optimized tools have been included in this study. Bone cement specimens were made from Reofacin-Palacos R (Merck, Wehrheim, Germany) according to the manufacturer’s instructions. The milling spindles with the appropriate extension shafts and tools were attached to a CNC milling machine (CPM2018, Isel, Germany). On the base plate a force-torque-sensor was used to mount the cement specimens so that forces of the milling process could be measured. A provision to cool the area of milling by rinsing with water was present, as was an infrared sensor to measure the temperature (Raytek Thermalert, TTI Inc., Williston, USA).

The CNC milling machine allowed line-by-line milling with controlled parameters such as feed rate, axial and radial infeed. Depending on the milling motor used, the revolution speed of the tool was either automatically controlled or adjusted itself corresponding with the other parameters and was measured. The software written for the experiments allowed the logging of all parameters (forces, revolution speed and temperature) with a frequency of 90 Hz.

All free parameters were varied and the correlation between these parameters, the material removal rate (MRR) and the forces have been investigated.

One test investigated the influence of cooling on forces and wear. The forces were used as a benchmark for wear. The introduction of heat into the work piece due to the milling process was investigated by contact less temperature measurement on the new cut surfaces immediately behind the tool.

Results: Major differences between different tool/motor combinations have been shown. Surgical milling systems never exceeded a MRR of 50 mm³/s.

The experiments concerning wear showed a progressive increase in wear when milling with water cooling. Milling without cooling showed a much more moderate growth in wear.

An increased feed leads to higher temperatures on the work piece. Above 10mm/s a significant increase in temperature was noticeable. However, using a robotic system with optimized milling paths, temperature and machining parameters could be adapted to different stages of the milling process. Detailed results and considerations will be presented in the paper.

Discussion: An assessment of the material removal rate clearly showed the superiority of the industrial motor with the optimized tool; besides the better suited geometry of the tool, the higher available mechanical power is
responsible for that. The optimized tool is under examination in combination with a clinical motor.

The cooling of the milling area is counterproductive from a technical point of view. The heating of the cutting edges makes the milling process easier, as long as the chips are well dissipated from the milling area. With regard to possible thermal damage to the living tissue, cooling seems unnecessary below a feed rate of 5 mm/s. This point is under further examination due to the potential risk. In any case it is obvious, that an exact control of machining parameters using a robot device seems to be mandatory.

The milling of bone cement, as a central element of the procedure proposed in MINARO, has a high potential of improvement. As relevant literature could not be found, own experiments were undertaken to throw light on that complex matter. An improved milling tool was developed and tested with success. The tool and the motor will be subject to further work.

References


Introduction: Arthroplasty is among the most common complex surgeries today. Its clinical outcome depends on (among other factors) the “quality” of bone preparation for implant insertion. Pioneering effort by DiGioia [1] advocated “closing the loop” in patient outcomes, by transferring conventional templates or computer-aided preoperative plans to the OR and assessing surgical implementation. TKR clinical scoring methods such as HSS, KSS/AKS, Oxford, BOA and others assess the overall outcome and patient satisfaction. However, they do not assess the bone cuts directly. Surgeons face a growing number of choices of current and future surgical techniques with conventional or navigated jigs, MIS, passive or active robotics etc. In each, a variety of different types of oscillating saws, mills and perhaps future water-jet and laser-cutting tools may be used. All these compound upon the traditional important choice of which implant to use.

Therefore, direct “quality management” by assessing the bone cuts themselves becomes very important. The literature currently lacks a generalized method to quantitatively assess bone cuts. This paper lays the foundation for such a method by analyses and experimental examination of the minimum number of parameters necessary. The distal femoral cuts of TKR are taken as a case study. A subset can be applied to the proximal tibial cut and other arthroplasties. The detail is sufficient to allow researchers and developers of navigation systems to evaluate different tooling, software and cutting methods. The methodology is also adaptable to allow surgeons to assess bone cutting in the OR.
Figure 1  (a) to (e) Schematics illustrating the difference between the potential implant fit/tightness, alignment, surface finish of the cut bone and gaps due to rogue planar cuts as separate characteristics of the “quality” of bone cutting.  (f) and (g) show the main parameters that resulted from the data-processing of the presented TKR case study. The main observations cited in the text, namely, “Implant location” for Bone-1 and “Roughness” of the “Anterior cut” of Bone-2 are highlighted in this Figure
Methods: Navigation and some form of digitization capability are the minimum instrumentation assumed here. Our analysis yields the following parameters to define bone preparation “quality”:

1) Implant Fit/Looseness (L)

This represents how loose the implant can be due to the resulting bone-shape. Using navigation, the bone and a trial-implant are tracked for a few seconds logging hundreds of different anatomical positions (including extremes) that the implant can take relative to the bone. L indicates implant “play” through the maximum ranges found in flexion-extension, varus-valgus and internal-external rotations and maximum AP translation of the implant relative to the bone before cementing.

2) Implant Misalignment (M)

This indicates the minimum errors in alignment that the cut bone will allow after insertion, even with optimum cementation technique. The same logged dataset from above is used. M is however calculated from the minimum deviations possible for insertion in all 3-rotations and 3-translations in the Grood and Suntay coordinate-system [2].

3) Bone-cut surface finish (Ra, Rpm and Rvm)

Good implant fit and/or alignment can be achieved but still leaving gaps between bone and implant (Fig. 1b and 1c) which can compromise bony ingrowth for cementless situations or exceed the maxima for good cementation. Sample surface data can be digitized by navigation or a Scriber intra-operatively, or CMM, CT or laser-scanning in the laboratory. “Ra” is straightforward and analogous to engineering surface-finish measurements, and was for bone in [3]. Ra is the average of a sample of absolute (neglecting sign) deviations from the mean in a direction normal to the cut surface. The sharp spikes and deep pits are disproportionately detrimental to both fixation and alignment. Therefore Rpm and Rmp (mean of 10-worse-peaks and valleys respectively) would capture these effects.

4) Accuracy of each planar cut (Pd, Pf, Pv, Pr)

Most TKRs require 4-5 distal femur cuts. Overall implant looseness, misalignment and roughness still do not detect if individual fixation surfaces of the implant are close and parallel with adjacent bone surfaces (Fig. 1c). If a cutting jig, navigation or robot systematically over-cuts one or more femoral plateaus, this can, but sometimes may not, affect overall fit and alignment. However they may compromise ultimate fixation. Correcting such systematic over-cuts once known postoperatively can be avoided in future
patients. Pd, Pf, Pv, Pr are translational and rotational errors between the best-fit plane of each digitized planar cut and its corresponding ideal. For this, the same surface finish dataset can be used.

Experiments were conducted on identical synthetic distal femoral bones cut with an oscillating saw to examine the above. Only two bones are presented here due to the confined space. Conventional combination cutting jigs were used on Bone_1, and a Freehand-Navigated CAOS system on Bone_2. On Bone_1 the cuts were intentionally misaligned, and the anterior cut of Bone_2 was deliberately made rougher and uneven. Digitization of both was done by CT scanning/reconstruction with (0.25x0.25x0.65 mm) resolution, yielding an average of 1800 points for each distal-femoral cut.

As shown in Fig.1 (f and g) the Ra, Rpm and Rvm parameters for the anterior cut of Bone_2 were found higher than for Bone_1 indicating inferior surface finish of the former. However, Pd, Pf, Pv, Pr and the overall misalignment (M) were all lower in Bone_2 despite its rougher surfaces, indicating superior potential for implant alignment. Finally, fit/looseness of both bones resulted similar for implant tightness; indeed, no such differences were deliberately created.

Discussion: The parameters proposed characterized the quality of bone reshaping independently of the surgeon, cutting-tool or surgical technique. They isolated and objectively quantified the errors of looseness from the misalignment of the implant. The surface finish and alignment of each planar cut were also isolated. Coherent and quantitative capture of the quality of bone cutting has potential as a standard test method for assessing bone-preparation in arthroplasty and for comparing navigation systems.

References
CT-fluoro based registration for minimally invasive hip surgery

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Introduction: Joint preserving hip surgery is a successful therapy in many young patients with hip deformity. In particular, femoro-acetabular impingement surgery [GGG] gained popularity and acceptance in the last years. With a trochanteric osteotomy and dislocation of the hip open impingement surgery affords wide tissue dissection in order to resolve the impingement with a relatively small surgery at the joint level. Thus, a less invasive approach is desirable. However, less invasive surgical techniques have an increased risk of inadequately assessing and treating the problem as long as the approach does not allow reliable and accurate information about the intraoperative situation [MTK].

Image guidance helps to overcome this drawback. For this purpose, a minimally invasive (MI) registration technique must be provided which is very accurate and robust. Matching of preoperative CT scans with intraoperatively acquired fluoroscopic (fluoro) images qualifies for this task. It essentially is a non-invasive technique that has proven to be accurate in spine surgery [MMM]. For using CT-fluoro based registration in hip cases an efficient and intuitive integration into the workflow must be provided. Additionally, a dedicated image acquisition strategy has to be provided to assure the robustness of the registration since hips do not have such prominent landmarks as vertebrae.

Within this contribution we provide a module for performing MI hip surgery based on a CT-fluoro registration technique. The accuracy and robustness of the registration have been evaluated in a study based on tests with plastic bones, cadaveric hip specimen, and finally, in clinical practice.

Methods: To achieve a CT-fluoro based registration the alignment of intraoperatively acquired fluoroscopic images in relation to a preoperative CT
scan has to be determined. For the calculation of this alignment a technique based on the generation of digitally reconstructed radiographs (DRRs) was used (cf. [LJR]). To achieve the best alignment between the given fluoroscopic images and the DRRs we optimized the pose with respect to a similarity measure based on gradient correlation. The optimization of the pose is realized by a technique using local approximations of the similarity function (cf. [Pow]). Convergence of the optimization is only guaranteed to a local and not to the global minimum.

For this reason, a landmark-based preregistration is performed. This gives a rough estimate of the pose. This approach improves the robustness of the registration significantly and enhances the running time of the algorithm since one starts with a pose quite close to the optimal solution. Additionally, the preregistration step is well integrated into the clinical workflow, since the relevant landmarks are also important for planning tasks. They have to be defined in the CT data set, preoperatively. Interoperatively, the surgeon has to acquire up to 6 points with a pointer device or by a point definition procedure directly on the fluoro images. The registration is then performed automatically. Thus a MI registration with little additional user interaction is achieved.

The proposed CT-fluoro based registration technique is a quite general technique that can be applied to different anatomical structures. Only the preregistration has to be adapted. Within this contribution we provide a registration module for the femur and pelvis. The registration accuracy depends on the specific anatomical structure and a dedicated strategy for image acquisition. For optimizing the accuracy one has to choose the poses for acquiring the fluoro images carefully. To get an accurate alignment we require two images for each structure. It is recommended that the directions of the shots should have an angle difference of at least 30°. Additionally, the images should contain prominent structures such as the pubic area or the trochanter major. With this set-up an accurate and robust registration can be achieved.

**Results:** The accuracy and robustness of the proposed registration was evaluated in different scenarios including 20 tests with plastic bones, 4 tests with cadaveric hip specimen and 3 clinical cases within an ethically approved study. A valid registration was obtained in each of the 27 test cases. The accuracy was within the range of 0.0-2.0 mm at the important structures close to the regions represented in the fluoro images. Only in the regions away from the imaged area, e.g. at the condyles, the error was up to 5 mm. However, the angular deviation of the important axes was also in the range of 0°-2°. To evaluate the robustness of the CT-fluoro matching the algorithm
was started with statistical variations of the initial pose. By this test it could be checked that the radius of convergence was large enough to cover the inaccuracies delivered by the landmark-based preregistration steps.

**Discussion**: In summary, accuracy, robustness, and applicability of the presented registration technique are promising. The technique is user-friendly and allows efficient integration of the registration into the clinical workflow. Only very few points close to the bone surface have to be acquired. A direct access to the bone structures is not necessary at all. Thus, the method qualifies for MI applications in hip surgery, in general. In this paper we have primarily shown its applicability for femoro-acetabular impingement surgery in experiments as well as in clinical practice. But many more types of MI hip surgeries can be pushed forward effectively by this approach.

**References**


Soft tissue balancing for navigated TKA

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Introduction: The main determinant of a long term successful TKA is to achieve a properly aligned and a well balanced knee in flexion and extension\textsuperscript{1,2,6}. Recent advances in computer navigation software have enabled orthopedic surgeons to predict alignments of a knee before committing to bone resection. Despite the accuracy, soft tissue balancing continues to be a challenge, perhaps at least partially, it is due to resecting the femur first, depriving the surgeon of (as Krachow described) millions of possible femoral component positioning that can readily correct most soft tissue imbalance\textsuperscript{3,4,5}. Interpretation of the navigation numbers of soft tissue balance is crucial to determine when to release soft tissue without losing the ideal mechanical axis. A protocol is proposed using the latest OrthoPilot\textsuperscript{®} 4.08 to predict whether soft tissue resection will be necessary in addition to achieving the ideal alignment with a stable balanced TKA.

Purpose

1. To use the data obtained from the Computer Navigation System to predict the indications for soft tissue resection in deformed knees undergoing TKA, before any bone is resected.

2. To achieve a balanced, stable TKA with the desired mechanical axis in coronal and sagittal planes at the conclusion of surgery.

Method: 50 consecutive patients with advanced knee arthritis underwent CT-free computer assisted navigation total knee Arthroplasty (TKA) using OrthoPilot\textsuperscript{®} software 4.08 with a Tensor of 2 flat independent pads to measure gaps. Cemented Columbus\textsuperscript{®} knee system was used retaining the posterior cruciate ligament without surfacing the patella.

Pre- and post-weight bearing radiographs were taken to check the alignment. Manual stress testing exams (medial/lateral; antero/posterior) during surgery was done to assess soft tissue stability and balance.
After routine data collection by the navigation system, stress testing of the knee in extension was carried out first to determine if the deformity (varus/valgus or flexion) can be corrected to zero mechanical axis. Then, the tibia was resected at zero degrees in coronal and sagittal planes, the tensor was applied to measure the gap difference between medial and lateral compartments of the knee in extension and flexion. Any difference of more than 5 mm was considered serious in which soft tissue resection was predicted. Soft tissue resection was not done till all bones are resected in accordance to the computer recommendations.

Final measurement of mechanical axis was performed with varus/valgus stress to record instability. Any gap of more than 1 – 2 degrees in extension or 5 degrees in full flexion was considered unstable or imbalanced. Final range of motion was also recorded.

Results: 5 out of 50 needed medial or lateral soft tissue resection. 8 needed posterior capsule release (medial side of post capsule or the lateral side or both). That is to say 10% needed collateral release and 15% needed posterior capsule release. Mean range of motion preoperatively was -1 to 120 with a post op of -2 to 127. The medial/lateral gap was > 5 mm in 5 cases and all of them needed collateral ligament guided resection. All the cases that needed posterior capsule release had a FFD of > 3 degrees off the sagittal mechanical axis.

Post-operatively, 7 out of 50 cases had varus/valgus stress testing of up to 5 degrees in flexion but in only 5 cases there was a 2 degree varus/valgus deflection in extension. The rest had 1 degree of varus/valgus stress deflection in extension and 3 or less degrees in full flexion.

The final mean mechanical axis was 0.25 in comparison to 3.5 degrees preoperatively.

Discussion: Computer assisted knee arthroplasty provides an accurate soft tissue balancing through real time feedback of alignment and gap size in all ranges of motion. Choosing the most accurate femoral positioning can correct all (stress correctable) knee deformities and all deformities with a medial/lateral gap difference of < 5 mm or mal-alignment of < 3 degrees off the mechanical axis. Greater deformities needed soft tissue resection. We defined a stable knee as the one with a stress deflection of 2 degrees or less in extension and 5 degrees or less of stress deflection in full flexion. Finally, a perfect mechanical axis does not necessarily mean a stable balanced knee; it is necessary to look into the stress varus/valgus degrees of motion in extension and flexion at the conclusion of surgery.
Limitation of preoperative templating of femoral components on plain radiographs: Rotational evaluation with synthetic X-rays on ORTHODOC

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Introduction: The innovation of computer-assisted surgery (CAS) allows us to carry out preoperative planning more accurately, and to perform surgery more precisely on the basis of optimal planning [1]. The conventional method without CAS, however, has been being performed from many years. It is a great achievement to be able to suggest improvements to the conventional method using techniques of computer-assisted surgery.

In conventional preoperative planning of the femoral components in total hip arthroplasty (THA), the preoperative antero-posterior radiographs of both hips should be taken with the femur rotated 15-20 degrees internally to reduce the effect of femoral anteversion [2-4]. Otherwise, information on the optimal stem size and the best fit between bone and prosthesis may not be acquired. There is no objective and quantitative criterion on how to evaluate the optimal preoperative antero-posterior hip radiograph, although subjectively it has been suggested that the extent of femoral rotation can be evaluated by the thickness of the lesser trochanter, which is between the contour of the proximo-medial femoral cortex and the end of the lesser trochanter [2].

The purpose of this study was to evaluate the effects of femoral rotation, especially to changes in the morphological appearance of the femur and the
size and position of the femoral prosthesis, using synthetic X-rays on the preoperative workstation ORTHODOC.

**Materials and Methods:** On the basis of computer tomography data, synthetic X-rays can be displayed as virtual plain radiographs with any magnification and any projected direction such as radiographs in an antero-posterior view or lateral view. The synthetic X-rays with a magnification of 100% were made from 50 femora of 46 consecutive osteoarthritic patients (2 men and 44 women), who underwent cementless THA.

We prepared antero-posterior synthetic X-rays on the basis of a coronal view of 0 degrees of femoral neck anteversion, which was defined as a neutral position, and we made three other antero-posterior synthetic X-rays at 15°, 30°, and 45° of external rotation referred to as the anatomical canal axis of the proximal femur. We measured the thickness of the lesser trochanter and templated using a virtual femoral prosthesis (VerSys Fiber Metal Taper, Zimmer) on the four femoral synthetic X-rays (neutral rotation, 15°, 30°, and 45° of external rotation) for each patient. Then we also measured each of the sizes and positions on the synthetic X-rays at 15°, 30°, and 45° of external rotation in comparison to the size and position in neutral rotation, defined as correct planning.

*Virtual templating in the femur with the Synthetic X-ray on ORTHODOC*
Results: The mean thickness of the lesser trochanter was 2.3 ± 3.1 mm in neutral rotation, 6.2 ± 3.1 mm at 15° external rotation, 9.1 ± 2.4 mm at 30° external rotation, and 11.4 ± 2.2 mm at 45° external rotation. There were significant differences in the thickness between any two rotational groups (p<0.05). It should be noted that the thicknesses of the lesser trochanter were less than 5 mm in 74% of the neutral rotational group.

A smaller size femoral stem was selected in 14 cases (28%) of 15° external rotational group, in 42 cases (84%) of 30° external rotational group, and in 47 cases (94%) of 45° external rotational group. The position of the femoral stems in the 15°, 30°, 45° external rotation groups was 2.6 ± 1.8, 5.8 ± 2.2, and 10.4 ± 2.8 mm higher, respectively, in comparison to that in neutral rotation.

Discussion: Our study had two major findings. First, femoral rotation was evaluated quantitatively based on the thickness of the lesser trochanter. To get proper preoperative antero-posterior radiographs of both hips, templating should be done with a lesser trochanter thickness of less than 5 mm. Second, in templating, the more the femur was rotated externally, the smaller the size of femoral prosthesis that was selected, and the higher the position of implantation of the femoral prosthesis, resulting in inequality of leg length.

In conclusion, femoral rotation is one of the most critical points in conventional preoperative planning for the femoral components in THA, and is assessable from the thickness of the lesser trochanter. In preoperative planning, surgeons should use it as a criterion for radiographs with a less than 5mm thickness of the lesser trochanter. They also need to understand the extent of the error in sizing and positioning, which is caused by femoral rotation. In addition, surgeons should evaluate the advantages of the use of CAS, especially for three-dimensional templating.

References
4. Engh CA: Recent advances in cementless total hip arthroplasty using the AML prosthesis. Techniques Orthop 1991; 6(3): 59-72
Computer assisted planning for hip resurfacing replacement surgery


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Introduction: Computer aided planning and surgery systems for total hip surgery exist in forms such as HipNav/HipROM in which the acetabular cup placement is planned [1]. Typically total hips have a relatively small ball for the femoral head. In the case of resurfacing hips, the implanted femoral head is larger – similar in size to the biological surface it is replacing. For resurfacing, this presents a new set of problems – in addition to obtaining a correct acetabular cup alignment, the femoral head must be positioned correctly so that the cuts to implant it do no cause notching of the femoral neck (a cause of stress fractures), and to ensure that the central stem of the resurfacing component passes down the neck at the correct angle. The planning system described here is used in conjunction with an intra-operative system for tracking tools, or in a stand-alone mode to plan difficult cases where it is not already obvious that resurfacing is a viable solution.

Method: The system is CT based – low resolution scans (4 mm slices) from the top of the pelvis to just above the acetabulum, and high resolution scans (1 mm slices) from the acetabulum down to the lesser trochanter. Voxel based data and surface models derived from segmented CT data are used. Segmentation and surface generation are similar to methods previously described for the Acrobot knee surgery system [2].

Geometry definition: The planning system defines a coordinate frame for the pelvis, femur, acetabulum and femoral head. A plane is generated through the left and right ASIS (anterior-superior iliac spine) points and most anterior pubis points. The origin of this reference plane is chosen to be the pubis center, and the orientation chosen so the Z axis points from this towards a point mid-way between the two ASIS points. The acetabular frame of
reference (FOR) is defined by fitting a sphere to points on its surface. The center point of the sphere is taken as the center of the frame of reference. A set of points on the acetabular rim is taken and a plane passed through them. A vector normal to this plane is passed through the center of the sphere and made to point outwards from the cup. The acetabular FOR is made relative to the pelvis. The femoral FOR is defined by passing a line through the piriformis fossa and the center of the shaft just below the lesser trochanter. With so little of the femur to use, choosing the axial rotation is awkward – given longer scans the condyles of the knee could be used, but we are keeping the radiated region as small as possible. Currently the axial rotation of the FOR is kept aligned with the CT scanner’s FOR.

The femoral head is defined by fitting a sphere to a series of points on the head. A plane is drawn through the neck defined by the tip of the greater and lesser trochanters and on the anterior side by the ridge of the tubercle. The CT data is projected onto this plane and a point is picked on the center of the neck. The orientation of the femoral head FOR is then chosen to be a vector running through the center of the neck and the center of the head. This is made relative to the FOR of the femur.

Typical femoral prosthesis plan showing component, semi-transparent bone and CT slice cross-section, and offsets selected from the measured anatomical frame of reference. The prosthesis is shown cut-through by the CT slice

CT slice aligned with prosthesis frame of reference
Planning component positions: The sphere diameter of the femoral head is used to obtain an initial estimate of the component sizes. A closest match for the femoral head is used. The acetabular component is chosen to match the femoral head component. The components are initially positioned on the center points of the spheres computed for the acetabulum and femoral head. The orientation is aligned with the anatomical axes, or for the acetabulum pre-set to a “standard” anteversion and abduction angle. In arthritic patients the femoral head will not be completely spherical so the computed center may be a little inferior from the ideal position. The surgeon is given the option of nudging either component in any direction or orientation and to adjust the component size.

Visualization: The bones are displayed as three-dimensional models with the prosthesis components integrated in the model. Transparency, 3D and CT slice views are available allowing the surgeon to check placement and ensure no neck notching occurs. The figure shows a typical femoral component plan.

Movement simulation: The surgeon is provided with a view of the pelvis and femur and can control the anteversion, abduction and internal/external rotation angles while the view shows the femur rotated by these angles allowing him to assess the range of motion possible.

Discussion: At the time of writing the system has already been used to plan a limited number of patients for conventional resurfacing treatment, in one case providing the surgeon with the confidence to perform a resurfacing approach in a case where, with less visualization available, a total hip may have been the obvious, but more invasive approach. While designed for use with the computer assisted navigation system, the planner in a stand-alone mode provides a useful tool for the surgeon working with difficult cases, enabling him to pre-select components and to ensure that a resurfacing hip is the optimum solution. The computer assisted system is currently being certified for use in theater and is about to undergo trials. Results will be available at CAOS 2005.

References
A novel 3D ultrasound to bone surface registration technique using the Unscented Kalman Filter

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Introduction: We propose a novel surface-based registration technique that employs the Unscented Kalman Filter (UKF) to register bone surfaces, extracted from a set of 3D ultrasound images, to the corresponding surface points, gathered from Computed Tomography (CT) data. In addition to estimating the registration parameters, the algorithm also reports the variance of each estimated parameter, which represents a confidence interval in the accuracy of the registration.

Registration is a crucial step in medical imaging applications such as the preoperative and intra-operative image registration, 3D presentation of the 2D datasets and multi-modality registration. The two general methods for image registration are intensity-based (also called similarity-based) and feature-based (also called surface based) approaches [1]. The former uses the intensities of the two images or volumes of the targeted anatomy to calculate the registration parameters. The latter extracts corresponding geometric features from two datasets in order to perform the registration. In CAOS applications, the most widely used feature-based registration methods are based on the iterative closest point (ICP) algorithm [2]. This technique has been previously employed for ultrasound to CT registration of bone surfaces by many researchers (e.g., [3, 4]).

However, there are major drawbacks to the ICP-based approaches. These techniques are extremely sensitive to the initial alignment between the two surfaces used for registration, which could easily lead to the false registration due to the local minimum. Furthermore, the registration errors are only
reported as absolute numbers by these algorithms, and it is impossible to evaluate the confidence interval of each estimated registration parameters.

Recently, Ma [5] has proposed a novel technique for estimating the transformation parameters and visualizing the error distribution of the estimated parameters, by using the Unscented Particle Filter (UPF). It is assumed that the estimated parameters have time varying Gaussian distributions so that the variance of the distributions decreases as the estimated parameters converge. While excellent registration results are reported, the algorithm converges very slowly due to the employment of 5000 particles.

The particle filter is a powerful method when one is dealing with a non-linear system with a non-Gaussian estimation parameters’ distribution. In the case of the Gaussian distribution assumption for the estimation parameters (as in [5]) one could significantly reduce the computation time by using the Unscented Kalman Filter (UKF) [6], while achieving the same performance. We have employed the UKF to demonstrate a novel technique for surface-based registration of 3D ultrasound images to CT volumes.

Methods: We have used the UKF to register a 3D ultrasound point cloud, extracted from actual 2D ultrasound images of a patient’s Scaphoid bone surface, to a set of mesh points, generated from CT images of the same bone. By using the ultrasound calibration method presented in [7], the 2D ultrasound images are transferred to the 3D real world coordinate system. The state vector (transformation parameters) considered for the UKF has six unknown parameters (three translations and three rotations) to estimate, assuming that the scale parameters between the two coordinate systems of ultrasound and mesh surface are available. In the first iteration, the state vector is initialized by an arbitrary estimate and only one random point is selected from the ultrasound cloud of points. This state vector is used to transfer the selected point to the mesh coordinate system and to identify the closest point on the mesh surface to the transferred point. The closest point is then transferred back to the ultrasound point cloud. The distance between this point and the original selected point is then fed to the UKF algorithm to update the state vector. The procedure is iteratively repeated by incrementally adding more points from the ultrasound point cloud to the algorithm in the next iterations.

Results: Two sets of experiments are performed to test the accuracy of the proposed approach. In the first experiment, a set of random transformations are applied to the ultrasound point cloud and for each transformation, registration parameters are calculated between the original point set and the
transferred one. This experiment assumes that the corresponding points between the two data sets, with the same size, are unknown. In this case, the convergence is very fast and the registration parameters are quickly estimated. In the second experiment, the ultrasound point cloud is registered to the bone mesh surface extracted from the CT data. Therefore this experiment assumes that the corresponding points are unknown and the two data sets, being registered, have different size and modality. In this case, at the first iterations, the algorithm automatically increases the variance of the state vector to capture the probable optimum estimates or global minimum points and then tries to decrease the variance of the estimated state vector around the most likely optimum estimate. The experiments show less than 0.5 mm root mean square error by using only 14 ultrasound images. The number of selected points from each ultrasound image in this experiment is 20. While the technique is not yet implemented in real-time, it runs significantly faster than the algorithm proposed in [5] (approximately 30 times faster).

Figure 1
**Conclusion:** We have proposed a novel surface-based registration technique for computer-assisted orthopaedic surgery applications. The proposed method highly accurately registers the bone surface points extracted from the 3D ultrasound and CT images, respectively. The importance of this method is that it is less sensitive to the close-guess initialization than ICP algorithm. Furthermore, it provides the distribution of the estimated registration parameters. This distribution demonstrates the confidence interval of the estimated registration parameters. The algorithm has significant potential to be used for clinical applications. Further studies are underway to test the performance of the algorithm on more clinical datasets and to reduce the running time.

**References**


Very low dose computer tomography (CT) based planning and outcome measurement in knee arthroplasty

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Introduction: The ability to both accurately plan the intervention and measure the outcomes in computer assisted orthopaedic surgery (CAOS) is crucial, for it allows more robust analysis of the efficacy of these systems [1, 2, 3].

We report on the optimization of CT radiation dose for both the planning and measurement of outcome in robotic and conventionally performed knee arthroplasty. CT is becoming the imaging modality of choice for both the pre-op planning and post-op assessment in CAOS. The perspective distortion associated with standard radiographs makes them an insufficiently sensitive tool for demonstrating accuracy in CAOS systems.

The radiation dose of traditional CT scans of the pelvis was around 10 mSv, equivalent to about 4.5 years of background radiation (average UK background radiation is 2.2 mSv per year), the Perth protocol for lower limb CT scans has a dose of 2.5 mSv [3]. The new scanners on the market enable us within seconds to obtain large volumes of data. Whilst it is accepted there is no true safe dose of radiation, these new scanners can facilitate the reduction of effective radiation dose. Our study looks at ways of further reducing radiation dose for pre-operative CAOS planning and post-operative assessment.

Methods: Studies were performed on a phantom pelvis and lower limb (real human bones in a rubber and water envelope) varying the KV from 140 – 120 whilst reducing the mA from 120 to 75 at the pelvis and from 100 to 45 for...
both the knee and ankle. Image quality was evaluated at the different doses. A Siemens Somatom Sensation 4 CT scanner was used for this study. A new protocol was defined and subsequently used to scan our patients both pre-operatively for planning and post-operatively for accuracy studies.

The areas scanned were defined on the scout film, the whole femoral head (0.5 cm above and below the head), 20 cm at the knee (10 cm on either side of the joint line) and 5 cm at the ankle (distal tibia and the talus) (Table 1). The scan protocol was 4 x 2.5 mm sliced collimation at the hip and ankle and 4 x 1.0 mm at the knee.

Effective dose (mSv) was calculated using 2 commercially available software packages (CT DOSE and CT-EXPO).

Results: With the reduction in the mA and scanned volume the effective dose was reduced from 2.2 mSv [4] to 0.761 mSv in females and to 0.497 mSv in males whilst maintaining a sufficient image resolution for our purposes. We found that a mA of 80 for the hip joint, 80 pre-op and 100 post-op (higher mA needed to reduce image artifacts from the metal components) for the knee and 45 for the ankle was sufficient for imaging in both pre-op planning and post-operative assessment in knee arthroplasty.

This contributed on an average effective dose to the hip of 0.61 mSv in females and 0.372 mSv in males, the knee 0.120 mSv and to the ankle 0.0046 mSv (Table 1)

Table 1  Results of CT Dose calculations

<table>
<thead>
<tr>
<th>Area scanned</th>
<th>kV</th>
<th>mA</th>
<th>Scan length (cm)</th>
<th>Collimation</th>
<th>Calculation using CT DOSE programme</th>
<th>Calculation using CT-EXPO programme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hips</td>
<td>120</td>
<td>80</td>
<td>5</td>
<td>4x2.5mm</td>
<td>0.610</td>
<td>0.372 0.636</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4x5mm</td>
<td>0.560</td>
<td>0.372 0.636</td>
</tr>
<tr>
<td>Knees</td>
<td>120</td>
<td>100</td>
<td>20</td>
<td>4x1mm</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>120</td>
<td>45</td>
<td>5</td>
<td>4x2.5mm</td>
<td>0.0046</td>
<td></td>
</tr>
<tr>
<td>Total effective dose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.735</td>
<td>0.497 0.761</td>
</tr>
</tbody>
</table>

Discussion: Over the last year we have reduced the effective dose to 1/3 of the dose reported in the Perth protocol. This has been achieved by reducing the areas of the body scanned and adjusting the mA for the various parts of the body whilst maintaining the x, y and z-axis throughout the scan. The areas
between the knee, hip and ankle that were not exposed to radiation are not necessary for the planning of knee arthroplasty although it is essential that the leg does not move during the scanning process. In order to prevent any movement the leg was placed in a radiolucent splint for the duration of the scan. For post op 3D assessment (co-registration of pre-op plan and post op scan) only the knee component of the protocol is necessary.

In this study we were solely looking at bone resolution and therefore the poor soft tissue image resolution was not relevant.

The femoral head and ankle were imaged in order to identify the mechanical axis of the femur, tibia and the whole lower limb, essential in planning knee arthroplasty.

We have not used lead shields in our study but others have shown that such shields over dose sensitive organs can further reduce effective dose (5). However the measurement of this reduction is difficult to quantify and validate.

Whilst radiation dose remains a justifiable concern to patients and clinicians, our study shows how small a dose may be used whilst not compromising image quality in CAOS.

References

Accuracy in arthroplasty: A 3 dimensional CT based measurement study

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Introduction: 3D CT enables component placement errors (the difference between planned and achieved positions) in joint arthroplasty to be measured and visualized in the three planes giving three angular and three translational numerical values. This gives six values per component and hence twelve different values can be used to quantify the error of placement in one knee replacement.

In this study we quantify post-operative error in knee arthroplasty using one value for each component whilst retaining 3D perspective.

Methods: Patients in our prospective, randomized, double blind controlled investigation of the Acrobot System in unicompartmental knee arthroplasty were studied [1].

All patients were pre-operatively CT scanned (hips, knees and ankles) and virtual surgery performed on 3 dimensional models of the patient’s skeleton to plan the position of the two components in all 3 planes. Transformation matrices for the planned component wire frames (3D) were computed. The Acrobot software imports this pre-operative plan and uses it to guide the cutter.

Following surgery both the robotic and conventional groups had a second CT scan to evaluate the achieved accuracy. Each patient’s post-operative CT scan was compared with the pre-operative plan. The position of the prosthetic components in the post-op scan is calculated and again a transformation matrix computed.
The pre-operative CT based plans were co-registered to the post-operative CT scan and values for the intersection (volumetric) between the digitized images (both planned and achieved) were calculated. Both the co-registered femoral and tibial component’s intersection was quantified with software packages supporting Boolean volume analysis (RHINO and Solid Works).

**Results:** The percentages of intersect (the overlap of the two images) between the planned and achieved component positions ranged from 4 – 98% (figure 1). As seen in the illustration an accurately performed operation may be 98% intersected whereas a less accurately inserted prosthesis may only intersect with 4% of the planned volume.

The results from the robotic group showed a much greater intersect compared with the results seen in the conventional group.

**Discussion:** At previous meetings of CAOS we have demonstrated the use of computer tomography (CT) and 3D CT to evaluate the outcome of both computer assisted and conventionally performed uni-compartmental knee arthroplasty [2,3]. This error can be demonstrated by firstly using the CT scan to define a true AP view of the knee, measuring in 2D the varus/valgus position of each of the 2 components and the alignment of the lower limb.
3D CT allows precise measurements of the achieved position for each component in all three planes.

The novel technique described in this study goes one step further in demonstrating the accuracy/error in arthroplasty and has enabled for the first time the illustration of this in a single measure which includes translational error in the 3 planes with the 3 angular errors (all six degrees of freedom).

The greater the percentage intersection between the planned and achieved images, the greater the accuracy of the surgery. Owing to the shape of the components (large articular surface) large intersections demonstrate more accurate reconstruction of the joint line.

We now use the term “accuracy” for this variable. We believe this to be the first time in the orthopaedic world that the term accuracy may be used accurately.

References


Navigated open wedge high tibia osteotomy – Advantages and disadvantages in comparison to the conventional technique in a cadaver study

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Introduction: Corrective osteotomies need to be precise as under- and overcorrection lead to disappointing clinical results. Even small alterations of the mechanical axis cause significant changes of the load distribution of the knee joint, bearing a significant cause of early degenerative changes and dysfunction.

Methods: 20 legs of human cadaver were randomly assigned to navigated open wedge high tibia osteotomy (HTO) (n=10) or conventional HTO using the cable method (n=10). Regardless of the pre-existing alignment, the aim of all operations was to align the mechanical axis to pass through 80% of the tibial plateau (80% Fujisawa line). After stabilization with a fixed angle implant (Tomofix, Synthes), the alignment was measured by CT.

Results: After conventional HTO, the mechanical axis was intersecting the Fujisawa line at 72.1% of the tibial plateau (range 60.4 – 82.4%, S.D. 7.2%). In contrast, after navigated HTO the tibia plateau was passed through 79.7% of the Fujisawa line (range 75.5 – 85.8%, S.D. 3.3%). The mean correction was significantly more accurate in the navigated group than in the conventional group (p=0.020). In addition, the variability of the corrections was significantly lower in the navigated HTO group (p=0.012).
Total fluoroscopic radiation time after conventional HTO was 63.8 (51 – 86) seconds, compared to 53.2 (38 – 73) seconds after navigated HTO. This difference was statistically significant (p=0.038). The average dose area products of the conventional HTO was 49.5 cGy/cm² (range 36.0 – 81.2 cGy/cm²) and did not differ significantly from navigated HTO (42.8 cGy/cm², range 28.3 – 58.1 cGy/cm²) (p=0.231).

The average time of the operative procedure for conventional HTO was 59 minutes (range 47 – 73 minutes) and was 23 minutes shorter than for navigated HTO (82 minutes, range 55 – 98 minutes) (p<0.001).

No tibia plateau fractures, fractures of the lateral cortex after incomplete open wedge osteotomy, or failed implant positions were observed in either group.

**Discussion and Conclusion:** This experimental study comparing navigated and conventional corrective osteotomies of the proximal tibia revealed, that navigation improved the accuracy of corrective osteotomies significantly. In addition, the variability of the corrections was significantly decreased.

A further advantage of navigation is continuous visualization not only of the frontal, but also of the sagittal and transverse axis. Undesired alterations of the tibia slope during corrections are difficult to recognize and to avoid. Open wedge high tibia osteotomy (HTO) has a tendency to increase the posterior slope, which may influence knee stability and kinematics. Especially corrections of complex multiplanar deformities might profit from this new technology due to continuous 3-dimensional imaging of the frontal, sagittal and transverse axis.

Navigated HTO provides exact intraoperative real time control of the mechanical axis and increases the accuracy of corrective osteotomies of the proximal tibia.
A sound-guided 3D navigation system for tibial intramedullary interlocking nail distal locking screws fixations

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Introduction: The standard treatment for the adult simple tibial shaft fracture is internal fixation with an intramedullary interlocking nail [1,2]. For the proximal locking screws, there are guiding tunnels located on the handle with high accuracy to assist the localization procedure. However, once the nail is inserted within the bone, the location of the distal screw hole becomes invisible, and there is no proper guiding tool for such procedure [3]. The proposed clinical problem is to develop a real-time navigation system that is precise and user friendly in the process of localizing the position of screw holes.

Methods: The proposed navigation system is developed based on the concept of integration, which is composed of the mechanical device, software component, and audio guidance device. The main design concept of this system is to use an audio guiding mechanism to help the surgeon to identify the exact position of the distal screw holes. Before insertion of the nail into the bone, registrations are done by any three chosen positions on the handle, and another three positions on the axis of the distal locking screw, indicated by a registration rod placed at the screw hole perpendicular to the nail. After insertion of the nail into the bone, re-registration of the three exactly the same proximal reference points are performed, and immediately, the computer in the system will calculate the transformation matrix. Subsequently, the new coordinates of the axis of the distal locking screw are then obtained. The surgeon can now start navigating the digitizer arm, and as the tip of the probe approaches the calculated axis of the distal locking screw,
beeps of different tones and frequencies can be heard from the speakers, according to the distance between the tip and target. As the exact position of the distal locking screw hole is confirmed, a cortical hole can now be created with a hand drill, and the locking screw is then inserted.

The proposed system has been well integrated, and the surgical protocol is designed as shown in the Figure.

**Results:** In vitro trials were performed with satisfactory accuracy, and a clinical case was then conducted. This was a young adult who sustained right tibial shaft fracture during a traffic accident, and the fracture type was ideal for intramedullary interlocking nail fixation. Since there was not an anchoring frame available for the system to be hooked to the operating table, a double deck trolley was temporarily used, with which the digitizer was placed on the upper deck under sterile coverage, and the controlling computer was positioned in the lower deck. The surgery was carried out smoothly, and navigation of the distal screws was successfully achieved.

![Sound-guided navigation system surgical protocol](image)

*Figure 1  Sound-guided navigation system surgical protocol*
Discussion: Surgical navigation is an emerging technology with rapid advancement since 2 decades ago, and several systems have been elaborated as well as commercialized; however, most of them are designed for joint replacements [4]. A system of audio feedback surgical navigation has been developed, using a 5-degree-of-freedom digitizer, designed specifically for fixation of distal locking screws of the intramedullary nails.

There are several problems to be overcome in the process of development. During the registrations, a minimal of three sets of coordinate are taken from the handle to create the imaginary axis of the nail, and another three sets of coordinates from the guiding rod for identification of the axis of distal locking screws. The proximal points chosen do not need to be the same for different brands of nail, but the exact positions have to be re-identified during navigation once the nail is within the bone. In this study, since there is no universal marker designed for registration, the sequences as well as the exact location to be registered may be mistaken.

The audio feedback mechanism has been used during the navigation, which is convenient in the way that the surgeon could focus the eyes over the operation field while paying attention to the change of the pitches by hearing; however, a drawback with such mechanism is that one cannot realize in time, once navigation is too much off the target, and will not know which direction to move.

The system compares the relative positions of the proximal and distal reference points of the nail, before and after insertion into the medullary canal. During the process of registration and navigation, the digitizer, the nail and the leg have to be absolutely stationary, or else their relationship would be distorted. Since there is no additional sensor on the digitizer for the movement of the target, a special holder may be required for the system to be more accurate.

Nevertheless, this audio feedback surgical navigation system is a simple and affordable system. It has been proven to be useful in the fixation of distal locking screws for intramedullary locking nail, and other applications shall be developed in the future.

References


2. Sabboubeh A, Banaszkiewicz PA, McLeod I, et al. Intramedullary nailing of multiple long-bone fractures of the lower extremity at the same surgery: a single-


Advanced arthroscopy training simulator. InsightMIST©

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Minimally Invasive Surgery (MIS) is the latest trend in surgery and it is performed with the use of small incisions, customized instruments, innovative imaging techniques and global navigation. The advantages are clear: less pain, trauma and blood loss, and minimal scarring. The result is a rapid recovery, high patient satisfaction and the best possible outcome. The main problem is that its performance requires the surgeon’s high skill and ability due to its inherent indirect view and manipulation.

Traditional learning methods are expensive and involve many problems. Since it is difficult to practice this type of procedures in corpses or animals, frequently the learning process is made from first contacts in high cost specialized courses and directly in the operating room under the supervision of an expert surgeon, with the consequent limitations and risks.

All these factors lead to the need for artificial Surgery Training Systems which may be able to provide a non-degradable realistic environment, in which novices may learn and try as much as desired, with no additional cost after the installation of the training system.

insighMIST is a Minimally Invasive Surgery Training Simulator, specialized in arthroscopic procedure, which takes advantage of reality virtual techniques to provide a simulated environment where the user can practice arthroscopic procedures. It is a complete training solution which includes arthroscopic instrumental like adapted hardware and simulation software.

The Arthroscopy Training System is scheduled in three phases.
The first phase is devoted to provide a realistic environment in which practitioners can develop hand-eye coordination dexterities, one of the key features when starting learning MIS techniques.

The second phase, now in the developing phase, is devoted to provide tactile feedback and tactile sensation. This will increase the system realism, because the surgeon through the instrumental will be able to touch and feel hard and soft surfaces. To obtain tact, a haptic device is used, so this sensation will be added to the visual feedback already provided, contributing to the immersion experience.

Additionally two complete arthroscopic procedures are included in the second phase of the simulator: Diagnostic arthroscopy and subacromial decompression. In the diagnostic arthroscopy module the surgeon has to identify pathologies in a set of virtual library. In subacromial decompression module surgeon has to repair basic subacromial decompression problems in a virtual patient.

The third phase, is devoted to generate ad-hoc scenarios from real medical imaging data from a patient with some unusual or critical pathology before actually performing an operation. This would allow surgeons to train before actually performing the real surgery. This may permit surgeons to decide aspects such as which is the best position for the patient, or the optimal entry points to introduce the instrumental. Additionally the case (with its resolution) could be included in the training case catalogue to increment the educational experience.

In summary, Virtual Reality techniques have been applied to build an advanced training simulator adaptable to different arthroscopic techniques with great fidelity. Realism is achieved through the gallery of real arthroscopic instruments models.

The different modules and phases of the simulator will allow the practitioner to complete progressively all his learning process.

The trainee will be able first to get acquainted to the anatomy and to localize the different zones. Afterwards, it will be possible to learn to practice and recognize different pathologies, even those which are rare and will be found only once or twice by an expert surgeon in a lifetime.

Practitioners will get used to work into stressful environments when they will have to accomplish the different exercises in which time will be a critical factor and noises and visual feedback will contribute to the stress component.
It offers a scale to measure the apprentice’s ability and precision as well as that of the experienced surgeon, thanks to its dexterity evaluation system.

The result is a portable, compact equipment, easy to utilize which will be able to cover all the different stages of apprenticeship, from learning the optics in this first phase to being able in the last one to plan and practise a whole operation beforehand by loading real patient data.

References


Evaluation of proximal femur bone mineral density using digitalized plain X-ray radiography of the hip

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Introduction: Many of the women affected by osteoporosis are not diagnosed until the fractures occur. This is largely due to the lack of a convenient, reliable and inexpensive screening technique for the diagnosis of osteoporosis.

The most widely accepted method for measuring bone mineral density (BMD) is Dual-energy X-ray Absorptiometry (DXA). However, the need for relatively expensive equipment and trained personnel lower the accessibility of DXA as a routine screening tool for osteoporosis in the general population. Plain pelvic X-ray radiography is a simple and inexpensive examination. In principal, the gray level of the bone in the X-ray radiograph is related to the BMD. Several factors render plain X-ray radiographs of the hip unsuitable for BMD measurements, mainly the variability in X-ray exposure levels and the soft tissue surrounding the bone.

In this study, we aimed to develop new modifications of plain X-ray radiography of the proximal femur. These modifications were designed to compensate for some of the interfering factors mentioned above.

Methods: The study population consisted of 99 women, divided into three groups: Group 1 (28 patients, mean age of 77.8±9.9 years) – elderly patients who were hospitalized due to a low-energy fracture of the neck of the femur. Group 2 (38 women, mean age of 67.5±9.1 years) – control group – elderly
women without a fracture. Group 3 (33 women, mean age of 40.4±7.34 years) – second control group – young women. Each patient’s left hip (the contralateral, non fractured, hip in group 1) was radiographed with a brass step-wedge positioned near the hip as a standard reference, using a computerized radiography system. A DXA examination of the same hip followed the plain radiograph.

On each radiograph, regions of interest (ROIs) of the proximal femur were determined in concordance with the ROIs of the DXA examination. The mean gray level was measured for each ROI. Several geometric parameters of the proximal femur were measured: the neck-shaft angle, femoral neck width and length, and the femoral head diameter. In addition, further regions were determined: three soft tissue regions surrounding the proximal femur (on the medial and lateral aspect of the femoral neck), and the various steps of the step wedge. The mean gray level was measured for these regions as well. Statistical methods: comparisons between the 3 groups were done using one way analysis of variance with Sidak correction for multiple comparisons. Multiple linear regression was applied to predict the DXA values.

**Results**: The difference in the gray level of the different ROIs within the proximal femur was not statistically significant between any of the groups. However, correction of the bone gray level to the exposure level, this done by dividing the gray level of the ROI to that of the step wedge, resulted in statistically significant difference between group 1 and either group 2 or group 3, but not between the two control groups. Similar results were obtained by correction of the gray level of the ROIs to the gray level of the soft tissue.

The DXA results were significantly lower in the fracture group in comparison to the non-fractured elderly control group, lower still in this group as compared to the younger group. Multiple R2 of 0.62 was found predicting the DXA value from the gray level of each ROI (corrected for the gray level of the step wedge), soft tissue gray levels (also corrected) and the geometric measurements.

**Discussion**: This study shows that after correction to the exposure level and to the soft tissue surrounding the bone, a plain digital radiograph of the pelvis can provide valuable information concerning the bone mineral content of the proximal femur. These preliminary results warrant further research aimed at exploring the potential value of this fast, accessible and relatively inexpensive technique to diagnose osteoporosis and the prediction of future fractures.
References


Table-mounted vs. bone-mounted reference frame attachment in navigation-assisted orthopaedic surgery

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Introduction: Fluoroscopy-based navigation systems enable surgeons to simultaneously correct parameters while placing implants in multiple two-dimensional views. This facilitates implant placement in all planes with less radiation and provides maximal accuracy. To enable a navigated procedure, a rigid bony tracker named reference frame is rigidly fixed to a stable bony structure. This may create technical obstacles such as interference with surgical instruments and the fluoroscope and create an additional albeit small operative site. Subsequently local wound complications may occur. As an alternative, we propose to attach the reference frame to the fracture table instead of the iliac crest, under the assumption that no motion between the table-mounted reference frame and the target organ will occur. We validate this assumption by comparing the navigation accuracy while fixing the reference frame to the patient’s bony anatomy and to the operating table.

Methods: The study population consisted of 7 patients with femoral neck fracture (AO/OTA 31B1, 31B2.1) who underwent fixation of the fracture with three cannulated 6.5 mm cancellous screws, using fluoroscopy-based navigation. In order to measure accuracy during the navigated procedure, the following steps were performed: Step 1 – The patient was positioned on a fracture table and the reference frame was attached to the iliac crest with two 3 mm Shanz screws. Three guide wires used for cannulated screw fixation were inserted under fluoroscopy-based navigation. Step 2 – New fluoroscopic
The Translation of the Trajectory from the Guide wire in anteroposterior and lateral views

images were acquired with the guide wires in place. Step 3 – The navigated drill guide was placed over each guide wire to record final navigated drill guide position. The resulting images include the actual guide wire positions (in lieu of the real implant) and the virtual trajectories of the navigated drill guide as computed by the navigation system. Ideally, when no relative motion occurs, these two positions should completely match; in practice, a small error appears. Validation of the navigation accuracy was performed by measuring the translational and angular deviations of the virtual trajectory image from the real image of the implant on the same fluoroscopic image in anteroposterior and lateral views. Step 4 – The reference frame was removed from the iliac crest and attached to the fracture table with bars and clamps of an external fixator. Step 3 was then repeated. Finally, the recorded images were downloaded and analyzed, with all measurements reported in-plane. Two tailed T-tests were used for statistical analysis.

Results: The data for 20/21 screws is presented. For the anteroposterior view, when the reference frame was attached to the iliac crest, the average translational deviation of the trajectory from the inserted guide wire was 0.91±0.80 mm at the entry site and 0.98±0.92 mm at the trajectory tip. When the reference frame was attached to the fracture table, the average deviation was 1.25±0.87 mm and 1.70±1.32 mm, respectively. The differences were not statistically significant. The angular differences were 0.86±0.72° in the iliac crest mounted reference frame group and 1.07±0.81° in the table mounted reference frame group, which is also not statistically significant. For the lateral view, when the reference frame was attached to the iliac crest, the
average translational deviation of the trajectory from the inserted guide wire was 1.79±0.74 mm at the entry site and 1.77±1.25 mm at the trajectory tip. When the reference frame was attached to the fracture table, the average deviation was 1.20±0.74 mm and 1.60±0.73 mm, respectively. The difference between those two groups is significant at the entry point in favor of the table mounted reference frame (p=0.015). Angular differences were 0.94±0.75° in the iliac crest mounted reference frame group and 1.15±0.74° in the table mounted reference frame group, not statistically significant.

**Conclusion:** In navigation-assisted cannulated screw fixation for femoral neck fractures, attaching the reference frame to the fracture table instead of to the iliac crest allows for similar accuracy of the navigation process with the possible benefit of reducing patient morbidity. This may have further application for table mounted devices and navigated surgical instruments.

**References**

Computer-assisted femoral head resurfacing

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Introduction: Femoral head resurfacing (FHR), in which only the head of the femur is replaced, is an increasingly popular alternative to total hip arthroplasty for younger patients because it preserves femoral bone stock [1-3]. While surgical access is typically good, it can be difficult to ensure proper alignment of the replacement head; mechanical jigs can take 45 minutes to obtain an acceptable alignment; even so, some of the implanted heads are later judged to be incorrectly placed [4]. The purpose of this paper is to present a fluoroscopy-free computer-assisted surgical (CAS) approach (in contrast with [5]). The primary research questions addressed here are (1) does our method yield less varus/valgus angulation relative to the preoperative plan than a commonly used mechanical method (e.g., the Centerpulse Durom), even when our method is performed by a novice surgeon and the mechanical by an expert, (2) what is the relative angular variability of the methods, (3) how much angular variability results from driving the pin and (4) is there any significant difference in the time taken by the two methods?

Methods: We designed a CAS system to transfer preoperative plans formulated on anteroposterior (AP) and mediolateral (ML) radiographs to the operating room (OR). The femur and several tools (a registration plate, a digitizing caliper and probe, and a drill guide) are optically tracked. The registration plate indexes off the superior aspect of the femoral head, greater trochanter and the posterior aspects of the femur, while the digitizing caliper and probe are used to sample points on the femoral neck; these points are used to orient the implant’s axis and to ensure that no notching will occur. The drill guide is hand-held and aligned using the CAS display, then held still while driving the pin.
After verifying our system with artificial bone models, we performed a cadaveric study using 5 pairs of proximal femurs, draped to simulate the operating situation. We mounted holding pins to each bone so that it could be repeatably placed in a jig and took both AP and ML radiographs. An expert surgeon (who regularly uses the Durom system) then used the radiographs to plan the desired implant axis; these angles were sent as input to a CAS program. Next, each bone was registered with our CAS system. On one of each pair of femurs, a novice surgeon used the CAS system to calculate a guide pin axis at the planned angles through the center of the femoral neck. The calculated target axis for the drill guide was recorded, and the final pin position measured after the novice surgeon drove the pin. The pin was temporarily removed and the expert then set the Durom jig according to established practice, but did not drive the pin, and the targeted pin axis was recorded. On the contralateral limb, the expert set the Durom jig and drove the pin. The Durom guide setting and the final pin position were measured. With both methods, the surgeon could adjust the version to better target the neck center. Following the experimental session, we remounted the bones in the X-ray jig and retook AP and ML radiographs of each specimen so that we could evaluate the actual pin placement.

**Results:** The results are shown in Figure 1. Top left: Varus/valgus position of the driven pin on postoperative X-ray relative to the planned line (circles; filled = Durom, open = CAS), along with the difference between the targeted pin axes before driving (Durom-CAS; open triangle). Top right: Difference between the positions of the targeted pin axes at the level of the femoral neck center (Durom-CAS). Bottom left: variability in the final pin angle relative to the targeted pin angle due to the driving process. Bottom right: Time required to aim the guide before driving the pin.

**Discussion:** Regardless of the method used, all driven pins looked reasonably well placed (in contrast to clinical experience with a different system [4]). The variabilities in deviation from the preoperative plan were considerably lower for the CAS method than the Durom method, although biases in all cases were less than 3.3°. This decreased variance for the novice surgeon working with the CAS method is important because an earlier pilot study had shown that the novice surgeon who performed this study had significantly greater variability with the Durom system than the expert reported here.

The Durom/expert axis settings were significantly retroverted relative to the CAS axis (average = 8°). The varus-valgus differences between the methods had low bias and were generally within 4° of one another, but differences ranged from 8° in valgus to 6.2° in varus. Translational differences were small at the neck center, typically about 2 mm.
The pin driving accuracy was similar for both methods and was small: typical errors were less than 2°. The CAS technique took less time than the Durom (not statistically significant). The Durom setup times for the expert in the OR have been much more variable than we found here, so these times are likely an underestimate of the true time needed in the OR. We suspect that there will not be as much variability with the CAS system because the process will be similar in both settings.

In conclusion, the CAS method we developed appears to allow a novice surgeon to implement a preoperative plan with significantly less variability in angulation (particularly in varus/valgus) than an expert working with the Durom system, while taking a comparable amount of time.

References

Mini-invasive implantation of a unicompartmental knee prosthesis might decrease the accuracy despite the use of a navigation system

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Introduction: Quality of implantation is an accepted prognostic factor after total (TKR) or unicompartmental (UKP) knee prosthesis. Navigation systems have proved to improve the accuracy of the bone resection after these two procedures (2, 4). Minimal invasive technique has also proved to facilitate the post-operative rehabilitation (3), but there are concerns about the potential of such procedures for a loss of accuracy (1).

Methods: The authors are using the OrthoPilot® system (Aesculap, Tuttlingen, FRG) on a routine basis for both TKR and UKR. The used version of the software helps the surgeon orienting the bone resections through a conventional approach. Infrared localizers are fixed on the distal femur, the proximal tibia and the foot. The tracking of their respective movements allows the software defining the kinematic center of hip, knee and ankle joints. The data are implemented with the palpation of some relevant anatomical landmarks on both medial and lateral femoro-tibial joints. Femoral axis is defined by the line between the center of the hip and of the knee joints, and tibial axis by the line between the center of the knee and of the ankle. Coronal reference plane contains the femoral axis and is parallel to the posterior femoral condylar line. Sagittal and horizontal reference planes are defined orthogonal to the coronal reference plane. Orientation of the resection guides is given by the system in the three reference planes. This version was modified to allow a minimally invasive approach without quadriceps splitting for UKR only. This version involves only palpation of
points on the medial femoro-tibial joint, while the lateral femoro-tibial points are calculated by the software.

For the purpose of the study we analyzed three groups of patients. Group A consisted of the 64 patients operated for a medial UKR with the minimally invasive technique. Group B consisted of 60 patients randomly selected among 140 cases operated for a medial UKR with the standard technique. Group C consisted of 30 patients randomly selected among 180 cases operated for a TKR with the standard technique.

Accuracy of implantation was measured on post-operative antero-posterior and lateral long leg X-rays. The UKR was implanted with the following goals: mechanical femoro-tibial angle from 175 to 180 degrees, coronal orientation of the femoral component in comparison to the mechanical femoral axis from 88 to 92 degrees, sagittal orientation of the femoral component in comparison to the anterior femoral cortex from 85 to 95 degrees, coronal orientation of the tibial component in comparison to the mechanical tibial axis from 85 to 90 degrees, sagittal orientation of the tibial component in comparison to the posterior tibial cortex from 85 to 90 degrees.

The TKR was implanted with the following goals: mechanical femoro-tibial angle from 177 to 183 degrees, coronal orientation of the femoral component in comparison to the mechanical femoral axis from 88 to 92 degrees, sagittal orientation of the femoral component in comparison to the anterior femoral cortex from 85 to 95 degrees.
cortex from 85 to 95 degrees, coronal orientation of the tibial component in comparison to the mechanical tibial axis from 87 to 93 degrees, sagittal orientation of the tibial component in comparison to the posterior tibial cortex from 87 to 93 degrees. The number of items in the desired range was summarized by each patient, giving an accuracy note between 0 and 5. The mean accuracy note was compared in the three groups by an ANOVA test at a 0.05 level of significance and post-hoc Bonferrini-Dunn correction.

**Results:** The mean accuracy note was 3.5 ± 1.2 in group A, 4.5 ± 0.8 in group B and 4.2 ± 1.0 in group C (p < 0.001). There was no significant difference between groups B and C (p = 0.24). There was a significant decrease in the accuracy note for group A (group A versus group B: p = 0.015; group A versus group C: p < 0.001).

**Discussion:** Minimal invasive technique for UKR is desirable for easier post-operative course. However, the long term results are mostly related to the accuracy of implantation, which should not be compromised by the operative technique. There is a risk to decrease the accuracy of implantation by using minimally invasive techniques. Navigation system might enhance the accuracy of minimally invasive techniques, as they allowed improvements of the conventional techniques. However, the used version of the navigation systems did not completely avoid the loss of accuracy in comparison to the conventional technique. The algorithms used to compensate for the absence of palpation of points on the lateral femoro-tibial joint have to be improved. Conventional technique remains the gold standard for navigated UKR.

**References**

Intra-operative registration of the knee kinematics by a navigation system. A pilot study

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Introduction: Navigation systems have proved to improve the accuracy of the bone resection during total knee replacement (TKR) (5). They might also be helpful to assess intra-operatively the knee kinematics before and after prosthesis implantation (4).

Methods: The authors are using the OrthoPilot® system (Aesculap, Tuttlingen, FRG) on a routine basis for TKR (2). The current standard version of the software helps the surgeon orienting the bone resections and allows measuring the ligamentous balancing. This version was modified to allow a continuous tracking of the 3D tibio-femoral movement during passive knee flexion and extension.

Infrared localizers are fixed on the distal femur, the proximal tibia and the foot. The tracking of their respective movements allows the software defining the kinematic center of hip, knee and ankle joints. The data are implemented with the palpation of some relevant anatomical landmarks. Femoral axis is defined by the line between the center of the hip and of the knee joints. Coronal reference plane contains this axis and is parallel to the posterior femoral condylar line. Sagittal and horizontal reference planes are defined orthogonal to the coronal reference plane. The kinematics was assessed by measuring the tibial movement in these three planes.

For the purpose of the study, following data were registered before and after implanting the prosthesis: Flexion-extension angle, varus-valgus angle, rotational angle, antero-posterior translation. Additionally, the gap between the contact point of the femoral component and the corresponding point of the tibial resection was measured after prosthesis implantation. Two successive registrations were performed by each of the 20 patients of the study before and after prosthesis implantation. The respective pre- and post-
implantation kinematic curves were compared for each patient to assess reproducibility. The pre- and post-implantation kinematic curves were compared for each patient to assess the modification due to prosthesis implantation. The results were compared to the currently available literature.

**Results:** The kinematic curves were plotted from maximal extension to maximal flexion.

1) Pre-implantation kinematics

   a) Varus-valgus angle: The variation of varus-valgus angle is mostly linked to the rotation of the distal femur. We observed a shift of the femoro-tibial angle to varus in 12 cases and to valgus in 8 cases. The difference between extension angle and 90° flexion angle was less than 5° in 16 cases.

   b) Rotational angle: The variation of the rotational angle is mostly linked to the automatic knee rotation. We observed an internal rotation of the tibia in 15 cases (between 5 and 25°), virtually no rotation in 3 cases, an external rotation of 10° in one case and an association of external and internal rotation in one case.

   c) Antero-posterior translation: The variation of the antero-posterior translation is mostly linked to the femoral roll-back. We observed a posterior translation of the femur in 12 cases (between 5 and 15 mm), an anterior translation in 2 cases (of about 5 mm), and virtually no translation in 6 cases.

2) Pre-implantation reproducibility: No significant difference was found between the two pre-implantation registrations by the same patients.

3) Post-implantation kinematics

   a) Varus-valgus angle: We observed a shift of the femoro-tibial angle to varus in 4 cases and to valgus in 4 cases. In 12 cases there was virtually no change in the varus-valgus angle during knee flexion. The difference between extension angle and 90° flexion angle was less than 5° in all cases.

   b) Rotational angle: We observed an internal rotation of the tibia in 12 cases (between 5 and 20°), virtually no rotation in 5 cases, and an external rotation in 4 cases (between 5 and 10°).

   c) Antero-posterior translation: We observed a posterior translation of the femur in 14 cases (between 5 and 15 mm), an anterior translation in 4 cases (of about 5 mm), and virtually no translation in 2 cases.
4) Post-implantation reproducibility: No significant difference was found between the two post-implantation registrations for the same patients.

**Discussion:** The observed 3D kinematics seem to be in agreement with the current literature in both in-vitro (3) and in-vivo (1) studies. We could observe the tibial internal rotation and the femoral roll-back during flexion. Some patients experienced paradoxical movement, both before and after implantation. However the post-implantation kinematics was generally closer to the expected one than the pre-implantation kinematics.

The software has definitely the potential to assess the intra-operative knee kinematics during various surgical procedures. It might help to try several solutions (orientation of the resections, implant combination or design, ligamentous balancing…) before final implantation, in order to choose the best individual compromise. The actual relevance of such a study remains to be defined. It might be interesting to compare these data with in-vivo kinematic studies for the same patients.

**References**

Mini-invasive implantation of a unicompartmental knee prosthesis. Towards a new instruments philosophy?

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Introduction: Unicompartmental knee replacement (UKR) is accepted as a valuable treatment for isolated medial or lateral knee osteoarthritis. Navigation proved to increase the accuracy of implantation in comparison to conventional, manual techniques (Jenny). Minimally invasive implantation might be associated with an earlier hospital discharge and a faster rehabilitation (Price). However these techniques might decrease the accuracy of implantation (Fisher). We wanted to introduce a new concept in minimal invasive medial UKR:

- to keep the minimal invasive approach;
- to use navigation;
- to fix all instruments outside the joint;
- to bring only resections tools into the joint.

Material and Methods: The authors are using the OrthoPilot® system (Aesculap, Tuttlingen, FRG) on a routine basis for UKR (Jenny). The used version of the software helps the surgeon orienting the bone resections through a minimally invasive medial approach without splitting the quadriceps tendon or the vastus medialis muscle. Infrared localizers are fixed percutaneously on the distal femur and the proximal tibia, and strapped on the foot. The tracking of their respective movements allows the software defining the kinematic center of hip, knee and ankle joints. The data are implemented with the palpation of some relevant anatomical landmarks on the medial femoro-tibial joint. Femoral axis is defined by the line between the center of the hip and of the knee joints, and tibial axis by the line between the center of the knee and of the ankle. Coronal reference plane contains the femoral axis
and is parallel to the posterior femoral condylar line. Sagittal and horizontal reference planes are defined orthogonal to the coronal reference plane.

The proximal tibial resection is performed with a conventional motorized saw blade guided by a free hand navigated orienting device.

For the femoral resection, a bow is fixed by three percutaneous screws to the distal femur. The bow is navigated to be oriented along the knee flexion axis. A first guide is fixed on this bow and oriented under navigation control to perform the dorsal condylar resection with a motorized saw blade. A second guide is fixed on the bow and also oriented under navigation control to perform the distal femoral resection with a burr. Neither guides are fixed directly into the joint.

20 patients have been operated on with this experimental technique for an isolated medial osteoarthritis. There were 13 women and 7 men, with a mean age of 69 years. Following items were noted: pre-operative coronal mechanical femoro-tibial angle on a long leg X-ray, duration of the operative procedure, intra-operative complications or difficulties, post-operative complication (specially those related with the bow fixation), duration of hospital stay, postoperative coronal mechanical femoro-tibial angle on a long leg X-ray, post-operative coronal and sagittal orientation of both prosthetic components on long leg antero-posterior and sagittal X-rays.

**Results:** The mean pre-operative coronal deformation was 6° of varus (range, 2 to 11°). Mean operative time was 75 minutes (range, 60 to 100 minutes). No intra-operative difficulty or complication was observed. One delayed rehabilitation was observed, with the need for a repeated hospitalization but without manipulation or reoperation. Mean hospital stay was 7 days (range, 6 to 10 days). The desired postoperative coronal mechanical femoro-tibial angle was obtained in all but one case, where a small hypercorrection with a valgus angle of 2° was observed. Coronal orientation of the femoral component was considered to be satisfactory in 18 cases, with 2 cases of excessive varus positioning. Sagittal orientation of the femoral component was considered to be satisfactory in 17 cases, with 3 cases of excessive flexion positioning. Coronal orientation of the tibial component was considered to be satisfactory in 19 cases, with 1 cases of excessive varus positioning. Sagittal orientation of the tibial component was considered to be satisfactory in all cases.

**Discussion:** The concept of extra-articular fixation of the resection device for knee prosthesis implantation has been described by Walker (4). The theoretical advantages are to decrease the damage to the operated joint. We developed an effective technique which can be used together with a
navigation system to enhance accuracy. No complication in relation to the operative technique was observed. The first experience was satisfactory. However the follow-up is too short and a longer study is to be performed.

References


Knee osteophytes have little influence on the coronal ligamentous balancing during total knee replacement

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Introduction: To get balanced ligaments is generally accepted as a relevant prognostic factor after total knee replacement (TKR) (5). A ligamentous release can be necessary to balance the knee (3, 4), and resection of the knee osteophytes is thought to be one of the stages of ligamentous balancing, as the ligament can reflect on the femoro-tibial osteophytes and be functionally overtightened or shortened (2). We wanted to quantify the influence of the osteophytes during TKR.

Methods: The authors are using the OrthoPilot® system (Aesculap, Tuttlingen, FRG) on a routine basis for TKR (1). The current standard version of the software helps the surgeon orienting the bone resections and allows measuring the ligamentous laxity. Infrared localizers are fixed on the distal femur, the proximal tibia and the foot. The tracking of their respective movements allows the software defining the kinematic center of hip, knee and ankle joints. The data are implemented with the palpation of some relevant anatomical landmarks. Finally the system displays on line the coronal and sagittal mechanical femoro-tibial angles. It is then possible to perform a stress test in varus or valgus to quantify the respective ligamentous laxity.

We studied 20 cases of varus gonarthrosis operated on for TKR under navigation control. The coronal mechanical femoro-tibial angle was first measured in maximal extension according to the standard technique. A second measurement was made with a maximal manual stress to valgus in order to passively reduce the deformation. Then the medial femoral and tibial osteophytes were carefully removed, and the third measurement was made,
again with a maximal manual stress to valgus. The thickness of the resected osteophytes from the femur and the tibia was measured by comparing the pre-operative and post-operative coronal plain X-rays. Pre- and post-resection coronal mechanical femoro-tibial angle in maximal valgus stress were compared with a paired Student test at a 0.05 level of significance, and correlation between this difference and the thickness of the resected osteophytes was studied with the calculation of the Spearman correlation test at the same level of significance.

**Results:** There was no difference between pre- and post-resection coronal mechanical femoro-tibial angle in maximal valgus stress in 10 patients. We observed a 1 degree difference in 9 patients, and a 2 degree difference in one patient. The paired difference between pre- and post-resection coronal mechanical femoro-tibial angle in maximal valgus stress was significant ($p < 0.001$). There was no correlation between this difference and the thickness of the resected osteophytes.

**Discussion:** The observed difference between the medial laxity of the knee before and after medial osteophytes resection was significant. However, the value of this difference is probably clinically irrelevant. There is no need for routine medial osteophytes resection only for the purpose of ligamentous balancing during TKR.

**References**

Measuring the tunnel positioning of an ACL replacement with a navigation system. Comparison with X-ray measurements

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Introduction: The main reason for failure after anterior cruciate ligament (ACL) replacement is a poor positioning of the bone tunnels (4). Conventional techniques involve a significant variability, even by experienced surgeons (2). Navigation systems have proved to improve the accuracy of implantation of knee prostheses (1, 3). These systems might enhance the accuracy of ACL replacement.

Methods: The authors used the OrthoPilot® system (Aesculap, Tuttingen, FRG). Infrared localizers are fixed on the distal femur and the proximal tibia. The tracking of their respective movements allows the software defining the kinematic center of the knee joint. The data are implemented with the palpation of some relevant anatomical bony and articular landmarks. Navigated aimers are positioned under the control of the system to simulate the intra-articular hole of both femoral and tibial tunnels. The system displays on line the anatomical position of the guide wire as well as the expected kinematic of the ACL graft by giving the simulation of the isometricity and of the potential impingement within the intercondylar notch. It is then possible to modify the position of the tunnels, or to perform a notch plasty on request.

20 patients were operated on by means of an arthroscopic assisted bone – patellar tendon – bone ACL replacement with an outside-in femoral tunnel. The guide wires were placed according to the feeling of the surgeon, and their position recorded by the system. The recorded position was compared to the conventional radiographic measurement of the position of the tunnels on plain antero-posterior and lateral X-rays. All radiographic measurements were calculated in relative values to correct for magnification. Results were
analyzed with a non parametric paired comparison and with the calculation of the coefficient of correlation with a 0.05 level of significance.

**Results:**

1) **Medio-lateral position of the tibial tunnel**
There was a significant difference in the paired absolute values of the medio-lateral position of the tibial tunnel between radiographic and navigated measurements ($p = 0.008$). However there was a significant correlation between these two measurements ($p = 0.05$).

2) **Antero-posterior position of the tibial tunnel**
There was no significant difference in the paired absolute values of the medio-lateral position of the tibial tunnel between radiographic and navigated measurements. However the power of the study was too low to prove an actual equality.

3) **Antero-posterior position of the femoral tunnel**
There was no significant difference in the paired absolute values of the antero-posterior position of the femoral tunnel between radiographic and navigated measurements. There was also a significant correlation between these two measurements ($p < 0.001$).

**Discussion:** Navigation systems have the potential to increase the accuracy of tunnel placement during ACL replacement. The accuracy of this still experimental software is encouraging. The antero-posterior position of both the femoral and the tibial tunnels can be accurately assessed by the system. The precision of the location of the medio-lateral position of the tibial tunnel should be improved. There are several potential causes of errors within the system (inaccurate palpation of the anatomical reference points, inaccurate palpation of the tip of the guide wire), but the accuracy of the technique of radiological measurement is also questionable (reproducibility of the measurement, accuracy of the location of the center of the tunnel). A three-dimensional analysis of the tunnel placement is desirable.

**References**

Computer assisted pedicle screw fixation clinical experience with a newly developed software

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**Abstract:** Identifying the pedicle and placing the screw right through the pedicle has always been a demanding procedure even for the most experienced orthopaedic surgeons. We have tried to improve the accuracy of pedicle screw placement using a newly developed and cheap software developed in CUSAT (Cochin University for Science and Technology), after a series of cadaveric experimental studies. The early results are encouraging.

**Materials and Methods:** We have done the study at medical college Kottayam, in forty pedicles of ten patients with fractured vertebra at thoracolumbar region over a period of 2 years from January 2002 to February 2004. All the patients were males with fracture of thoracolumbar junction sustained after fall from coconut trees. Eight of them had paraplegia and two had para paresis. The inclusion criteria was single level fracture with intact pedicles, transverse processes and spinous processes of immediate proximal and distal vertebral bodies. The pedicle screw placement was done using a software developed by Cochin University for Science and Technology. It is based on paired point matching.

**Procedure:** Pre-operative CT scan sections are taken at the level of mid point of transverse process for one vertebra above and one below the involved one. The dicom image is converted into bitmap image and reference lines are drawn through the transverse processes and the spinous processes. The screw trajectory is attained in the image at the most suitable path of the pedicle. Intraoperatively reference pins are placed exactly at the same areas as of transverse processes and the spinous processes. The intraoperative image is live captured using a camera and is matched with the preoperative image and the awl is advanced into pedicle corresponding to the screw trajectory in CT image.
Observation: The pedicle wall violation was demonstrated with 1 mm thin CT scans post-operatively. Out of forty pedicles instrumented in ten patients using computer assistance, ideal placement and less than grade 2 perforation (AMIOT) were observed in 32 cases. Grade 3 lateral wall perforation was observed in 6 cases, inferior wall perforation in one and medial wall perforation in one. Ideal placement and clinically insignificant perforation was noticed in 80% and Grade 3 perforation in 20%. There were certain limitations during surgery like difficulty in getting land marks for matching when the fracture was extending to the proximal and distal vertebral bodies. Hence the study was confined to single level fracture. For clinical use in multi level fractures, the software needs to be modified.

Discussion: In any computer assisted procedure based on paired point matching, the accuracy depends on correct localization of anatomical landmarks during surgery and the subsequent matching. This is possible only when the surgical anatomy is not distorted following trauma. Hence we were forced to instrument the intact pedicles on either side of the fractured vertebral body. In extensive fractures involving several vertebral levels, the accuracy may be compromised if this software is used. The major attraction of this software was the negligible cost factor. Attempts are underway in Cochin University of Science and Technology to overcome the present limitations.

Conclusion: Computer assisted pedicle screw fixation is a good technique for accurate placement of pedicle screws. The accuracy was comparable to other software for pedicle screw placement. With further modifications the accuracy can be improved in future.

References
Minimal invasive surgery and navigation total hip prosthesis

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Introduction:
- Navigation is largely used to perform knee prosthesis with a growing number of valuable reports.
- For hip prosthesis computer assisted surgery is still questionable.
- The main reason to be assisted in this already well established surgery is to obtain a perfect positioning of the implants hoping that it will increase the life duration of this implants, specially in young patients.
- The navigation should provide references independent of the surgeon and reproducible whatever the position of the patient in the orientation of the cup and stem.
- One of the major problems is cup positioning as long as we will not really know what the ideal position is. Some studies emphasize the great dispersion of cup positioning comparing different surgeons.
- One of the other problem is to be able to use computer assisted surgery with a minimal invasive approach witch reduces the recovery time of the patients.
- Two years ago we have started a comparative study on cup positioning with or without navigation using the Ortho-pilot system and a minimally invasive surgery.
- The goal was to evaluate if navigation gives a better precision on inclination and anteversion of the cup and does not complicate minimal invasive surgery.

Material and Method: We have used the Ortho-pilot system of navigation with a classical pre-operative planning with templates. The patient is lying dorsally on an orthopaedic table.

We use an anterior mini-invasive approach of six centimeters long going directly to the capsulae between Tensor Fascia Latae and Sartorius without severing any muscle or tendon.
The anterior capsulae is excised. The hip is anteriorly dislocated. The neck is cut according to the pre-op planning. The position of the leg directed by the manipulation of the orthopaedic table permits to expose easily the acetabulum and the femoral canal.

- At the end of the procedure we just have to close the aponeurosis of the Fascia Latae.
- For navigation, we register the pelvic plane through three landmarks: The two anterior iliac crests and the pubis.
- The reaming and the final positioning of the cup will be appreciated according to that plan guided by the computer controlling inclination and anteversion.
- We do not navigate the stem for the moment but after reduction of the prosthesis with the trial stem, the computer can check the leg length and the offset compared to the initial position.

Results:

- We have been able to study 78 cups, 38 with conventional positioning and 40 navigated by the same surgeon, using the same technique and the same prosthesis. The study was prospective.
- The post-op positioning of the cup was controlled by C.T. scan.
- The C.T. SCAN. The slide used was the one going through the greater diameter of the head. The plane of reference was the horizontal of course different from the pelvis plane used to position the cup during the surgical procedure. So that the figures cannot be used as absolute but as relative for comparison.
- For inclination, the figures given by the computer per-op and the C.T. scan post op are similar.
- For anteversion the figures are quite different (mean 6° for the computer per-op 16° for the C.T. scan, because of the variation of the reference plane)
- In unit-lateral cases there is no significant difference between the operated and the control side, navigated or not, just a little reduced anteversion in the navigated (mean 6° for 16° control)
- Finally there is no significant difference between the navigated and none navigated for inclination (mean 45°) and anteversion (mean 17°).

Discussion: We have not found significant differences between the navigated and conventionally positioned cup but in the first case the position is reproducible whereas in the second case it is operation-dependent.

After a learning curve reasonable in time the use of the navigated tools did not lengthen significantly the operating time (about twenty minutes).
As we have shown it does not impair a minimally invasive approach which is one of the goals of our surgery.

As he gets more familiar with the system the performance of the surgeon may be better. He will be able to appreciate more accurately.

- The re-establishment of the anatomy
- The perfect positioning of the implants
- The maximal joint stability.

The problem to check the true anteversion is to find a reliable plan specially because of the difference of orientation in lying or standing position. This needs to appreciate the lumbar lordosis and its compliance. We do not know the ideal position of the cup. Is there a valid reference for all patients? Is the ideal position of the acetabulum dependent on:

- an orientation according to a vertical plane of a standing patient (the classical 45° inclination, 15° anteversion)
- an orientation according to the pelvis plane with its variations from lying to standing.

We also have to evaluate the accuracy of the post-op C.T. scan to control the position of the cup. This exam is a static one, in a position determined by the apparatus. The position of the acetabulum is of course different from that on the operating table or in standing position. What is actually of great value is the control of the leg length and the offset at the end of the procedure.

We are able to appreciate the variations of the offset according to the variations of the leg length.

We can also check this offset dependent on the femoral stem shape, specially the neck-shaft angle. This angle is not always appropriate to re-establish the original offset. This fact brings a reflection on the necessity to use modular prosthesis with different shaft-neck angle.

Finally we are now able to navigate the stem which really permits a total hip navigation.
Automated preoperative 3D planning for multi-component implants based on leg length evaluation in total hip arthroplasty using CT data: Pilot study

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Introduction: In preoperative planning of total hip arthroplasty (THA), various conditions need to be considered, such as cup coverage ratio, stem fitness, leg length, range of motion, and so on. The final goal of this study is to mathematically describe and quantify these conditions and then develop a system which suggests the optimal combinations of size, position, and angle of the implants using 3D CT data of the patient based on them. Previous 3D planning systems for THA provide interactive 3D visualizations of the relations between the implants and patient skeletons, and the surgeons decide the plans, that is, the size, position, and angle of the implants, based on the surgeons’ experience. However, it is often difficult for the surgeons to decide the plans satisfying the conditions simultaneously. Further, the decided plans are not based on objective and quantitative criteria. In our system, the computer systematically searches and provides the candidates of the implant
sizes, positions, and angles which simultaneously satisfy the various conditions involving THA planning. In our previous works, we reported the automated planning sub-systems for the cup and stem. However, these sub-systems were independent of each other. In the present system, the neck length of the stem is selected based on the evaluation of the leg length difference to complete the THA planning.

**Methods:** We assume that the sizes, positions, and angles of the cup and stem have already been determined using the automated planning sub-systems [1][2][3] and the pelvic and femoral coordinate systems were determined on their 3D models [4]. In this pilot version, Macmine heads and Freeman stems were used. The stem had three neck length variations (-4, 0, 4 mm). The length difference between left and right legs was used to select the neck length. The length difference was defined as the difference between the center position of left and right femoral coordinate systems whose axes are aligned to the standard cephalocaudal axis. Generally, the cephalocaudal axes of left and right femurs are not aligned when CT images are taken. Therefore, we used the cephalocaudal axis of the pelvis as the reference of THA planning. The stem was rotated around the rotation center of the femoral head component defined as the cup center so as to be aligned to the cephalocaudal axis of the pelvis. If the other side of the hip joint were healthy, the acetabulum was approximated by a sphere to determine its rotation center. Similarly, the other side of the femur was aligned to the cephalocaudal axis of the pelvis. After the alignment, we measured the leg length difference for each neck length variation and automatically selected the length with the minimum length.

**Results:** We used three preoperative CT data sets of the THA patients. The automated preoperative planning results of cup and stem, which were used as input data, were all accepted by an experienced surgeon. The surgeon set the maximum leg length difference to 10 mm. The automated planning methods were implemented on Windows XP, Pentium 4 2.8 GHz. The computation time was around 3 hours to complete the whole automated planning processes including individual planning of the cup and stem placement.

The results are summarized in Table 1. The average leg length difference was 3.56 mm, and the minimum and maximum differences were -0.49 and 7.03 mm, respectively.

**Discussion:** Although all of the results were within the maximum limit of 10 mm, the leg length of case 2, whose cup and stem placement was acceptable, was close to 10 mm. We consider that this large difference was caused by the restrictions of the implants design. Two approaches are considered to avoid
the problem. One is to perform the preoperative planning with other types of implant systems and compare it with the previous one, and the other is to readjust the planning by finding the best compromise optimizing the tradeoff between upper positioning of the cup and lower positioning of the stem by reducing its size. Another viewpoint of this result is that the system indicated the limitation of the preoperative planning by maximizing the fixation strength of the cup and stem. The surgeon can take either of the two approaches when the leg length difference was above or close to the maximum limit.

**Table 1 Comparison of proposed automated planning with surgeon**

<table>
<thead>
<tr>
<th>Differences</th>
<th>Minimum leg length difference</th>
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<tbody>
<tr>
<td><strong>Cup</strong></td>
<td><strong>Stem</strong></td>
</tr>
<tr>
<td>Size</td>
<td>Position (mm)</td>
</tr>
<tr>
<td>Case 1</td>
<td>1</td>
</tr>
<tr>
<td>Case 2</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td>0</td>
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<tr>
<td>Average</td>
<td>0.33</td>
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**References**


Higher accuracy of cup positioning by using an image-free navigation system

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Introduction: In order to reach a conclusion about the accuracy and usefulness of image-free navigation for correct cup positioning, in the present prospective study acetabular cups were placed with the aid of an image-free navigation method, followed up by computed tomography and compared with the results of a conventional free-hand operative technique.

Methods: 45 patients were enrolled prospectively in the single center study between 8/2004 and 12/2004. In all patients total hip arthroplasty was indicated because of primary osteoarthritis of the hip. The patients were randomized to the control group (n=22) with conventional, free-hand THA placement or to the study group (n=23) with navigation-assisted THA placement. All the operations were performed through an anterolateral approach with the patient supine. Press-fit cups (Duraloc, DePuy, Warsaw, In, US) and cement-free hydroxyapatite-coated stems (Corail, DePuy, Warsaw, In, US) were implanted. In both groups, a cup inclination of 45° and cup anteversion of 15° were the ideals striven for. The image-free navigation system VectorVision ct-free hip 3.1 (BrainLAB AG, Heimstetten, Germany) was used for computer-assisted THA placement in the patients of the study group.

The operation times (skin incision to end of skin suture) were recorded to assess the increased time required by the computer-assisted technique. Furthermore, as a guide to perioperative blood loss, the decrease in haemoglobin within the first 24 hours and the volume of blood-stained secretion in the wound drains measured within the first 48 hours were documented and compared.
The cup positions were determined postoperatively on pelvic CT using the CT-based planning software (VectorVision hip 3.1, BrainLAB AG, Heimstetten, Germany).

**Results**: The average increase in the duration of operation was 8 min in the computer-assisted study group. With regard to perioperative blood loss, there was no significant difference between the control and the study groups (p=0.583). Neurovascular or septic complications were not recorded in either group.

An average inclination of 42.3° (30 – 53°; ±7.04°) and an average anteversion of 24.0° (-3 – 51°; ±15.02°) were found in the control group and an average inclination of 45.0° (40 – 50°; ±2.81°) and an average anteversion of 14.39° (5 – 25°; ±5.01°) in the computer-assisted study group.

The deviations from the desired cup position were highly significantly lower in the patients of the study group (p<0.001): The average deviation from the desired inclination (45°) was 5.6° with the conventionally placed cups (range: 0 – 15°, SD ±3.90°), and the average deviation from the desired anteversion (15°) was 13.7° (range: 1 – 37°, SD ±10.41°). After computer-assisted cup placement the average deviation from the desired inclination (45°) was 2.3° (range: 0 – 5°, SD ±1.60°), and the average deviation from the desired anteversion (15°) was 4.0° (range: 0 – 10°, SD ±2.95°).

While only 50% (11/22) of the cups in the control group were within the safe zone, 91% (21/23) of the cups were placed in this target region in the computer-assisted study group (p=0.003).

When the figures for inclination and anteversion given by the image-free navigation system intraoperatively after verification of the cup position were compared with the corresponding results of the postoperative CT-based determination of the position, there was an average deviation of 2.4° (range: 0 – 5°, SD ±1.75°) for inclination and an average deviation of 4.6° (range: 1 – 11°, SD ±3.62°) for anteversion.

**Discussion**: The high proportion of cups placed outside the “safe zone” after conventional cup placement observed in the present study, with considerable deviations particularly with regard to anteversion, is in agreement with other studies (DiGioia et al. 1998, Hassan et al. 1998, Saxler et al. 2004).

In the present study, the accuracy of cup placement was significantly improved by using the image-free navigation system in patients with primary osteoarthritis of the hip compared to free-hand placement, and outliers outside the Lewinnek “safe zone” could largely be avoided.
In contrast to the image-assisted, CT-based or fluoroscopy-based navigation methods, image-free navigation requires neither additional pre- or intraoperative imaging. The image-free navigation method thus does not cause any additional radiation burden for the patient or the operation team and the additional time remains justifiably low. In view of the various mechanical complications, which are attributed to incorrect cup placement, the additional intraoperative time required for the image-free navigation method seems to be justified by the demonstrable improvement in precision of placement.

References
Preliminary report of the navigated THA for dysplastic hip with OrthoPilot

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Introduction: In total hip arthroplasty, cup and stem positioning has a great influence in postoperative dislocation and durability. Cup malposition reduces range of motion and creates impingement to the stem, and it will be resulting in dislocation. Navigation systems are very useful to prevent malpositioned settings of cups and stems. In particular, to treat dysplastic hips in Japan, navigation systems are useful to determine the cup positions, for example, to identify the level of the height from the tear drop line and the depth to the inner wall. In this presentation, I would like to share my experience and the know-how on the procedures for the dysplastic hips to set the cup in good position.

Methods: OrthoPilot is a navigation system that does not require any preoperative procedures such as CT scans. Navigation can be achieved merely with intraoperative registration. Software modules for total knee arthroplasty and anterior cruciate ligament reconstruction, as well as cup navigation, are provided in the system. At the beginning periods, we had used this system for 27 cases of the dysplastic hips with the original cup software. At present, we use the dysplastic software and the THA software that were created in Germany for trial from last year.

Results: Only two cases in 27 navigated with the original software had significant discrepancies between the visual cup position and the navigation display. In one case, plain radiography showed anteversion, however, the CT image clearly indicated retroversion. Although the calculated angles on the navigation system showed retroversion, it was normal in visual intraoperatively. Thus, we trusted our visual cup position, and placed it in the
accurate position visually. There was a problem in the patient’s position in this particular case. In another case, the intraoperative calculated angles showed anteversion, although it was normal in visual, as the previously described case. As a result, however, the radiographic angle was correct. I am not clear of the reason for the discrepancy between the visual cup position and the navigation display for this particular case. However, in both of these two cases, inclination angles were slightly larger than the normal cases.

Discussion: To set the cup in good position in dysplastic hips, we must first determine the depth of the reaming and its center. Positioning of the hip center is the most critical point. The undermost position of the double floor should be used as a reference for such positioning. I would suggest that it is essential to sketch a preoperative plan for the lines from this point. The teardrop appears most prominent in plain radiography, but tomography or 3D-CT will be required during operation to visualize the teardrop covered with osteophytes. Dysplastic hip software measures the accurate distance to the medial wall inside and the distance from the teardrop line to the reamer center in this system. In the periods of using the original cup software, we measured the distance to the medial wall by making the pilot hole at the bottom of the cup with the depth gaze. But it could not be seen on the screen. In the new software, even with the same maneuver, the display of the depth is clearly seen on the display. The level of the height from the teardrop line could be seen additionally. These two numbers could lead us to the good position of the cup. In THA software, the navigation of the cup side is the same with the original cup software. However, we can see the relationship of the cup and the stem in total, such as the impingement between the cup and the stem, the leg length discrepancy, medialization or lateralization of the head from preoperative positions, etc. It is very beneficial to know these points for the operation.

References
Computer-assisted pre-operative planning for hip joint-preserving surgery

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Introduction: Femoroacetabular impingement arises from the abnormal shape of the femoral head and/or acetabulum. By reducing the increased radius of the femoral head and the ossified acetabulum, impingements of the hip joint can be removed. And more, periacetabular osteotomy is an effective way to reorient the acetabulum in young adults with symptomatic anterior femoroacetabular impingement due to acetabular retroversion [3]. As a diagnosis and a pre-operative planning of this surgical treatment, we implemented bone reshaping process in a computer system. It included a diagnosis of impingements based on the morphology. Surgeons could select the region to cut and could pre-assess impingement-free motions.

Methods:

1. Reconstruction of 3D (three-dimensional) bony model

As we were interested in young patients with incipient disease, we used MR (Magnetic Resonance) images. We are considering patients especially when there are no radiographic signs of osteoarthritis. For the diagnosis of the symptoms, we developed a both bone-specific and cartilage-specific imaging method. From MR Images, we reconstructed a pelvis and a femur model. For the accuracy in the hip joint region, different slice thicknesses were considered. Four series of spin-echo images were obtained for each specimen using a 1.5T Intera MRI system (Philips Medical Systems, Best NL) at the Hospital University of Geneva. Iliac – 6 mm thickness (gap between slices: 0.6 mm), between the femoral head to the neck-2 mm (gap: 0.5 mm), the rest of femur-12 mm (gap: 0.6 mm), the knee – 4 mm (gap: 0.9 mm). We manually outlined the boundaries of the bones in each image slice. Three-
dimensional surface models were generated by connecting adjacent contours with a polygonal mesh.

2. Incorporation of joint kinematics

The surface models were imported into a graphics-based in-house functional planning system. Coordinate systems were established for the pelvis and femur based on anatomical landmarks [4]. Kinematic descriptions of the hip were defined for each model based on the bone surface geometry. A temporary hip joint center (HJC) was located by fitting a spherical shape on the acetabular rim region, which shows a more spherical shape than the femoral head. Pivoting this temporary initial HJC circumduction motions were simulated. If there were a collision between the acetabular rim and the femoral head during motions, another candidate has been selected. The candidates for the HJC were in array of points separated by 0.1 mm in a cube of side 3 mm. An iterative process was performed until there was no collision between bones [1].

3. Bone reshaping

3.1 Femoral head: By fitting a sphere which covering all the vertices of femoral head and measuring the distance between the center of a sphere and the vertices, we could analyze the region to be cut. Thus, the femoral head-neck junction could be cleared from the impingement.

3.2 Acetabulum: The bony rim of the acetabulum could be decided by impingement test, and it could be resected interactively by plane cutter with free angles until the over-covered region had been removed. It was the same function as an osteotomy is used in a real surgical process.

3.3 Periacetabular osteotomy: 12 control points were added to the periacetabular module of our planning system. The osteotomy line was represented as a series of points that were fit with a Kochanek-Bartels cubic spline. [2] Users could control this line by manipulating control points interactively.

4. Range of motion (ROM) computation

Our planning system allowed three plane motions (Rotation, Flexion/Extension, and Abduction/Adduction), successive motions (e.g. 90° Flexion and rotation) and circumductions. By combining impingement detection tools, we could calculate specimen’s range of motions.

Results: Subject specific bony models and pre-operative planning tool have been implemented. Models could be navigated in a user-friendly way and the
femoral head shape was colored as a distance from the center of the sphere, so the bumpy region could be easily detected. And more, ROM could be assessed before and after the osteotomy in this system. This system was developed based on the young healthy volunteers’ MR Images (mean age: 28.3 (S.D. 3.6)), so we could reduce the exposure of radiation. It could provide essential hip kinematics and factors influencing hip ROMs, particularly in extreme hip positions.

Discussion: For every patient, impingement-free motions need to be achieved based on a correct pre-operative planning system. By using our system, a surgeon can examine the 3D models prior to surgery, obtain a proper visual result, and generally reduce the overall time of the surgical operation. Thus individual (per patient) correction can be achieved and the range between under-correction and over-correction can be narrowed. Surgeons can predict the regions where impingements occur and can compare the range of motions before and after cutting. Even though we presume our system, which was developed based on healthy volunteers’ datasets, could be applicable to the patients. This system needs to be applied to the patients’ dataset. By considering the sum of all of the patients’ individual clinical and radiographic variables, the treatment alternative should be taken into account.

References


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Computer-assisted navigation in the acetabular component positioning in total hip joint replacement: a randomized controlled clinical study

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Introduction: Positioning of the acetabular component is a key factor in the proper functioning and longevity of the hip endoprosthesis. Malpositioned component is prone to dislocate and is more liable to cause polyethylene wear and subsequent osteolysis. Lewinnek et al. suggested that positioning the cup in 40±10° inclination and 15±10° anteversion minimizes the risk of dislocation (“safe zone”). The aim of our study was to compare conventional hip arthroplasty to computer-assisted CT-based navigation hip replacement in a randomized prospective clinical trial.

Methods: 37 Patients (41 hips) that were referred to Orton Hospital, Invalid Foundation, Helsinki, Finland during November 2001 until August 2003 for primary total hip joint replacement, were randomly assigned (sealed envelopes) for either conventional arthroplasty or a CT-based computer assisted navigation surgery (CAOS/Navi). Inclusion criteria were primary or secondary non-traumatic hip joint arthrosis or secondary posttraumatic arthrosis. Exclusion criteria included: a. severe mental disorder (dementia) or abuse of alcohol or narcotic addiction, b. active infection, c. anesthesiologically unfit cardiopulmonary status, d. patient refusal of participation, e. revision surgery. All the patients were subjected to insertion of (un-cemented monoblock) Hedrocel TM acetabular cup component. Plain pelvic roentgenographs and CT scans were obtained from the patients pre- and postoperatively. The preoperative planning was based on CT scans. The cup position was measured perioperatively after cup component placement also
by C-arm fluoroscopy. Posterior approach to hip joint was used for all patients. The Medivision TM CT-based navigation system was used in all operations. The surgeons involved (J.L. and S.V.) had both operated at least ten patients with this CAOS/Navi technique before the start of randomized series (pilot series). The major preoperative diagnoses included congenital luxation of the hip or DDH and secondary arthrosis (17 cases) and primary arthrosis (15 cases). One patient was in each of the following diagnoses groups: posttraumatic arthrosis, poliomyelitis, rheumatoid arthritis, epiphyseolysis of the femoral head and osteolysis. There were 30 females and 7 males in the series. The mean age of the patients was 54.43 years in the CAOS/Navi group and 52.35 years in the conventional group.

**Results:** In four patients out of the 37 patients referred to the clinical counseling, the clinical condition necessitated a bilateral hip operation thus totaling the number of hips to 41. However, two patients refused operation and decided to choose conservative treatment. In three patients (including one bilateral case) the surgeon-patient negotiation led to choosing of hip resurfacing (Birmingham Hip Replacement) instead of conventional total hip joint replacement. In one patient the osteolysis of acetabulum required the use of special prostheses and reinforcement-type acetabular component. One patient was excluded due to a recent myocardial infarct. These dropouts excluding, a total number of 31 patients and 33 hips were included in the final randomization.

There were no complications in either group during the follow-up of 2 months to 2 years. The operation time was statistically significantly longer in the CAOS/Navi group. No difference between the conventional and CAOS/Navi group was found in the acetabular cup orientation in inclination or anteversion as studied by postoperative CT or C-arm fluoroscopy. As studied by postoperative CT scans, the anteversion was 12+/-5 degrees in the CAOS/Navi group and 13+/-5 degrees in conventional group (N.S.). The inclination angles were 42+/-4 degrees in the CAOS/Navi group and 40+/-7 degrees in the conventional group (N.S.). The operation time was 150+/-46 minutes in the CAOS/NAVI group and 110+/-53 minutes in the conventional group (p<0.05).

**Discussion:** We could not demonstrate any statistically significant improvement in postoperative acetabular component inclination or anteversion when applying CT-based computer-assisted navigation to acetabular component positioning in total hip joint replacement instead of conventional procedure. The longer operation time and extra time (and extra exposure to radiation) needed for preoperative CT imaging is a drawback in CT-based navigation. However, CT-based navigation still have a role in
education, research and in the total hip replacement in special indications such as congenital dysplasias and other anatomical deformities. Furthermore, our series was limited to 33 hips in 30 patients. More extensive studies are needed to fully evaluate the advantages and disadvantages of computer-assisted acetabular cup positioning in THR. Theoretically, the CAOS procedures will find their most valid applications in the mini-invasive THR where exposure is limited and a need for aids to 3D visualization of the surgical field are apparent.

References

Computer-assisted navigation increases safety and precision of sacro-iliacal screw insertion: A report of technique and first clinical cases

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Introduction: Fixation screws are used in sacroiliacal region to stabilize acute pelvic rim fractures, to alleviate posttraumatic or idiopathic pain in SI joint and to give additional support for stabilizing rods in scoliosis corrections. Insertion of sacroiliacal screws is a challenging task due to the complex and variable anatomy of human sacroiliac region (1).

Based on trigonometric analysis of the postoperative CT scans of patients who had iliosacral screws placed for various reasons, Templeman et al (2) stated that the corridor for safe sacroiliacal screw placement is very narrow allowing for only 4° deviation of screw track angle. Literature on problems related to misplaced sacroiliacal screws is scanty, possibly reflecting surgeons’ general reluctance to report on complications. Routt et al. (3) who had percutaneously inserted sacroiliacal screws into corpora of S1 and S2 to treat unstable pelvic ring fractures, reported that 2.05 percent of screws were misplaced (2). Pattee et al. (4) published a case study of a S1 nerve root compression which occurred in a patient whose right SI joint was fixed with five screws to treat posttraumatic arthrosis.

Screw insertion in the sacroiliacal region bears a resemblance to pedicle screw placement since both are demanding procedures due to anatomical complexity and the vicinity of vulnerable neurovascular structures. In the lumbar region the pedicles are short osseous tubes, which by nature tend to restrict malaligned insertion of screws. However, in the sacroiliacal region anatomical landmarks are not readily distinguishable nor is there a similar
A randomized clinical study showed that the accuracy and safety of pedicle screw insertion was markedly improved by the use of computer-assisted navigation (Laine et al. Eur Spine J, 9: 235-240, 2000). The objective of our study was to assess the clinical applicability and accuracy of computer-assisted navigation in sacroiliac screw insertion.

Methods: Our study group consisted of five female and three male patients with a mean age of 47.2 (range 14 – 66) years. The preoperative diagnoses and indications were: Posttraumatic SI joint pain due to hemipelvic fracture and/or rupture of symphysis (4 cases), non-traumatic SI joint pain (pseudoarthrotic or arthrotic) (2 cases) and scoliosis associated with meningomyelocele or spinal degeneration (2 cases). Preoperatively, all the patients were subjected to spiral CT scanning. These CT scans were used in planning of safe trajectories for screws before the actual operation, as well as to define anatomic landmarks for paired-point matching.

A total number of twenty-two screws were inserted using a CT-based optoelectronic navigation system (SurgiGATE Spine 2.1 TM, Medivision, Oberdorf, Switzerland): eleven to body of S1, two to S2 and nine to sacral ala region. The surgical protocol for computer-assisted optoelectronic navigation has been described in detail earlier (5). In brief, a curved incision was made from the L5 spinous process to the distal margin of SI joint. The dynamic reference base was fixed to the spinous process of S1. A paired-point matching as well as a surface matching was performed. The guidance mode, which displays preplanned trajectories on the monitor, was used for screw track preparation. Cannulated A-O screws (7.3 mm cancellous or 4.5 mm cortical) were used throughout the study.

Results: The position of the screws was analyzed from postoperative CT scans by an independent radiologist. A perfect surface and paired-point matching was achieved in all cases and all screws were inserted in anatomically correct positions with SurgiGATE Spine 2.1 TM. The insertion of screws was totally reliant on SurgiGATE Spine 2.1 TM and additional perioperative fluoroscopy was not used. No complications related to screw positioning per se were noted. However, one wound edge necrosis required revision and skin transplantation.

After the mean follow-up time of 24 months (range 12 – 36 months), all patients were satisfied with the result. The clinical and radiological evaluation of the patients will be presented.
**Discussion:** In conclusion, the clinical data obtained from our initial series of eight patients suggests that the potentially hazardous insertion of screws in the sacroiliac region could be transformed into a more safe and controlled procedure by utilizing computer-assisted navigation. There is extra time consumed in preoperative planning of the surgery but this is at least partially compensated for by abandoning unnecessary intraoperative fluoroscopy. However, further studies with larger groups of patients is necessary in order to evaluate the true clinical value of the computer-assisted navigation in sacroiliac screw placement.

**References**

The effect of a laterally elevated wedged insole on the locus of the dynamic loading axis of the knee during gait

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Introduction: A laterally elevated wedged insole has been one of the conservative treatments for patients with medial compartment osteoarthritis of the varus knee. The aim of this treatment is to reduce the forces on the medial compartment of the knee. The effect of this insole on the mechanical axis in dynamic status, however, is not clear. The purpose of this study was to assess the effect of a laterally elevated wedged insole on the locus of the dynamic loading axis of the knee during gait using a 4-dimensional motion analysis system.

Methods: The subject of this study was a patient with medial compartment OA of the varus knee (51 years old, female). The knee alignment was 5° varus. On bipedal standing radiographs, the axial alignment of the lower limb (hip-knee-ankle angle) was 7° varus for the left knee and 8° varus for the right knee. OA stage of the knee according to Kellgren and Lawrence criteria on plain radiographs was grade 3 for the right knee and grade 2 for the left knee. Three laterally elevated wedged insoles of silicon with elevations of 7 mm inclined at 11°, 10 mm inclined at 16°, and 13 mm inclined at 21° were compared. The insoles were fixed to the bilateral soles of the patient with a supporter designed to fit around the ankle and foot joint. For the gait analysis system [1], the bone structure of the lower limb and the relative position of skin markers were
acquired from CT images. Motion capture data was acquired from spherical skin markers with the VICON system. Skeletal model movement during gait was calculated based on the movement of the markers. The locus of the dynamic loading axis on the knee joint was defined as the point on the proximal tibia joint surface that intersected with the loading axis of the lower limb, which passed through the center of the femoral head and the centroid of multiple points of the distal tibia joint surface. This system can visualize the locus of the dynamic loading axis on the knee joint. The coordinate point of the locus (the passing point of the loading axis on the knee) was evaluated by calculating the ratio of the point on the proximal tibia joint surface to the medial compartment joint width that was defined as the distance between the origin and the most medial point on the proximal tibia joint surface. Using this system, we acquired motion capture data during gait with no insoles (Group A), 7 mm-inclined insoles (Group B), 10 mm-inclined insoles (Group C), and 13 mm-inclined insoles (Group D). Four acceptable trials were obtained for each group. To compare the passing point of loading axis on the knee joint surface, the characteristic points of heel contact, loading response peak, and terminal stance peak in the stance phase of gait were selected from the force plate data. To compare the lateral movement of the dynamic loading axis, the lateral distance from the point of heel contact to the point of loading response peak in the stance phase was calculated as a ratio of the medial compartment joint width on the tibia joint surface. The data was analyzed statistically among the four groups with a one-way repeated measure analysis of variance (ANOVA).

Table 1  Group A: Gait with nothing insole, Group B: Gait with 7 mm-inclined insoles, Group C: Gait with 10 mm-inclined insoles, Group D: Gait with 13 mm-inclined insoles
* The coordinate point of the locus (the passing point of the loading axis on the knee) was calculated as ratio of distance to medial joint width in the lateral direction
**Lateral movement distance of the dynamic loading axis between heel contact and loading response peak was calculated as ratio of distance to medial joint width in lateral direction.

<table>
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<th>rt_Group A</th>
<th>rt_Group B</th>
<th>rt_Group C</th>
<th>rt_Group D</th>
<th>lt_Group A</th>
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<tr>
<td>Heel contact (%)*</td>
<td>75±4</td>
<td>78±6</td>
<td>71±5</td>
<td>76±7</td>
<td>30±4</td>
</tr>
<tr>
<td>Loading response peak (%)*</td>
<td>133±2</td>
<td>114±8</td>
<td>113±10</td>
<td>106±11</td>
<td>82±2</td>
</tr>
<tr>
<td>Terminal stance peak (%)</td>
<td>122±19</td>
<td>130±16</td>
<td>126±17</td>
<td>117±15</td>
<td>84±16</td>
</tr>
<tr>
<td>Toe off (%)*</td>
<td>164±14</td>
<td>173±3</td>
<td>161±7</td>
<td>165±5</td>
<td>131±10</td>
</tr>
<tr>
<td>Lateral movement (%)**</td>
<td>58±3</td>
<td>37±6</td>
<td>42±13</td>
<td>30±7</td>
<td>52±5</td>
</tr>
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</table>
**Results**: The knee pain during gait with any of three insoles was reduced subjectively. However, the patient complained of the 13 mm-inclined insoles due to the feeling of incongruity in the ankle. The passing points of loading axis on the knee at the timing of heel contact, loading response peak, terminal stance peak, and toe off and the lateral movement of the dynamic loading axis between heel contact and loading response peak were shown in Table 1. Among the groups, the passing point of the loading axis on the knee at the timing of heel contact, terminal stance peak, and toe off were almost the same in the lateral direction. The passing point of the loading axis at loading response peak was significantly smaller during the gait with any of the three insoles than that during the gait with no insoles in the right knee (P<0.05). Lateral movement from the point of heel contact to the point of loading response peak was significantly larger during the gait with no insoles than those during the gait with any of the three insoles except for the left knee with 7 mm and 13 mm-inclined insoles (P<0.05). Thus, the laterally elevated wedged insole affected the passing points of loading axis on the knee in the early stance phase.

**Discussion**: The effect of laterally elevated wedged insoles was reported on radiographs [2]. On static radiographs, we can evaluate the only static status at a time and the only change in axial alignment of the lower limb. Using a 4-dimensional motion analysis system, we evaluated the effect of laterally elevated wedged insoles on the locus of the dynamic loading axis of the knee in dynamic status. In the right knee of this patient, the subjective knee pain and the lateral movement of the loading axis was reduced during gait with any size of elevated wedged insoles, however, the patient felt uncomfortable in the ankle with the 13 mm-inclined insoles. The lateral movement of the loading axis during gait with 7 mm-inclined insoles was smaller than that with 10 mm-inclined insoles. So we chose the 7 mm-inclined insoles for the right knee of the patient. In conclusion, we evaluated the effect of laterally elevated wedged insoles on the locus of the dynamic loading axis of the knee in dynamic status using a 4-dimensional motion analysis system. The size of the laterally elevated wedged insoles affected the passing points of dynamic loading axis on the proximal tibia joint surface in the early stance phase of the gait. Using this system, we were able to choose the best size of laterally elevated wedged insoles for a patient with medial compartment OA of the varus knee.

**References**

Surgical tools in navigation. A new parallel drill guide for femoral neck fractures

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Introduction: Navigation technologies often use conventional surgical tools which are equipped with navigation markers, consequently further simple simulation of e.g. drill procedures or single screw placement becomes possible. However some indications often need an exact parallel placement of two or more screws to achieve correct ﬁxation after reduction. Examples for necessary exact parallel drill guide placement are dens fractures, femoral neck fractures, talus and tibia plateau fractures. Existing complex mechanical tools, like a speciﬁc (Manninger) parallel-drill-guide (PDG) for femoral neck fractures, can be simulated and implemented into navigation to include all advantages the PDG offers for an exact parallel placement of two or three screws. We compared the conventional PDG technique with a fully implemented navigated PDG in a cadaver and plastic bone study and showed beneﬁts and difficulties with the new system.

Methods: Initially a conventional PDG, the Manninger Screw System (DePuy) was used for further implementation in a Vector Vision (Brainlab) navigation system. A permanent ﬁxation of reﬂecting markers, convertible for contralateral use, was done on the conventional PDG. Based on the requirements for the adequate parallel screw placement, including exact distances and course of the screws, the software implementation was done by navigation engineers, including a complete display of the navigated PDG and the drill procedures on the screen. Initial comparison of the conventional PDG with the navigated tool was done on 10 vs. 10 plastic bone models. Conventional technique included two c-arms and predetermined operation with the manual PDG system. The navigated trials were done with only one c-arm, a beta Trauma Modul PDG Version and the navigated PDG. Compared were the deﬁned accuracy, the Tip Apex Distance (TAD) was
used to determine the drill procedures, parallelism of all placed screws, radiation time and the total operating time. Secondary randomized same tests were done on 10 vs. 10 fresh frozen human cadavers.

**Results:** Implementation of the navigated PDG was done excellent in the software and the application without further problems useable. The accuracy of the plastic models and cadaver tests were comparable. Results of conventional and navigated PDG did not show significant differences according to the TAD (p=0.094). Radiation time for the conventional group was 48 seconds (s) for the plastic and 56 s for the cadaver trials. The navigated group needed 21 s for the plastic and 23 s for the cadaver tests. However the navigated group needed 67 % and 59 % of this time only for correct set up and picture acquisition. Comparison of the total operating time showed significant differences, conventional PDG: 14 minutes for the plastic models and 16 for the cadaver models. Navigated plastic models: 23 minutes, navigated cadaver trials 26 minutes.

**Discussion:** Navigation in traumatology, especially involving all kind of drilling procedures showed improvement of accuracy and essential reduction of radiation time in some clinical and basic research studies. This included simple drilling procedures of femoral neck fractures. However so far only simple adaptations including single screw placement with the help of temporary fixed markers were done, consequently specific operative requirements like screw parallelism or specific navigated tool imaging were so far not included. But still the definite bone morphology of different anatomic sites requires exact parallel placement of osteosynthetic screws to achieve a stable fixation. An effective integration of a specific PDG is shown in our study, providing high accuracy and effective reduction of the radiation time. Surgeons are able to combine advantages of the mechanical guides with the navigation. Initial tests with parallel drilling procedures for the osteosynthetic dens and talus fracture treatment have started already in our clinic and so far shown same promising results. Further large clinical studies have to improve our initial findings and value of the navigated PDG.
Intraoperative 3-D imaging of perilunate dislocations: A decision guidance

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Introduction: Perilunate dislocation injuries are rare, the operative result dependent on the accuracy of initial reduction of the complex morphology of the carpal row. Immediate reduction often requires an open surgical approach, while definite interpretation of the reduction result is complex due to remaining subluxations and ligament instability of the complex 3-dimensional correlation of the carpal row. Radiological analysis of the configuration and arrangement of the carpals, setting of the specific axes and detection of intercarpal gaps is not always accurate with plain 2-D C-Arm imaging. Therefore postoperative CT scans are done mostly. Alternatively the Iso-C 3D imaging allows intraoperative demonstration of multiplanar reconstructions. We report about the first clinical intraoperative use and value of the Iso-C imaging at perilunate luxation injuries compared to conventional c-arm imaging.

Methods: During the last 18 month we treated 4 patients with perilunate luxation injuries, associated with severe other injuries. All cases required an initial open reduction, with combined volar and dorsal approaches in all cases. Transfixation of the specific carpal row with k-wires including initial ligament reconstruction was done at every injury. Intraoperatively alignment and reduction control of the complex carpal congruency was first done with conventional c-arm imaging in multiple plains. Additionally an automatic Iso-C 3D image scan was done, providing intraoperatively multiplanar reconstructions. All acquired images of the carpal row were intraoperatively evaluated by the operating surgeon. Both image modalities were then compared according to the image quality, value of achieved reduction control including remaining subluxations, reconstruction of the scapholunate angle and placement of the k-wires. A visual analog scale (VAS) (0: worst, 10:
best) was used for the interpretation by the surgeon. If necessary identified failures were revised during the same operative procedure. A postop computer tomography (CT) scan was done in all cases and compared to the intraoperative multiplanar reconstructions of the Iso-C3 D.

**Results:** All Iso-C Scans were possible without technical problems. Despite the quantity of placed K-wires, and associated artifacts, all multiplanar reconstructions could be evaluated by the surgeons. A replacement of two K-wires was done in one case. In two cases a correction of the reduction was done. All failures were only detected in the Iso-C imaging, the 2-D C-Arm images did not reveal significant failures or were insufficient to judge about remaining gaps or the anatomic alignment. Postop CTs did not show any further significant reduction or implant placement failure of the K-wires. The image quality was judged 7 on the VAS for the Iso-C 3D imaging and only 4 for the conventional c-arm images. Results for the value of achieved reduction were 4 for the c-arm and 8 for the Iso-C 3D imaging. A direct comparison of the postop CT and Iso-C showed congruency in most of the multiplanar reconstructions.

**Discussion:** Perilunate luxations are complex morphologic and dynamic injuries, representing severe 3-dimensional luxation and subluxation of the carpal wrist. The exact evaluation of the surgical reduction is even under open operative procedures demanding and often reduction failures only detectable in postop CTs. The Iso-C 3D offers a precise intraoperative reduction and implant placement control, including measurement of the scapholunate angle and other dissociations, including further gaps of the carpal row. The image quality can be disturbed by metal artifacts, but was satisfactory in our group. 3-D imaging allows a more reliable reduction control, especially in complex carpal row injuries than conventional 2-dimensional c-arm images. Consequently this might lead to a reduced number of necessary reoperations including further clinical treatment in the future for complex carpal injuries.
Intraoperative 3-D imaging control of tibial plateau fractures

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Introduction: The exact anatomic reduction and correct implant placement is essential for the long-term outcome of surgically treated tibial plateau fractures. Especially minimally invasive procedures do require an exact intraoperative imaging to avoid inadequate reduction and implant misplacement. However 2-D C-Arm imaging is limited in the evaluation of the definite bone morphology and complex 3-dimensional intraarticular fracture pattern. Consequently postoperative computer tomography (CT) is often required as a final result control and evaluation. Alternatively the Iso-C 3D offers intraoperative 3-D images, providing multiplanar reconstructions. Immediate result control including operative correction in the same operative procedure becomes possible. We report about our clinical experience and value of intraoperative Iso-C 3D imaging at tibial plateau fractures compared to the conventional c-arm imaging and postoperative CT control.

Methods: Between January 2003 and November 2004, 26 intraarticular tibial plateau fractures were introperatively scanned with the Iso-C 3D (Siemens, Germany). In 20 cases an ORIF was done, in 6 cases a minimal invasive, arthroscopy based, procedure was performed. After initial reduction, fixation and result acceptance, conventional 2-D c-arm images in two planes was done for an initial result control. Secondary an Iso-C 3D scan was performed during the operation. The Iso-C 3D generates multiplanar reconstructions out of 100 c-arm images, during one automated rotating scanning procedure around the tibial plateau. Evaluation of the multiplanar reconstructions was done by all operating surgeons and evaluation of remaining intraarticular steps and implant misplacements directly compared with the c-arm images. Image quality and intraoperative value of both modalities were evaluated by all surgeons by a visual analog score (VAS, 0: worst to 10: best). Identified remaining articular steps or hardware misplacements were corrected during
the same operative procedure. Post operative CT scans were done in all cases and compared to the intraoperative multiplanar reconstructions.

**Results**: Three (11%) Iso-C 3D scans had to be repeated caused by insufficient positioning during the scan. Direct scanning procedure took always two minutes. Intraoperative positioning and set up of the system needed 194 seconds (140 – 480). Examination and analysis of all multiplanar reconstructions by the surgeon was measured with an average of 327 seconds (139 – 551). In six cases (23%) a direct intraoperative correction was done, three reduction corrections and three implant corrections were done. Five of those cases did not reveal significant articular steps (>2mm) or screw misplacement in the conventional C-Arm images and were only detected in the Iso-C 3D images. Another exact subchondral k-wire placement was confirmed with the Iso-C 3D. Postoperative CT scans confirmed the intraop Iso-C imaging, no further significant steps or misplacements were identified. According to the image quality of both modalities: the medium VAS for the c-Arm was assessed 5; for the Iso-C 3D 7. The intraoperative value: 6 for the c-Arm and 8 for the Iso-C 3D.

**Discussion**: Exact reduction of tibial plateau fractures is essential for the operative outcome and long-term result. 3-D imaging is more precise in the interpretation of the complex intraarticular fracture pattern, thus reflecting the complex anatomic shape of the tibial plateau. The Iso-C 3D allows a reliable intraoperative control of reduction and hardware placement. Revision surgery based on postop CT data might be avoided in the future. As shown in other studies the Iso-C3D enables identification of articular steps >1 mm, corresponding potentially further postop CT scans might be avoided if the Iso-C 3D imaging quality is adequate enough. Controversary high initial costs, extra intraoperative positioning and scanning time of the Iso-C 3D is still necessary. Further prospective clinical studies need to evaluate the value at other anatomic regions.
Economic value and consequences of intraoperative 3-D imaging at calcaneal fractures

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Introduction: The value and consequences of intraoperative 3-dimensional (3D) imaging, based on multiplanar reconstructions, of intraarticular calcaneus fractures with a 3-dimensional image intensifier (Iso-C 3D) has been shown in previous cadaver and clinical studies. However our collective of surgical treated calcaneus fractures showed an intraoperative correction rate of 40 %, based on either identified reduction failures or implant misplacements in the Iso-C 3D imaging. Based on these essential intraoperative revision rates due to the 3-D imaging, we defined a study to evaluate the potential economic benefit of intraoperative 3-D imaging at calcaneal fractures. This included total cost reductions, overall reduced expenses and potentially reduction of hospital time for calcaneal fractures.

Methods: Retrospectively we compared operatively treated intraarticular calcaneus fractures, scanned intraoperatively with the Iso-C 3D with those which were interpreted only with conventional c-arm imaging intraoperatively. In all cases a postoperative computer tomography (CT) scan was done. In 12 (40 %) of total 30 fractures scanned with the Iso-C within the last years, a direct intraoperative revision was done, based either on a reduction failure (7 cases) or an identified implant misplacement (5 cases). Postop CT scans did not reveal any further failures or misplacements. We compared 10 earlier reoperated calcaneal fractures due to primary missed intraoperative steps or misplacements, without any 3-D imaging during the operation. In all cases failures were only identified in the postop CT scan. We compared all potential extra costs, including all economic burden per case based on the knowledge of one single reoperation which could have been prevented by an intraoperative Iso-C scan.
Results: The medium prolonged operative time based on the Iso-C 3D imaging including the revision was 16 minutes (m), including setup time, draping, scanning and analyzing of the reconstructions. No further failures had to be operatively revised. The medium time needed for an operative correction for the regular cases, without intraoperative 3-D imaging was 84 m (46-150m). The prolonged time on the ward was calculated with 3 days (2 – 8). Based on internal and state hospitality financing schedules the following costs were calculated:

Operative extra costs per case: Personnel costs including nurse and doctor 4.6494 Eur/minute; material, rent, amortisation: 5.38 Eur/minute; ward cost/day: 209.53 Eur/day. The medium calculation of all costs for one revision case was 1259.91 Euro. These costs would have to be estimated for every reoperated calcaneus fracture, based on initially missed reduction failure or implant misplacement.

Discussion: Operatively treated intraarticular calcaneus fractures often need postop 3-D imaging with a CT for the exact interpretation of the reduction and implant or screw placement. Intraoperative 2-D imaging doesn’t always reveal the reconstruction and reduction failures due to the complex 3-dimensional anatomy and bone morphology of the calcaneal bone. Reoperations might be the consequence. The Iso-C 3D enables a reduction of reoperations based on primary identified intraoperative failures. Expenses for reoperations, Cut’s and clinical after treatments are essential. The Iso-C 3D offers a new intraoperative imaging quality and value for the surgeons comparable to CT scans. Post-op CTs might be avoided in the future, if the quality and value of the multiplanar reconstructions is acceptable. Initial costs and extra personnel for the intraoperative use of the Iso-C have to be mentioned. Prospective randomized studies have to improve our findings in detail.
Intraoperative ultrasound navigation to determine the mechanical leg axis

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Introduction: The success of a corrective osteotomy (e.g. HTO) of the lower or upper leg is mainly dependent on the postoperative course of the mechanical axis [1]. The main problem of kinematic navigation systems are the determination of the exact hip center with the Pivot algorithm [3]. For many years we have been using an ultrasound navigation system to measure the mechanical leg axis preoperatively [2]. Therefore we developed a new prototype system to determine the center of the femoral head by ultrasound during an operation for measuring the mechanical leg axis.

Fig. 1 Intraoperative determination of the center of the hip with a 6 MHz linear probe. The probe is connected with an infrared localizer system (Polaris Northern Digital Inc., Canada)
**Methods:** In a prospective study, we measured the mechanical leg axis before and after a corrective osteotomy with a navigated ultrasound system (ZEBRIS, SIEMENS Germany). The accuracy of this system to determine the mechanical leg axis is about +/- 1°.

During the operation we use an infrared localizer system (Polaris Northern Digital Inc. Canada) combined with a 6 MHz linear ultrasound probe (ESAOTE, Netherlands). With this system we were able to determine the center of the femoral head by ultrasound with two scans of the hip perpendicular to the bony surface. The kinematic center of the knee joint is determined by slowly flexing and extending the knee from 0° to 90°. Visual cues guide the movement of the knee joint to assure accurate registration. The center of the ankle joint is determined by use of a metal plate that contains an adapter to hold a rigid body to the foot with a rubber band. With the metal plate attached, the ankle joint is then flexed and extended. With the three joint centers, the mechanical leg axis can be calculated.

**Results:** Between April 2004 and January 2004 we were able to measure the mechanical leg axis pre-, intra- and postoperatively of 19 legs in 19 patients. The mean age of the 11 men and 8 women was 42 years (range 20 to 64 years). The preoperatively measured mechanical leg axis was between 173° und 186°. We performed 14 open wedge and 5 closed wedge osteotomies to correct the leg axis. The mean difference between the pre-, intra- and postoperative measurements was 0.3° with a maximum of only 2°.

**Discussion:** The intraoperative use of navigated ultrasound under sterile conditions is possible. The procedure is simple, easy and quick. The accuracy of the postoperative results can be explained by the accuracy of the navigation systems. These first results are very encouraging and it seems that the use of a navigated ultrasound system can increase the accuracy of corrective osteotomies considerably.

**References**

Cone beam CT for image guided surgery: Pre-clinical investigation in tibial plateau fractures

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Introduction: Tibial plateau fracture commonly occurs due to trauma resulting from a combination of axial loading and valgus force applied to the knee. The goal of tibial plateau fracture fixation is restoration of normal joint function and prevention of posttraumatic osteoarthritis. Achieving adequate anatomical reduction of the joint surface during open reduction and internal fixation of these fractures remains a challenge. Acceptable intra-articular step-off is suggested to range from 2 to 10 mm. Previous clinical studies have shown up to 44% of tibial plateau fractures resulting in degenerative arthritis at a follow-up of 7 years.

Currently, fluoroscopy is the main intraoperative imaging modality for judging the quality and precision of reduction during tibial plateau fixation; however, articular depression is often under-appreciated on fluoroscopic images. While fracture complexity and the spatial relation of fragments can be demonstrated with CT images, this technique has been used to date solely in pre-planning for operative treatment and post-surgical assessment.

A new and promising technology in 3D intraoperative imaging is offered by the application of flat-panel detectors (developed for radiographic/fluoroscopic imaging) to cone-beam CT (CBCT). CBCT provides 3D volumetric image reconstructions from 2D projections acquired across a given source-detector trajectory about the patient. Recently, this technology has been adapted to a mobile isocentric C-arm platform to allow intraoperative use. CBCT demonstrates isotropic, sub-mm 3D spatial resolution, soft-tissue detectability and allows volumetric imaging of large anatomical sites within an open geometry.
The aim of this study is to determine the potential benefits of utilizing intraoperative CBCT in the fixation of tibial plateau fractures in a preclinical evaluation. We hypothesize that intraoperative 3D CBCT imaging can improve the reduction of tibial plateau fractures by providing high resolution images of the tibial plateau and 3D localization for intraoperative guidance. In addition, this study aims to optimize the CBCT imaging parameters for the knee and compare performance of flat-panel CBCT to other intraoperative imaging techniques in assessing the quality of tibial plateau fracture reduction.

Methods: Three tibial plateau fractures were simulated in fresh frozen cadaveric knees through combined axial loading and lateral impact. The fractures were reduced by a single surgeon under the guidance of fluoroscopy and CBCT (both provided by the C-arm system). Judgment as to whether initial joint surface alignment was achieved was made by fluoroscopy. The reconstruction was then assessed using CBCT. If further reduction was deemed necessary, localization of remaining displaced bone fragments were made with the guidance of an aluminum Kirshner wire (KW) using CBCT images. CBCT image quality was assessed with respect to projection speed (fast – 200 projections/slow 500 projections, dose (0.1 to 5.0 mGy), and reconstruction filter (smooth/sharp).

Results: CBCT imaging provided superior visualization of fine and low-contrast structures as compared to fluoroscopy. In 2 of 3 cases in which fluoroscopic images indicated that successful initial reduction had been achieved, CBCT imaging revealed areas of malalignment and displaced fragments. Using KW placement with intra-operative CBCT, localization of remaining displacement of the joint surface.
these fragments was easily accomplished and anatomical reduction achieved. In all cases the final CBCT scan provided exquisite visualization of articular details in assessing the quality of reduction, assured no intra-articular debris and no intra-articular hardware, sparing the need for a post-operative CT scan. Compared to an existing C-arm system for 3D imaging (Siemens Iso-C3D) which incorporates an X-ray image intensifier as the imaging detector, the flat-panel CBCT system exhibited superior spatial resolution and greatly increased visualization of soft-tissue structures.

CBCT image noise was found to increase gradually with reduced dose, although the visibility of fine and low-contrast structures was maintained down to ~0.9 mA (1.0 mGy), below which image quality rapidly degrades. Image acquisition time increased from 60 s for “fast” scans (200 projection) to 150 s for “slow” scans (500 projection), with a corresponding increase in dose by a factor of 2.5, but little appreciable difference in image quality for the imaging tasks considered. More important was the spatial resolution of image reconstructions: High-resolution images (0.4 mm voxel size) provided excellent delineation of plateau depressions, whereas voxelation at nominal resolution (0.8 mm voxels) somewhat limited the detectability of subtle, lower-contrast features. Although “Smooth” filtering provided somewhat improved delineation of soft-tissue structures, image quality overall was judged superior for “Sharp” reconstruction filters.

Discussion: Intraoperative visualization in orthopedic surgery is an ongoing challenge, particularly in complex fracture reduction. The tibial plateau fracture requires anatomic reduction of the joint surface to avoid development of degenerative osteoarthritis. The key for successful reduction is good visualization of the joint surface. This study demonstrates a clear advantage of intraoperative flat-panel CBCT over the common practice of 2D fluoroscopy in the reconstruction of tibial plateau fractures with superior image quality to Iso-C3D. CBCT imaging realized benefits in fracture type diagnosis, localization of fracture fragments, and intra-operative 3D confirmation of anatomic reduction. Intraoperative rather than postoperative confirmation of the anatomic joint reduction can remove uncertainty in the quality of reduction that might compromise clinical outcome or even require additional surgical intervention.

The high image quality of CBCT enabled visualization of osseous anatomy, joint surface, subtle fragments, and some soft-tissue components. The choice of image acquisition mode and reconstruction depends on both the imaging task (what the surgeon is attempting to ascertain from the image data) and the procedural constraints (the amount of time available for acquisition/reconstruction). Images at higher dose and spatial resolution (requiring more
time) might be acquired immediately prior to and following the procedure, providing the surgeon with high-quality “pre-operative” and “post-operative” images, while “intra-operative” images may be acquired and reconstructed according to more stringent time constraints. Intraoperative CBCT imaging has particular promise in improving joint reconstructive surgery and minimally invasive orthopaedic surgical techniques.

References

Complete hip navigation in THA – Technique and first results with Orthopilot 2.0

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Introduction: Conventional hip replacement techniques have been proven to produce not always a perfect implant alignment (1). After validation of cup navigation technique (2) now complete hip navigation with the OrthoPilot® system including stem navigation is available. Using this navigation modulus the precision of the implant position may be further improved.

Methods: After registration of the anterior pelvic plane by palpation of 3 bony landmarks, i.e. the superior iliac spines and the symphysis 2 rigid bodies carrying infrared LEDs are firmly fixed to both, the pelvis and the femur. Their signals will be detected by stereo cameras and transmitted to a computer work station. Rigid bodies will be attached to calibrated instruments to guide all further surgical steps by the monitor screen. For the part of cup navigation navigated parameters will be the direction and depth of reaming, and the inclination and anteversion of the cup position (2). Then the center of the implanted cup is recorded by pivoting a trial head inside the trial cup. The difference between the initial original acetabulum and the new cup center is a necessary information to calculate the consecutive changes in leg length and femoral offset for the stem. Further recorded navigation parameters are the direction, (ante)torsion and depth of the stem osteoprofilers as well of the final stem position. Finally changes of leg length and femoral neck offset can be measured and compared to the initial body attitude.

Since January 2004 in 61 patients the titanium pressfit system Plasmacup/Bicontact has been implanted using the complete hip navigation modulus OrthoPilot® 2.0. The preliminary results were analyzed clinically and radiologically within a 2 week postop period. From standard pelvic X-rays in ap projection the cup inclination was measured directly. The cup
anteversion angles, however, have been calculated from these X-rays using the correction formula of Pradhan (3).

**Results**: No specific complications have been observed. After overcoming initial technical problems with the application of the femoral rigid body and the software algorithm the intraoperatively registered data of the 61 patients were plausible. 5 surgeries because of losening of a rigid body had to be finished by manual technique without any disadvantages.

**Table Intraoperative registered data and clinical examination for the pilot group (n=61 patients)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination of trial cup (°)</td>
<td>42.2</td>
<td>45-47</td>
</tr>
<tr>
<td>Inclination of final cup (°)</td>
<td>42.3</td>
<td>35-52</td>
</tr>
<tr>
<td>Anteversion of trial cup (°)</td>
<td>16.0</td>
<td>10-23</td>
</tr>
<tr>
<td>Anteversion of final cup (°)</td>
<td>15.8</td>
<td>7-24</td>
</tr>
<tr>
<td>Antetorsion of stem (°)</td>
<td>17.1</td>
<td>8-31</td>
</tr>
<tr>
<td>ROM Orthopilot (ARO - 0 - IRO) (°)</td>
<td>73 – 0 - 27</td>
<td>(52-89) – 0 – (13-42)</td>
</tr>
<tr>
<td>ROM clinically i.o. (ARO - 0 - IRO) (°)</td>
<td>62 – 0 - 34</td>
<td>(50-70) – 0 – (25-50)</td>
</tr>
<tr>
<td>ROM Orthopilot extension – flexion (°)</td>
<td>0 – 0 - 109</td>
<td>0 - 0 – (98-121)</td>
</tr>
<tr>
<td>ROM clinically i.o. extension – flexion (°)</td>
<td>0 – 0 - 108</td>
<td>0 - 0 – (90-120)</td>
</tr>
<tr>
<td>Leg lengthening (mm)</td>
<td>6.5</td>
<td>(-2) – 12</td>
</tr>
<tr>
<td>Medialisation of hip center (mm)</td>
<td>4.9</td>
<td>(-4) – 12</td>
</tr>
</tbody>
</table>

**Discussion**: The newly integrated stem navigation modulus into the Orthopilot system now offers the chance of complete navigation and intraoperative simulation of the cup and stem position in an optimal relation. In the first cases duration of surgery had been prolonged, but after the learning curve of about 30 cases, surgical time was prolonged by 12 minutes only. As a result both, optimal ROM and lowest risk of femoro-acetabular impingement should occur. A lower dislocation rate and even an increased implant longevity may be expected.

**References**

Ultrasound acquisitions for minimally invasive knee surgery using morphometric models – An accuracy analysis

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Introduction: Morphometric models are widely used today in computer assisted knee surgery [1][2]. The accuracy of these deformable models can reach sub-millimetric levels in the bone surface areas that have been digitized. The planning of the optimal position and size of implants requires an adequate surgical exposure of the knee to access important landmark bone surfaces. Although this maybe acceptable in conventional or “open” surgery, these bone surfaces are not always accessible in minimally invasive surgical (MIS) techniques currently used by more and more practitioners [3].

Our research deals with the clinical application of ultrasound (US) for transcutaneous digitization of the bone surface used to register models in MIS [4]. In order to optimize the US image acquisition parameters in our computer assisted surgical protocol, we first carried out a study on the accuracy and the robustness of using deformable statistical model to reconstruct the distal femoral surface as a function of the relevant input parameters.

Methods: A digitizing probe and a passive optical camera (Polaris, NDI) allow surface points acquisition on a femur dry model. The available BoneMorphing® algorithm from Praxim-Medivision generates the morphometric bone model which fits the surface points datasets acquired by palpation. The dry bone is different from those included in the database of surface models used within the BoneMorphing algorithm.
In order to compute an initial attitude (IA), as done in clinical routine, we first acquired the transepicondylar and the mechanical femur axes, which are aligned with the described one in the morphometric model.

In addition, a surface model of the bone was generated by segmenting a CT with a 0.3 mm intra-slice thickness.

We acquired over 13000 points with a homogenous distribution, covering the entire distal surface of the dry femur. These points are divided into seven anatomical zones: Medial distal condyle, lateral distal condyle, medial epicondyle, lateral epicondyle, trochlea fossa, anterior diaphysis and posterior diaphysis.

A first BoneMorphing on the “dense” set generated a first reference model. We evaluated the accuracy of the morphing using the dense dataset by computing the average absolute distance error between the CT Model and the morphed model. As the initial attitude cannot be set accurately on the CT model, we performed a rigid registration to match the CT model to the dense data set.

To quantify the effects of acquired points density during BoneMorphing, 3 sparse data sets are built from the dense set. They are obtained by decreasing the density of the acquired points to respectively 1250, 625, and 125 points preserving their homogenous repartition. The aim of the study is to estimate the BoneMorphing elastic registration error when deforming towards the sparse sets. This error is determined by averaging the absolute distances between each point on the morphed model generated with the sparse datasets and the closest point on the surface facet of the dense morphed model, our reference.

Since the initial attitude may have a low reproducibility (due to inter- and intra-surgeon variability), we varied the position of the points used to construct the initial attitude. Thus, we randomly translated the knee center point and the axial rotation references (around the transepicondylar and femur mechanical axes) by 1, 5, and 10 mm and 2, 5, and 10° respectively.

Results: The average absolute distance error between the CT surface model and the Bone Morphing model generated with the dense dataset was 0.9 (+/-) 0.6 mm standard deviation. Table 1 summarizes the results for the average errors between the models generated with the sparse data points and the model generated with the dense data points. Rows indicate the initial attitude influence.

In addition, to simulate the 2D US probe point acquisition on the bone contour, we have also selected 700 points datasets in which the acquired
points lie in planes in each anatomical zone. We tried different locations and densities in each predefined anatomical zone. When acquiring several acquisitions for each anatomical (7 zones, 10 acquisitions of 10 points for instance), the results are comparable to the results with the homogenous repartition.

Table 1 – Influence of input parameters on morphometric model accuracy

<table>
<thead>
<tr>
<th>Error Sparse Morph/Dense Morph</th>
<th>13000 points</th>
<th>1250 points</th>
<th>625 points</th>
<th>125 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA – 0mm, 0°</td>
<td>N/A</td>
<td>0.6 ± 0.1 mm</td>
<td>1.0 ± 0.8 mm</td>
<td>1.9 ± 0.6 mm</td>
</tr>
<tr>
<td>IA – 1mm, 2°</td>
<td>0.4 ± 0.0 mm</td>
<td>0.7 ± 0.2 mm</td>
<td>0.9 ± 0.8 mm</td>
<td>1.9 ± 0.6 mm</td>
</tr>
<tr>
<td>IA – 5mm, 5°</td>
<td>0.7 ± 0.5 mm</td>
<td>0.7 ± 0.2 mm</td>
<td>1.5 ± 1.9 mm</td>
<td>2.0 ± 0.6 mm</td>
</tr>
<tr>
<td>IA – 10mm, 10°</td>
<td>0.7 ± 0.5 mm</td>
<td>0.8 ± 0.4 mm</td>
<td>1.7 ± 1.9 mm</td>
<td>2.1 ± 0.9 mm</td>
</tr>
</tbody>
</table>

Discussion: The results presented above show that with a dataset of a few hundred points, we can reconstruct the surface of a distal femur with an average absolute accuracy of average 1 mm, assuming that we can obtain a reasonable IA. Regarding the error distribution as function of the anatomical zones, an average absolute accuracy inferior to 1 mm has been observed for condyles and trochlea fossa in all acquisitions with at least 625 points. The error reported are mainly located on the diaphysis, where the density of acquisitions is the lowest and is more sensitive to a bad initial attitude.

Moreover, the results of this study can be used to determine optimal quantitative guidelines for guiding US image acquisitions in computer assisted surgery. In particular, we define a minimum acquisition threshold for each specific anatomical zone and use this, along with graphic representations of the scanning plane relative to the initially adjusted bone model, to guide the surgeon during the US acquisition phases of the protocol.

In conclusion, we have shown that US reconstruction of the distal femur using a deformable model can be optimized to increase accuracy and speed in surgery, assuming that we can accurately identify the bone surface points in the images. We are currently carrying out a clinical study in which we acquire tracked US images in computer assisted knee surgery with patients having undergone CT scans to validate our proposed acquisition protocol.
References


TSA CT-based navigation protocol: Preliminary results

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\textbf{Introduction}: The optimal placement of the glenosphere during a total shoulder arthroplasty (TSA) is currently an open issue due principally to the complexity of the shoulder joint, the prosthesis design and the limited surgical exposure \cite{1}. Providing the surgeon with a visual feedback would allow the navigation of dedicated ancillaries. This paper aims at describing a new navigation methodology based on a commonly used CT-based registration technique applied to the TSA based on the delto-pectoral technique exposure constraints. Some encouraging registration results are presented.

\textbf{Methods}: In the context of computer assisted orthopaedic surgery a critical issue is to match a computed model of the scene to the real situation within the operating room. In case of TSA the main difficulty lies in the definition of an anatomical reference; its acquisition is compatible with the envisaged surgical technique and exposure, and easily identifiable during both planning step (i.e. Selection on CT) and preoperative acquisition. In the classical rigid registration process this work focuses on anatomical reference definition and acquisition robustness.

This anatomical reference is computed from CT, on which the operator plans one anatomical landmark and one axis (superior to inferior scapula angle for instance). Then, a second axis is automatically computed. Next stages are more usual, and we present some performance estimation on global registration performed thanks to this initial attitude on a dry model of the shoulder joint.

A surface model of the bone was generated by segmenting a CT with a 0.3 mm intra-slice thickness on which the anatomical reference was computed semi-automatically. We acquired its counterpart on the dry model.
using a specifically designed digitizing probe and a passive optical camera (Polaris, NDI, Canada). The alignment of the planned axes and the acquired directions gave a first approximation of the rigid transformation between the CT model and the patient’s shoulder.

On the scapula surface 1300 points were acquired in 4 predefined areas compatible with the envisaged surgical technique and exposure. The cumulative area of these zones doesn’t exceed 15 cm². A rigid registration, based on a distance minimization using the Levenberg-Marquardt optimization, was performed to match the CT model to the dataset.

The accuracy of initial attitude acquisition has been evaluated by performing the average absolute distance between the dataset and the CT model before the rigid registration. We also evaluated the robustness of initial attitude by translating randomly the planned landmark and axes. The rigid registration was then performed using this initial attitude and we calculated the average absolute distance between the dataset and the CT model.

A preliminary evaluation of the accuracy of the complete registration protocol is provided by computing the absolute average distance between a typical dataset acquired on the glenoid surface and the CT model. In this experiment, a 200 points dataset on glenoid and a 500 points dataset acquired on the anterior surface of the scapula were used. The first set is representative of the registration accuracy in the main region of interest whereas the second one is representative of a good orientation.

Table 1  Accuracy and robustness of IA acquisition and impact on registration

<table>
<thead>
<tr>
<th>Translation and solid angle error</th>
<th>Avg absolute distance error before registration</th>
<th>Avg absolute distance error after registration</th>
<th>Avg distance error on glenoid</th>
<th>Avg distance error on scapula</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA – 0mm, 0°</td>
<td>0.5 ± 0.4</td>
<td>0.6 ± 0.3</td>
<td>0.4 ± 0.2</td>
<td>0.6 ± 0.5</td>
</tr>
<tr>
<td>IA – 1mm, 1°</td>
<td>0.5 ± 0.5</td>
<td>0.6 ± 0.6</td>
<td>0.4 ± 0.3</td>
<td>0.7 ± 0.5</td>
</tr>
<tr>
<td>IA – 5mm, 5°</td>
<td>1.8 ± 1.5</td>
<td>0.5 ± 0.4</td>
<td>0.3 ± 0.3</td>
<td>1.0 ± 0.4</td>
</tr>
</tbody>
</table>

Results: The average absolute distance error between the CT surface model and the matched model with the 1300 points was 0.6 mm (+/-) 0.3 mm standard deviation. Table 1 summarizes the results for the models registered with 3 different initial attitudes. The first row corresponds to a perfect
acquisition of the anatomical reference, whereas the next rows introduce an error during this acquisition. In the worst IA computation, the rigid registration process converges to an acceptable solution.

**Discussion:** CT-based navigation accuracy is conditioned by the registration technique performance. The methods based on distance minimization using Levenberg-Marquardt optimization have become a reference [2]. However, the convergence of this method requires a good first approximation of the rigid transform between the preoperatively collected anatomical points and the CT-computed model. Moreover, the necessity of a good initial positioning is amplified by the low size of the accessible palpation areas offered by the envisaged surgical technique and exposure. This approximation is usually performed using landmarks pairing [3] or surgical techniques priors (CT/OR patient positioning). The accuracy of landmarks pairing on small areas may be insufficient and no surgical techniques priors can be exploited here due to the high mobility of the scapula.

So we had to develop a method for computing semi-automatically an anatomical reference attached to the shoulder having a good robustness and reproducibility. The acquisition of this planned reference is done with a dedicated probe.

Results on dry bone model show good average accuracy even with reasonable error during the anatomical reference acquisition. This paper depicts the feasibility of the navigation for TSA. Current work is focused on the validation of the navigation protocol on specimen and evaluating postoperatively the good prosthesis placement (i.e. planned versus achieved placement).

**References**


Development of robotic model of external fixator for bone deformity correction of mal-unioned lower extremity

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Introduction: External fixation has been widely used in bone fracture fixation and deformity correction because of its ability of joint movement for correction of residual fracture gap or deformity [1]. However, it is difficult to accurately correct a given deformity because optimal adjustment is determined by the trained eye of a clinician, and not by biomechanical data, which is necessary for precise adjustment of the fixator joints [2]. In addition, the length of radiographic exposure to the clinicians during the procedure can be prolonged since bone segment alignment is evaluated by empirical methods and trial-and-error. It would be very useful to determine the precise fixator joint adjustments needed to accurately execute the correction plan and manipulate the fixator joints by robot-type powered actuator system.

The objective of this study was to develop an open-link type robotic external fixator model of a unilateral external fixator to simulate the required adjustments necessary for optimal bone fracture reduction and deformity correction. The inverse kinematics analysis algorithm was developed to determine the necessary fixator joint adjustments under given bone deformities and fixator application configurations. The developed robotic model was tested to perform the robotic-assisted surgery of the bone deformity correction of mal-unioned femur.

Methods: A 7-DOF robot model based on a clinically popular unilateral external fixator (Dynafix EBImedical, USA) was developed in this study. In the robot model, the DX116 motors system (Robotis Inc., Korea) was used to construct the revolute joints and the prismatic joints of the fixator. This DX116 motor system is relatively light, small in size, and very inexpensive,
making it ideal for construction of the preliminary robot model. The robot system is controlled by Matlab (Mathworks, USA) with the accuracy of 0.3 deg rotation and 0.03 mm in translation, according to our test. Geometric dimensions of the robot model were measured and the joint types were defined to facilitate the inverse kinematic analysis.

A 4 x 4 homogeneous transformation matrix was utilized to express the kinematic loop equations of the fixator-femur system in order to define six bone deformity parameters at the fracture site [3]. Then, the necessary adjustments of the rotational and translational joints of the fixator robot model were estimated by the inverse kinematics analysis technique [4].

For validation of the model, a correction of 30 deg of varus angular deformity was simulated using robotic execution. Different adjustment options, such as sequential adjustment with small increments and simultaneous adjustment, were tested in order to fully illustrate the 3-D fixator adjustability and the ability of the simulation to achieve accurate alignment correction during treatment. After robot simulation, the residual deformities in AP and lateral directions were measured to evaluate the simulation results.

**Results:** In the case of the correction of a 30 deg varus angular deformity, the solution of the fixator joint variables was obtained for the developed fixator system, with the following result: \( r_1 = 12 \text{ deg}, r_2 = 0 \text{ deg}, r_3 = 0 \text{ deg}, r_4 = 0 \text{ deg}, r_5 = 18 \text{ deg} \) from proximal to distal joints of the fixator; \( t_p = 9.3 \text{ mm}, t_d = 25 \text{ mm} \). Based on the joint values calculated from the inverse kinematics analysis, the robotic execution of the fracture treatment to correct the given deformity was performed (Figure).

![Result of bone deformity correction using a robotic model of an external fixator](image)
The deformities in AP and lateral directions between the bone segments was 2 deg and 1 deg respectively, and these results would be within the clinical tolerance.

Discussion: External fixation is commonly used to stabilize long bone segments following fracture or for bone lengthening [1]. This surgical treatment has several advantages such as adjustment capability, elastic fixation, easy removal from the bones, and mechanical stimulation. Despite the many advantages of external fixation, it has not been favored as the treatment of choice even when clinical indications are favorable for such treatment because of improper pre-operative planning and inaccurate execution from the surgical planning [2]. In order to obtain long-term good clinical results, the precise execution of external fixation based on the pre-op planning is important [2, 5].

The present robot model provided accurate correction of bone deformity surgery of mal-unioned femur. By incorporating the robot model with the image-guided system and computer-aided planning, the combined tools could be useful for executing knowledge-based robotic-assisted fracture treatment, enhancing clinical performance and facilitating changes in the design configuration for the external fixator.

References

The accuracy of femoral anteversion determined by navigated ultrasound

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Introduction: The maximum range of the individual anteversion is about 55 degrees and the absolute values are primarily dependent on the measuring method [2]. Therefore the healthy side must be used as a reference to diagnose a torsional deformity. There are a lot of different methods published within the last 20 years. Today the gold standard is the measurement of the anteversion by computer tomography. The widely used method is the procedure according to Waidelich [3]. The accuracy of conventional ultrasound techniques are not as good as the CT techniques. The combination of the ultrasound and the navigation systems to the so-called 2.5D ultrasound systems seems to be equally good [1]. The aim of the study is to compare the accuracy of the 2.5D ultrasound with the most frequently published computer tomographic methods.

Methods: We used the CT data sets of the hip and knee of 25 patients performed between 2000 und 2002 with a Philipps CT. The mean age was 42 (range 20 to 58). The slice distance from the tomographic cross sectional images was 1 mm. The indication for the CT investigation was the determination of the anteversion.

With the software Mimics Version 8.0 we were able to read the raw data sets and simulate the methods to measure the anteversion according to Weiner [4], Waidelich [3] and Yoshioka [5]. The advantage of the method of Yoshioka the so-called CARTIA method is that he uses the functional axes of the proximal femur to calculate the anteversion. We also used the ultrasound landmarks according to Keppler [1]. Therefore we were able to compare the
individual antetorsion and the left–right difference of the different methods on the same patients.

**Results:** The absolute values of the individual anteversion varied +/- 5.4° (SD) between the CT methods. The reason for this are the different definitions of the anteversion. The clinically more important left–right difference varies in the computer tomographic methods between +/- 6.0° (SD) and +/- 7.5° (SD). We couldn’t show a significant difference of the CT methods. In comparison to the ultrasound landmarks, the range was only +/- 3.3° (SD).

**Discussion:** The ultrasound landmarks are at least as accurate as the published CT landmarks. Therefore it is justified to use 2.5D ultrasound to measure the anteversion pre-, intra- and postoperatively. The main advantage of the ultrasound method is that there is no radiological hazard, the procedure takes only a two minutes and the surgeon is not dependent on the assistance of an X-ray technician.

**References**

Three dimensional evaluation of the patello-femoral joint using MRI

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Introduction: The patello-femoral joint is an important mechanism, because it amplifies and transmits the quadriceps femoris muscle power. The patello-femoral alignment should be evaluated, considering the direction of the quadriceps femoris muscle. The Q angle (the quadriceps angle) is sometimes used for the evaluation of the direction of the quadriceps femoris muscle; however, the Q angle has a weak point in that it can allow one to underestimate the real mal-alignment, when the patella subluxates. We report our three-dimensional evaluation method of the patello-femoral joint using MRI, considering the direction of the quadriceps femoris.

Methods: The control group included 17 subjects, for a total of 34 knees, with an average age of 28.8 ± 9.0 years old. The recurrent dislocation of the patella group included 11 patients, for a total of 12 knees, of which 5 knees were evaluated again after the re-alignment operation. The average age of subjects in this group was 17.9 ± 4.7 years old. The patello-femoral osteoarthritis group included 4 patients, with a total of 4 knees, with an average age of 70.7 ± 10.1 years old. There was also one male patient, 16 years old, with osteochondritis dissecans of the patello-femoral joint.

MRI was performed with the patient in a supine position, hip joints neutral between abduction and adduction and between internal and external rotation, knee joints at 30 degrees of flexion, and ankle joints neutral between internal and external rotation (Gyroscan T10-NT, Philips, The Netherlands). We set the scan range for MRI between 10 cm distally and 20 cm proximally from the center of the patella. We obtained coordinate data using Scion Image image-analysis software (Scion Corp., USA) after MRI data were downloaded into a personal computer using POP-Net software (Image One, Japan). To begin our analysis, we first found the center point (point Q) of the cross sectional area of the quadriceps muscle on the MRI 20 cm proximal
from the center of the patella. Next, we found the bi-sectioning line (line E) of the patellar facet of the femur on the MRI at the center of the patella. After that, we determined the ideal plane (ideal E plane) of the extensor apparatus that was made from point Q and line E, because we thought that from a biomechanical point of view, the patella’s stability is ideal when the E plane intersects the patellar facet of the femur centrally and perpendicularly. We evaluated the patello-femoral alignment by the distance of the patella and the tibial tuberosity from the ideal E plane. These analyses were performed using Visual Basic ver. 6.0 (Microsoft, USA). Statistical analysis was performed using an unpaired T-test (SPSS software 10.0.7J).

Results: In the control group the deviation of the patella was 0.1 ± 2.4 mm, and that of the tibial tuberosity was 7.4 ± 4.2 mm. In the dislocation group the deviation of the patella was 8.9 ± 11.0 mm, and that of the tibial tuberosity was 13.6 ± 7.5 mm. After the operation the deviation of the patella was 1.9 ± 4.6 mm, and that of the tibial tuberosity was -2.7 ± 6.1 mm. The patella and the tibial tuberosity were satisfactorily corrected on the ideal E plane. In the patello-femoral osteoarthritis group the deviation of the patella was 5.9 ± 1.7 mm, and that of the tibial tuberosity was 15.5 ± 6.1 mm. In the case of patello-femoral osteochondritis dissecans the deviation of the patella was 1.8 mm, and that of the tibial tuberosity was 14.6 mm. In the patello-femoral disorder groups the deviation of the tibial tuberosity was significantly larger than in the control group (P<0.01).

Discussion: Our results suggested that one of the main causes of patello-femoral disorder, such as recurrent dislocation of the patella, patello-femoral osteoarthritis, and patello-femoral osteochondritis dissecans, is anatomical lateral deviation of the tibial tuberosity. We think that patello-femoral alignment can be evaluated by the length of deviation of the tibial tuberosity from the ideal E plane, as femoro-tibial alignment can be evaluated by the femoro-tibial angle. Moreover, using our method we can determine how much the tibial tuberosity should be corrected, as we can determine how much the angle of a varus knee with medial osteoarthritis should be corrected from a patient’s femoro-tibial angle.

Conclusions: Patello-femoral mal-alignment can be evaluated based on the length of deviation of the tibial tuberosity from the ideal plane of the extensor apparatus that intersects the patellar facet of the femur centrally and perpendicularly. The tibial tuberosity of patients with patello-femoral disorders should be corrected on the ideal plane.
Computer-assisted spherical osteotomy with a curved-bladed tuke saw

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Introduction: Techniques of cutting bone spherically are useful for orthopaedic surgeries such as rotational acetabular osteotomy or revision of well-fixed cementless acetabular sockets. Conventionally, curved chisels have been used for such spherical osteotomy, however, it is difficult to control the tip of the blade precisely even under fluoroscopic guidance or under a navigation system. Moreover, chisels have a potential risk of damaging blood vessels or nerves. Therefore, in order to perform spherical osteotomy precisely, quickly and safely, we have developed a novel computer-assisted surgical tool utilizing a Tuke Saw (Finsbury Instruments, UK) with a curved blade and with a CT-based optical navigation system. The normal Tuke Saw is a bone saw which is used for plane osteotomy in orthopaedic surgery. It has a saw-shaped blade which rotates and vibrates at 2000 cycles per minute with a diameter of 1.5 mm. In this study, the accuracy and feasibility of this curved-bladed Tuke Saw in spherical osteotomy were examined in comparison with the conventional curved chisel. First, hemispherical osteotomy with these surgical tools was performed on rectangular parallelepipeds of Sawbones. Next, as a preclinical study, rotational acetabular osteotomy on cadaveric pelves was performed with the curved-bladed Tuke Saw on one side of the hemipelvis while with the curved chisel on the other side.
Methods: (A) Hemi-spherical osteotomy using Sawbones blocks. As a model of cancellous bone, Sawbones’ rectangular parallelepiped blocks of cellular solid polyurethane foam (Pacific Research Laboratories, USA) were used. The planning of hemi-spherical osteotomy for the model bone block was made with its center placed on the surface of the block and with its radius of 50 mm. The curved-bladed Tuke Saw and the curved chisel both with a blade of the same radius as that of the sphere of the plan (50 mm) were used for spherical osteotomy and these surgical tools were compared for accuracy and for feasibility. Hemi-spherical osteotomy for the model bone block was performed with these surgical tools under an optical surgical navigation system with an optical three-dimensional positionmetry sensor (OPTOTRAK 3020, NDI, Canada). The LED optical trackers of this navigation system were attached to the model bone block and to the surgical tool. The osteotomy was performed by three hip specialist surgeons who are skillful at rotational acetabular osteotomy. After osteotomy, CT scans of the model bone blocks were performed with the slice thickness 1 mm. With the CT images, the distance error of the actual osteotomy surface from the sphere of the plan was measured according to the depth from the surface of the model bone block. At the same time, the average thickness of bone loss was calculated by measuring the weight loss of the block from the initial status and the surface area of the actual osteotomy surface. The procedure time for each hemi-spherical osteotomy was also measured. The trials of hemi-spherical osteotomy were repeated five times for each surgical tool for each surgeon. That is, the trials were repeated fifteen times for each surgical tool.

(B) Rotational acetabular osteotomy on cadaveric pelves. Eight cadaveric pelves were used. The planning of rotational acetabular osteotomy (spherical osteotomy) was made with an adequate radius and with an adequate position for each side of the hemipelvis for each pelvis. Rotational acetabular osteotomy was performed with the curved-bladed Tuke Saw with a suitable radius of the blade on one side of the hemipelvis while with the curved chisel with a suitable radius of the blade on the other side. Osteotomy was performed by hip specialist surgeons under a CT-based optical surgical navigation system in a similar way with the Method (A), above mentioned. After osteotomy, CT scans of pelves were performed. The postoperative CT images were superposed on the preoperative CT images using the volume registration method. Then, the average distance error of the actual osteotomy surface from the sphere of the plan was measured for each surgical tool.

Statistical analyses were performed using the Student’s t-test with a significance level of 0.05.
Results: (A) The distance error of the actual osteotomy surface from the sphere of the plan became larger as the position went deeper from the surface of the block. At the position of more than 50 degrees from the surface of the block, the distance error with the curved-bladed Tuke Saw was significantly smaller than that with the curved chisel. The distance error at the position of 75 degrees from the surface of the block was 1.8 +/- 1.6 mm (mean +/- SD) with the curved-bladed Tuke Saw while 4.5 +/- 1.7 mm with the curved chisel, and the difference was significant (P < 0.05). The average procedure time for spherical osteotomy was 7.8 +/- 3.3 minutes with the curved-bladed Tuke Saw while 21 +/- 9 minutes with the curved chisel, and the difference was significant (P < 0.05). The average thickness of bone loss was 1.48 +/- 0.41 mm with the curved-bladed Tuke Saw while 0.44 +/- 0.27 mm with the curved chisel, and the difference was significant (P < 0.05).

(B) The average distance error of the actual osteotomy surface from the sphere of the plan was 1.8 +/- 1.9 mm with the curved-bladed Tuke Saw while 2.5 +/- 2.1 mm with the curved chisel, and the difference was significant (P < 0.05).
**Discussion:** With the curved-bladed Tuke Saw, the distance error was smaller and the procedure time was shorter than those with the curved chisel. Therefore, it can be said that both the accuracy and feasibility of the curved-bladed Tuke Saw are higher than those of the curved chisel. The average thickness of bone loss with the curved-bladed Tuke Saw was larger than that with the curved chisel, however, the value of 1.5 mm is thought to be acceptable for clinical use, and the normal Tuke Saw is actually used for plane osteotomy. In addition, the nature of the Tuke Saw motion is safer for the surrounding soft tissues than that of chisels. Clinical use of this surgical tool for spherical osteotomy is considered to be quite easy and encouraging.
Semi automated and non invasive determination of bone landmarks using a navigated US

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Introduction: The sonography is an important method which is used in nearly every medical sector. It is based on the reflection of ultrasound waves at the layer of tissue. In the last few years the ultrasound method started to be introduced in surgery [1]. With the help of navigation it is possible to determine the position of the 2D US plain in a 3D coordinate system. Due to this fact it is possible to determine every 2D points in the US image. In the CAS accurate determination of landmarks is of major interest. Usually, these landmarks must be exposed during surgery [1]. Our goal is to avoid the exposure of bone surface for interactive finding of landmarks by using intraoperative US that can localize the bone non invasively. The surgeon scans the landmarks. Afterwards the data are displayed and the landmark could be identified.

This paper describes a US method for accurate single step determination of leg length. A US with 6 MHz linear probe is combined with an optical localizer system. A reference Rigid Body (RB) fixed to the lower extremity eliminates errors associated with patient position or motion. The leg length of an artificial leg (see Figure 2) was determined as well as of two patients’ legs (see Figure 3). The hip, knee and ankle center is needed. These were measured with a new US technique semi-automatically

Methods: A conventional US imaging system (Aquila Esaote, The Netherlands) was used together with an infrared localizer system (Polaris Northern Digital Inc., Canada). For localizing the reference and US probe (see Figure 2 and 3) two passive rigid bodies are used. The 2D US images were taken in such a way that all landmarks were clearly visible. By skilful
positioning of the probe on the leg the anterior, lateral, and posterior parts of the femur and tibia can be recorded. The following steps in the procedure are necessary for a determination the leg length:

- Longitudinal measurement of femur head
- Transversal measurement of femur head
- Transversal measurement of knee
- Longitudinal measurement of ankle
- Transversal measurement of ankle.

Figure 1

Figure 2

Figure 3
To get the demanded measure a dataset of an artificial leg with a given geometry (see Figure 2) is used. The positions of each center in the coordinate system of the fixed adapter are known by precise measurements. They were established from AESCULAP AG & Co KG by measuring the cone apertures with a Zeiss (Oberkochen, Germany) UMM 850 coordinate measuring machine. The centers of the artificial leg were scanned beyond a balloon filled with water.

For the determination of the femur head center a semiautomatic algorithm is used. First on the femur head, a region of interest (ROI) is defined manually. In this ROI, arc of the circle are determined automatically by image processing. Second, a sphere is approximated to the two arcs (see Figure 1). Center and radius of the sphere are calculated.

**Results**: Using a Coordinate Measuring Machine (UMM 850 Zeiss, Oberkochen, Germany) the artificial leg has the following properties: 872.3 mm.

The artificial (see Figure 2) leg has the following properties using a US determination (10 times):

- Mean: 871.8 mm
- Deviation: 0.7 mm.

This shows that the repetition accuracy of this US measurement is very high.

The left legs of two patients were measured with the system too (see Figure 3). We received the following results from ten measurements:

Patient 1:  Mean: 829.6 mm  Deviation: 1.4 mm
Patient 2:  Mean: 806.3 mm  Deviation: 1.0 mm

**Discussion**: In the preceding test with the artificial leg the “US leg length” tool showed exact and reproducible results. However, under real conditions the system shows a higher deviation. They increased from 0.7 to 1.4 mm. The cause of that are inevitable test conditions. In comparison of the results of patients leg to the artificial leg, there is a difference at the recording of the femur head. With the artificial leg the femur head is shown as a semicircle, but with the real patient, there is only one arc of the circle visible. This is caused by the tissue around the femur head and pelvic bone.

**References**

Reliability study of the CT based system for range of motion calculation within the native hip joint

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Introduction: The conflict between the femoral head and the acetabular rim (known as femoroacetabular impingement (FAI)) can cause pain, limit range of motion (ROM), and lead to early osteoarthritis of the hip joint in young and physically active patients [1]. Surgically trimming the overdeveloped part of the acetabular rim and resecting the aspherical portion of the femoral head can increase impingement-free hip motion and should reduce pain as well as prevent further degeneration and osteoarthritis of the hip joint. A new CT based computer system was developed to calculate the preoperative range of motion, to identify the acetabular and femoral location of impingement, as well as to simulate the post-operative hip motion after the surgical reshaping.

Methods: To perform impingement simulation with the assistance of the new system a CT scan of the patient’s pelvis with approximately 15 cm of the proximal part of the femur and 4 cm of the distal femur covering the epicondylus area has to be acquired. On the basis of the CT data and the IAP software (ISG Technologies, Inc.) chosen for image processing, a volumetric-based 3D model of the hip joint is created (segmentation). To respect the individual patient’s geometry a pelvic reference coordinate system based on
the anterior pelvic plane concept [4] is established. On the femoral side to calculate the anatomic alignment the strict geometrical definition presented by Murphy [3] is applied. Next, the acetabular contour is marked on the 3D model to exclude undesirable impingement within the acetabular socket area, which otherwise would limit the motion analysis to non-dysplastic hips. To calculate the range of motion within the individual virtual hip joint a fast and accurate impingement (collision) detection algorithm was used that has been presented before [2]. Applying this method to the volumetric data of the patient’s hip joint allows the automatic simulation based on anatomic coordinate systems to perform ROM analysis. Passive manipulations of the hip joint are usually performed during routine physical examination. This motion can be simulated and quantified in an anatomically based way. In order to simulate the correction of the hip joint deformity reshaping the virtual model of the patient’s hip joint can be performed. At last, taking the new volumetric data into consideration, the automatic simulation of the increased ROM of the hip joint is repeated and results are presented in a report. To handle all of the image processing and visualization tasks a SunBlade100 workstation (Sun Microsystems, Inc.) was chosen.

Table 1  Results of the reliability study of the CT based system for range of motion calculation within the native hip joint.

<table>
<thead>
<tr>
<th></th>
<th>Intra-CC first rater</th>
<th>Intra-CC second rater</th>
<th>Inter-CC</th>
<th>Cronbach’s alpha</th>
</tr>
</thead>
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<tr>
<td>Flexion</td>
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<td>0.87</td>
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<td>Extension</td>
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<tr>
<td>Adduction</td>
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<td>0.99</td>
<td>0.95</td>
<td>0.99</td>
</tr>
<tr>
<td>Abduction</td>
<td>0.97</td>
<td>0.96</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>Internal Rotation</td>
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<td>0.92</td>
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<tr>
<td>Internal Rot in 90° Flex</td>
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<tr>
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<td>0.78</td>
</tr>
</tbody>
</table>

The 3D model creation, anatomic landmarks identification as well as the acetabular outline definition can influence ROM findings. Therefore, an extended reliability study of this simulation system has been carried out on 39 patients’ data sets of both FAI and normal hips. To determine intra- and inter-observer reproducibility, two trained observers were performing the ROM test-retest simulation on blinded CT data with two-months intervals. During each test the 3D model of the patient’s hip joint was generated, the anatomic landmarks for both pelvic and femoral reference plane were identified, the acetabular rim contour was marked on the 3D model, the ROM simulation was performed, and finally the values of impingement-free
movement quantified as flexion, extension, adduction, abduction, internal and external rotation as well as internal and external rotation in 90° flexion were collected. At this point in time, the amount of data collected is insufficient to allow statistical analyses. We are expecting that the first results will be available at the time of the conference.

**Results:** Excellent reliability of this method was found for intraclass correlation coefficients (intraclass-CC) for each of the two examiners (raters), interclass-CC for all tests, and internal consistency – Cronbach’s alpha (see Table 1).

**Discussion:** This system will help surgeons analyzing the FAI mechanism and will provide them with an essential tool for preoperative planning. Moreover, this 3D computer assisted method allows virtually exploring and evaluating an appropriated surgical treatment in diverse hip pathologies. The CT scan data and the 3D models as well as the information about simulated impingement-free ROM and the collision zones will be used as the basis for intraoperative surgical navigation.

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**References**


Computer-assisted range of motion prediction in normal and impinging hips

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Introduction: Femoro-acetabular impingement (FAI) is the leading cause of end-stage arthrosis of the hip.¹ Two different types of FAI are recognized and referred to as femoral (cam impingement) or acetabular (pincer impingement) deformities, or both. The acetabular cause of impingement is excessive anterior coverage. The femoral cause of impingement is typically due to reduced head-neck offset. Both conditions lead to femoroacetabular impingement at the end-range of motion. This repetitive bony contact results in labral and chondral lesions, pain, and eventual progressive osteoarthrosis of the hip. Clinically, FAI is revealed on physical examination by limitation of range of motion in flexion and especially flexion/internal rotation.

The current study uses CT data and custom-made kinematic simulation software to investigate the affect of anatomic factors on predicted range of motion (ROM) of normal and impinging hips.

Methods: 55 CT data of patients with normal hips and hips with FAI were used in this investigation. These CTs were collected from a pool of 144 CT scans taken either for clinical evaluation of patients with FAI or were hips contralateral to hips undergoing CT-based navigation of total hip arthroplasty. Exclusion criteria included joints with previous hip surgery, post-traumatic deformity, end-stage osteoarthrosis (Tönnis grade ≥2) or dysplasia. The remaining hips were classified as either being normal or
having FAI based on clinical assessment of the CT studies and plane radiographs.

To analyze the amount of impingement-free motion of the selected hip joints and to find where the bony contacts occur we used a previously presented CT-based system. This simulation software allowed to reconstruct a virtual 3D model of the patient’s hip joint using common intensity thresholding and segmentation techniques. To follow the anatomical orientation of the individual patient, a pelvic reference coordinate system based on the anterior pelvic plane concept as well as the strict geometrical definition for the femoral anatomic system was used. Next, the acetabular rim was marked on the 3D model to define the potential areas of impingement on the acetabular side. Motion simulation and a collision detection algorithm were then applied to the volumetric data of each hip joint to resulting in an automatic range of motion analysis. In order to simulate motions performed during routine physical examination, impingement in internal rotation was studied in 5 degree increments through ranges between 70 and 110 degrees of flexion and 20 to -20 degrees of adduction. Clinically, after preservation surgery of the hip joint, the location and extent of the acetabular trimming was documented using a clock system in which 12 o’clock pointed slightly posterior to the head of the patient, 6 o’clock to the center of the acetabular notch and 3 o’clock directed anterior on both joints. We used this method to describe the location of the impingement points detected on the acetabular rim during virtual ROM examinations.

**Results**: Based on the plain radiographs and CT measurements the 55 patients’ hip joints were classified either as being normal (33 subjects) or having femoroacetabular impingement (9 with cam type impingement, 6 with pincer impingement, and 7 with combined (mixed) abnormalities). The mean patient age for the control and impingement group was 53 years (range 25-74 years) and 35.4 years (range 19-49 years) respectively. There were significantly more male patients in the FAI group (95.5%) as compared to (60.6%) (p = 0.00175) in the control group.

For each of the simulated patterns the mean of impingement-free range of motion was significantly smaller (p < 0.000, z-test) within the FAI group than in the control one [see Figure 1.]. Furthermore, by increasing adduction to the already flexed femur the mean range of internal rotation decreased significantly in both groups (p < 0.0001, z-test).

The average of the impingement location detected on the acetabular rim and quantified using the clock system was 1.8±1.8 o’clock for the control group. In the FAI group this value was 2.5±2.7 o’clock (1.8±2.1 in the cam, 2.3±1.9...
in the pincer and 3.5±3.6 in the combined subgroup). Moreover, more than 95% of the detected impingement area was lying within one standard deviation of the mean [Figure 1.].

**Discussion:** Improved understanding of the pathokinematics of patients with FAI is essential to allow improved diagnosis and treatment of this common cause of hip arthritis. The current study demonstrates that both normal hips and hips with FAI impinge in similar locations and that both groups had progressive decreases in motion with increasing hip adduction. The study shows also that patients with FAI experienced impingement at significantly lower ranges of motion. Currently, many of the structural abnormalities can be identified on conventional plain radiographic. The pincer impingement can be diagnosed on a standard anteroposterior view of the pelvis by noting that the femoral head is covered more by the anterior rim than by the posterior one. On the femoral side, the cam impingement can be seen on true or frog lateral radiographs. However, planer radiographs are projectional images and therefore carry inaccuracies caused by the overlay of anatomical
structures and a non-standardized positioning of the patient, so that the early degenerative changes can be subtle and may not be recognized. In contrast using a 3D model of the hip joint with a simulation system can well predict the amount of impingement-free ROM and the location of the collision zones. It thus could improve the early detection and diagnosis of the hip abnormality. Moreover, we expect that this information will help surgeons to explore and evaluate an appropriated surgical treatment of the impingement hip of any individual patient.

References
Fixing peritrochanteric fracture with gamma nails with fluoronavigation – A comparative study of operative procedures of two different designs

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Introduction: Gamma nail is one of the intramedullary fixations for peritrochanteric fractures with the advantages of closed treatment of fractures. We started using fluoronavigation in Gamma-AP nailing in 2001. With the availability of the Gamma-3 nail which was designed to facilitate MIS and fluoronavigation, we conducted a prospective operative study to compare the two nailing systems with the use of fluoro-navigation.

Methods: Geriatric patients with peritrochanteric fractures were included in the study. 35 peritrochanteric fractures were treated with Gamma-AP nails and 32 were treated with Gamma-3 nails. All surgeries were done with fluoro-navigation (Stryker Navigation System). With the newly designed adapters that were attached to the Gamma nail instruments, the surgery was done with fluoro-navigation guidance for the entry of the medullary canal, nail insertion, lag screw insertion as well as the distal locked screw insertion. Intraoperative records of X-ray shots, duration of surgery, and length of surgical wounds were taken. Postoperatively, the TADs were recorded and the patients were followed-up for at least 9 months where fracture healing, complications and functional recovery were documented in the Fracture clinics. The data were analysed with student-t test where p<0.05 was considered statistically significant.
Results: The results of intraoperative findings are shown in the Table. No complication was recorded during surgery in both groups. The average tip-apex-distance (TAD) for Gamma-AP was 12.7 and that for Gamma-3 was 10.56. Postoperatively with an average follow-up period of both groups of 6.9 months, all fractures healed. All patients remained ambulatory except one in the Gamma AP group where lag screw cutout occurred. The lag screw was removed subsequently and the patient remained chair bound.

Discussion: Gamma-3 is a modification of the Gamma-AP system for the treatment of peritrochanteric fractures with intramedullary fixation. The modification includes instruments and implants. Both facilitate MIS in treating these very common fractures and the advantages of MIS are of special importance among geriatric patients. This study shows that the surgical incision, duration of surgery and the need for frequent X-ray exposure are further reduced. The position of the implants can be inserted accurately. As one of the major concerns with intramedullary fixation of the proximal femoral fractures in osteoporotic bone is the position of the lag screw in the femoral head and neck, fluoronavigation has its unique advantages to monitor precisely the position of the lag screw and is well shown in this study with the TAD and the postoperative results.

Intraoperative findings on peritrochanteric fractures treated with Gamma-AP and Gamma-3 nails

<table>
<thead>
<tr>
<th></th>
<th>Type of Nails</th>
<th>Mean</th>
<th>SD</th>
<th>p*</th>
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<tr>
<td>OT time (Min)</td>
<td>Gamma AP</td>
<td>44.476</td>
<td>8.376</td>
<td>&lt;0.05</td>
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<td></td>
<td>Gamma 3</td>
<td>32.60</td>
<td>4.720</td>
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<tr>
<td>No. of X-Ray for Reduction</td>
<td>Gamma AP</td>
<td>5.619</td>
<td>3.399</td>
<td>0.18</td>
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<tr>
<td></td>
<td>Gamma 3</td>
<td>5.9</td>
<td>0.966</td>
<td></td>
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<tr>
<td>No. of X-ray for navigation</td>
<td>Gamma AP</td>
<td>11.081</td>
<td>1.987</td>
<td>&lt;0.05</td>
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<tr>
<td></td>
<td>Gamma 3</td>
<td>5.9</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>Wound length (mm)</td>
<td>Gamma AP</td>
<td>68.70</td>
<td>19.8</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td>Gamma 3</td>
<td>53.20</td>
<td>5.89</td>
<td></td>
</tr>
</tbody>
</table>
**Conclusion:** This study confirms the advantages of the application of fluoronavigation in Gamma nailing with the advantages of decreasing X-ray exposure and accurate implant position. The surgical trauma is decreased with smaller incisions with the improvement of the instrument and the implant design. It is further concluded that the combination of fluoronavigation and instrument and implant designs helps to achieve maximal benefit of MIS in fracture management.

**References**

Load related trabecular architecture variations in the scapular glenoid; modeling and validation

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Introduction: The trabecular bone remodeling is essential to the understanding of the mechanical and morphological changes resulting from shoulder injury and surgical intervention. Morphology of the trabecular bone of the shoulder has been studied in a limited way and pertains primarily to healthy bone. The present study attempts to predict variations occurring in the trabecular architecture of the glenoid region of the scapula resulting from variations in the loading condition on the Glenohumeral (GH) joint. Such variations of loading patterns may result from injury, occupational demands and athletic activities. The added knowledge will contribute to a better understanding of the consequences of shoulder injuries, the relevant prosthetic implants, tissue engineered scaffolds, and planning of the corresponding rehabilitation regimens. This methodology is not shoulder specific and can be applied to the analysis of bone morphology of other joints.

Methods: Twelve cadaveric scapular specimens were harvested and sliced sagittally at 2 mm intervals. The slices were washed, dried and digitally imaged (640 x 480 pixels) at a 35 µm resolution with the objective of quantifying the actual trabecular architecture of the glenoid by using the MIL (mean intercept length) method [1]. Six regions of interest (ROIs: 100 x 100 pixels in each ROI) were demarkated on each digitized image (Figure 1). Vertically, the glenoid was divided into three regions: the “Upper”; the “Bare” (the area of maximum concavity of the glenoid joint surface) and the “Lower” region. Each of the regions contained several slices depending on
the individual specimen. The different images of a particular region were analyzed and averaged for that region.

An algorithm was developed, based on a premise that variations in the trabecular architecture between individuals are primarily influenced by habitual daily activities of the person. The following mechanical factors were considered: 1) Incidence (frequency) of the functional shoulder activities and; 2) motion trajectories of the activities (obtained via motion analysis) and the corresponding principal stresses in the glenoid, which govern the trabecular bone formation. The incidence of the functional shoulder activities can be obtained from ergonomic studies. The magnitude of the principal stresses corresponding to the shoulder activities were determined, using a dedicated finite elements program. The algorithm derived describes the predicted predominant trabecular direction TR in terms of:

1 – n: indices of the functional shoulder activities
f: incidence of the functional shoulder activity
d: trajectory (direction) of the principal stress
m: normalized principal stress.

The reliability of the developed equation was verified via comparison with the actual trabecular architecture determined from the 12 cadaveric scapular specimens. The daily functional shoulder activities to be considered in the above algorithm were adopted from Anglin et al. [2]. The mechanical factors generated by the daily functional shoulder activities were then determined and applied to the algorithm. A standard condition was assumed to be when the incidence factor was f = 1, namely, the same incidence for all conditions. The incidence of each daily functional shoulder activity was varied and applied to the algorithm to test its capability of identifying the
trabecular variation. The magnitude of the principal stresses corresponding to the motion trajectories was computed by the finite elements model.

**Results**: The average predominant trabecular direction relative to the horizontal axis (Figure 1), which connected two end points of the glenoid articular surface, was 89.4 ± 10.1 for the entire glenoid. The predominant trabecular direction was determined from the 12 cadaveric scapular specimens. The predominant trabecular directions determined for all ROIs were also compared with the results on all ROIs predicted by the above equation. The average predominant trabecular direction for entire glenoid predicted by the above equation was 78.9 ± 4.6, under the standard condition. That is, the difference between the average actual and predicted trabecular architectures was 10.5 for the entire glenoid. The difference was almost ranged into the maximum standard deviation (10.1) of the actual trabecular architecture. In detail point of view, the differences in the upper, the bare and the lower regions of the glenoid were of 8.8, 9.0 and 13.7, respectively. The differences were generally in the anterior and the posterior aspects than those of the central aspect of the glenoid. The specific conditions, which applied the difference incidences to the equation, predicted the different trabecular architecture corresponding to the characteristics of the functional shoulder activity incidences defined in each condition. The specific conditions showed characteristics of the trabecular bone remodeling toward the anterior or the posterior aspects of the glenoid compared with the actual trabecular architecture.

**Discussion**: This is a pilot study attempting to quantify trabecular architectural variation (remodeling) due to variations in the loading conditions of trabecular bone. At the present, only planar trabecular architecture was analyzed, however, three-dimensional architectural analysis is underway and will be reported in the future. The results obtained to date are promising and suggest that significant changes in the pattern of the trabecular patterns can occur as a result of the loading conditions in the GH joint and confirm that such changes can be predicted with our model. Such changes may result from injury, occupational activities and other daily functional habits and can be obtained with the same musculoskeletal model used here. The determination of the incidence factors of the functional daily activities will be refined in the future via more comprehensive motion analysis in healthy and pathological individuals.

**References**
Introduction: Recently, the distal locking, as the essential part of the CAOS research in the intramedullary nailing of lower limb fracture therapy, has made an effective progress both in researches and in applications [1, 2, 3], which results in the improved positioning and locking rate of the hole, the decreased X-ray radiation dose to the medical staff and patients, the partial alleviation of the physical fatigue of surgeons, etc. However, few literatures have emphasized the research of the necessary surgical planning steps prior to the locking such as the selection of nail length, the determination of nail entry point and orientation, the bone reduction information, etc., all of which are necessary to further improve the surgical output even for development of the digital operation room. Based on our current research on the orthopaedic robots, this paper experiments a compact and lower cost full-length planner for CAOS research of nailing of lower limb fracture to sustain and stabilize the fracture limb, to dynamically adjust the anatomy pose during operation, etc.

Methods: The desired full length planner is divided into hardware and software. The hardware is not only a bone reduction mechanism but also a connection base for the robot (the modified version of [3]) and the fracture limb so as to fix the relative position of them. It has been tested for many times in laboratory experiments. The software is designed for composing multiple C-arm projections with limited FOV (Field-Of-View) to form a panorama of entire fracture anatomy (similar to [4]) to provide the essential
data about the anatomy for surgical planning, such as the length of nail, etc. The core algorithms have been carried out and their code implementations have been finished using C++ language and the software integrating and testing is being done in Visual C++ IDE at present. From the aspect of clinical application, only the experimental simulation of hardware is discussed here.

The hardware consists of the main frame and the reduction module connected to the end of frame (shown in Figure 1). The frame adopts a special structure design which eliminates the interference with the operational space, and pole-based modular decomposing which facilitates the apparatus sterilization. The reduction module can be controlled by the surgeon to reduce the fracture bones through one degree-of-freedom linear motion which can simplify the intra-operative operations.

The cadaver experiments of tibial fracture have been done using the planner cooperated with the robot for more than 10 cases to validate the structure rationality, clinical adaptability of the hardware. The main operating steps are: fix the limb on the main frame through Kirschner pins at the ankles and install the reduction bar; then automatically or free-hand control the motored reduction mechanism to reduce the fractured bones according to the reduction distance derived from the analysis of X-ray projection.

Figure 1  Cadaver experiments
**Results:** The above experiments have attained the desired requirements and shown that the main frame has enough intensity to sustain the limb and endure force impacting during the operation. Also, the flexibility and practicability of the planner (mainly the hardware) have been accepted by the operation surgeons.

**Discussion:** The experiments illustrate the effectiveness of the system in surgeries, and also expose some problems or pitfalls of current structure. (1) It is hard to clean the blood pollution on the woodiness knee holder of the main frame. The alternative materials or surface masking should be investigated (2). The installation of reduction module on the main frame is somewhat difficult. The improved structure or the simplified installation program should be considered in the next revision (3). The exact information of the nail should be provided by the full length planning software.

**References**


Development of a computer-assisted, motorized injection device for high viscous materials

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Introduction: In certain surgical interventions on the spine, such as vertebroplasty, bone cement is injected into a vertebral body to stabilize fractures. While these procedures can provide immediate pain relief to the patient, they carry the risk of cement leakage into the venous system or the spinal canal, which can lead to pulmonary embolism or cause spinal cord and nerve root compression [1, 2]. It has been reported that the risk of leakage can be reduced when bone cements are injected at a high viscous state [3]. Currently, the injection is performed either manually with traditional syringes or by using threaded plunger systems [4]. Using traditional syringes, it is not possible to build up enough pressure to inject cement at high viscosity levels. While manual threaded plunger systems generate higher pressure, they reduce the level of control over cement flow by eliminating tactile feedback and by suffering from slow reaction time. Additionally, none of today’s manual injection devices are able to measure parameters defining the procedure, such as injection pressure, injected volume, flow rate or the injected material’s viscosity.

We are presenting a computer-assisted, motorized injection device for high viscous materials that is able to measure injection parameters and uses traditional syringes as material containers. It incorporates a flow-stop mechanism and a spatially separable actuator, which provides scaled force feedback to the user while allowing operation from outside high-radiation areas caused by fluoroscopic imaging systems.

Methods: To address the shortcomings of today’s instrumentation, a motorized, computer-assisted cement injection device has been designed and
Injection device with force-feedback actuator

built. It is able to generate 5 MPa of pressure in a 20 ml polycarbonate syringe (Merit Medical Systems, Inc., Utah, USA) compared to the 1 MPa in a 2 ml syringe manually achievable. It is driven by a DC motor coupled with a reduction gear and a magnetic encoder (Maxon Motor AG, Switzerland), that delivers 1500 N compressive force on the syringe plunger as well as precise position and speed information, which is used to calculate the injected volume and the flow rate. The injection device is able to determine the pressure created in the syringe with an integrated load cell (Omega Engineering Inc, Connecticut, USA) by measuring the force applied to the plunger. Additionally, the viscosity of the injected material is calculated based on flow- and pressure measurements.

The system is operated from a hand-held, syringe-like actuator that is apt to provide scaled force feedback to the user based on the force measurements on the syringe. The user pushes or pulls the plunger on the actuator to drive the plunger of the syringe. Since these motions are processed programmatically, filtering and scaling of signals is possible, enabling fault prevention as well as subtler control over the injection procedure. For example, a 30 mm stroke on the actuator can be scaled down to result in 0.1 ml cement injection. Similarly, 1500 N of force applied to the syringe plunger can be scaled down to result in 30 N force feedback on the actuator. Furthermore, the actuator and the injection device are spatially separable, allowing the surgeon to control the procedure from outside high-radiation fields. The device also provides an emergency stop mechanism, which immediately stops the cement flow by retracting the syringe plunger at high speed.

Results: The device has been characterized in several experiments to verify the safety and amount pressure achievable, the accuracy of parameter
measurements and the suitability for an operating theater. Pressures up to 5 MPa were repeatedly built up and held for several minutes. The polycarbonate syringes used are apt to withstand the pressure – no damage has been observed in our experiments involving more than 30 syringes. The encoder on the drive unit generates over 16’000 pulses per 1 mm advancement on the syringe plunger, which theoretically allows to measure the injected volume at an accuracy of 1/48’000 ml (3 mm advancement result in injection of 1 ml). However, an accuracy of 0.1 – 0.3 ml was observed due to the compliance of the syringe plunger. A first attempt to calibrate viscosity estimation has been performed using the system as a capillary rheometer by attaching a cannula of a known diameter and length to the injection device [5]. The device measurements were tested against four Newtonian viscosity standards (Cannon Instrument Company, State College PA, USA) rated at 41, 72, 200 and 380 Pa·s at 25 degrees Celsius. Measurement errors in this first test ranged from 5% to 15% with increasing viscosity. The device has been used in animal and cadaver studies and proved to be a valuable tool. Cement injection even into non-osteoporotic, non-fractured vertebrae was easy, computer-control allowed good repeatability and the integrated data logging made additional measurements obsolete.

**Discussion:** The computer-assisted, high pressure injection device has the potential to render cement injection procedures safer by offering the possibility to inject high viscous materials with an unprecedented level of control. A better repeatability and documentation is achieved by monitoring and logging of relevant injection parameters, which also paves the way for statistical identification of parameters leading to complications (e.g. too low viscosity). At last but not least, the device can help lowering costs by utilizing traditional syringes as disposable material containers.

**References**


Computer aided 
hip resurfacing arthroplasty

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Introduction: There has been a renewed interest in hip resurfacing arthroplasties following successful outcome studies in both Europe and the United States. The technique has been applied to the difficult problem of the younger, more active individual, in whom long term follow up studies with conventional total hip arthroplasties have shown higher rates of failure than in their traditional older and lower demand counterparts. Limited follow up reports of this procedure have highlighted femoral neck notching, and varus positioning, as the two largest sources of preventable early implant failure. To address these and other alignment issues, we have developed a CT based computer planning and intra-operative assist technique that allows for pre-operative templating, intra-operative registration, and tracking of the component.

Methods: All patients undergo a preoperative CT scan of the pelvis and proximal femur. Virtual templates are then applied, and appropriate component sizes and alignment are chosen. The goal is to insert the femoral component parallel, or in slight valgus, with respect to the anatomic neck. Intra-operatively the proximal femur and pelvis are registered using an imageless digital referencing body system. Using real time CT guidance, the femoral guide is inserted according to the preoperative plan. Appropriate cuts are made and components chosen. On the acetabular side, the planned diameter of reaming is performed and computer guided placement can be used.

Discussion: This procedure has been performed on sixteen hips, with no early complications. Both the posterior and anterolateral approach have been used. In all cases the pre-operative sizing was confirmed intra-operatively, and applied. The pre-operative femoral alignment plan was followed, and allowed accurate placement of the guide pin, and component, despite
variations in proximal femoral anatomy and head shapes. The average pre-operative neck shaft angle was 129 degrees, and the average post-operative component shaft angle was 132 degrees. A Wilcoxon signed ranks test on related samples was performed and showed no significant difference in this early series of 11 hips (p=.21). Lateral images were measured for the distance from the center of the neck to the tip of the stem. In all cases the stem was within 2 mm of this point.

In the largest published North American series to date, Amstutz et. al. reported that their two main modes of femoral component failure were neck fracture and aseptic loosening. Correctible factors that they noted included: Notching the native femoral neck; and component malalignment. They noted an increased rate of femoral component failures in their group with only a seven degree lower component-shaft angle. This computer aided technique addresses both of these concerns.
A multi-purpose computer planning and guidance system is used. It can be adapted to both CT and fluoroscopic based imaging. Previous publications have described its benefit for other complex multi-dimensional corrective orthopaedic procedures.

The resurfacing arthroplasty option is now being applied to a younger and more active patient population. Their higher physical demands, over extended follow up periods will leave little room for error. An accurate system of pre-operative templating, and intra-operative guidance is a valuable and necessary addition to this technically demanding procedure.

References

Short term clinical follow-up comparing rotating vs. fixed bearing navigated TKR

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Introduction: Mobile and fixed bearing in TKR are still discussed controversially. Both types of prosthesis show excellent clinical 10-year-survival rates of up to 95%.

Comparative studies could not demonstrate the superiority of one or the other design. As Computer Assisted Surgery (CAS) systems allow a precise gap measurement and stress analysis and have attracted more and more interest over the past years, it was aim of the current prospective matched pair study to elucidate whether there are differences for as well subjective as objective criteria between CAS TKR for mobile and fixed bearings after two years.

Methods: In a retrospective matched-pair analysis we investigated 40 patients. Demographic data where identical in both groups. 20 patients received a cruciate retaining PFC Sigma® total knee prosthesis (DePuy®, Warzwa USA) with fixed bearing and 20 patients with a mobile bearing within a computer assisted implantation (VectorVision®, BrainLAB®, Munich Germany).

Two years after TKR all patients took part within a clinical follow up. From all patients the Western Ontario and McMaster’s Universities Osteoarthritis Index (WOMAC) as well as the Knee Society Score was obtained. We performed standardised fluoroscopic assisted stress radiography to test varus-valgus stability in extension with equal medial and lateral force of 15 N (Telos®, Marburg, Germany, SE 2000) and 80 degrees flexion according to the established technique described by Stähelin.

Moreover, each patient was investigated according to a standardized measurement using an isokinetic muscle force protocol with 60°/sec. and
180°/s (Biodex™-3 dynamometer; Biodex Medical Systems, Inc., New York, USA).

Statistical analysis was performed using the paired Student T-Test and Box plots.

**Results:** WOMAC Score: WOMAC Score showed no different values for both study groups (RP: 23.05, SD: ±15.0; 22.57, SD: ±18.5).

We found nearly identical values as well for the Knee Score (RP: 83.14 SD: ±11.7; fixed: 86.5, SD: ±9) as the Function Score (RP: 91.6, SD: ±13.02; fixed: 89.52, SD: ±12.53) and the Total Knee Society Score (RP: 174.88, SD: ±23.83; fixed: 176.09, SD: ±16.52).

Biodex® measurement showed statistically significant values for isokinetic muscle force in flexion as well for 180°/s RPflex180: 52.83 Nm, SD: ±13.96; fixed flex180: 46.3 Nm, SD: ±16.76; p=0.01 and 60°/s. RPflex60: 68.62 Nm, SD: ±23.26; fixed flex60: 58.22 Nm, SD: ±23.43, p=0.004. Extension values were not statistically significant. RPext180: 56.32 Nm, SD: ±18.16; fixed ext180: 51.56 Nm, SD: ±19.36. RPext60: 84.09 Nm, SD: ±29.58; fixed ext60: 76.87, SD: ±28.16.

We found statistically better values for the RP group except in flexion for valgus stress. In extension we found for varus stress RPvarus: 2.4°, SD: ±1.2°; fixed varus: 4.1°, SD: ±1.2°; p=0.001. Values for valgus stress in extension revealed: RP valgus: 2.0°, SD: ±1.4°; fixed valgus: 3.0°, SD: ±1.3°; p=0.01.

Lateral opening with varus stress showed following values: RP varus: 3.4°, SD: ±1.8°; fixed varus: 5.9°, SD: ±3.2°; p=0.007, concerning medial opening with valgus stress no statistically values could be detected: RP valgus: 3.1°, SD: ±1.4°; fixed valgus: 4.0°; SD: ±1.5°; p=0.1.

**Discussion:** In comparing the data of fixed vs. mobile bearing in our series we found no differences between both groups for Knee Society Score. Woolson and co-workers also did not find significant differences as well as Ranawat in a recent study comparing rotating-platform and fixed-bearing in the same patient. They could not detect any radiological loosening of prosthesis. Although we did only fluoroscopic imaging for stress testing, we could not find any early radiolucent lines or loosening of prosthesis. A large multicenter study coordinated by Price et al. could demonstrate only a small statistically significant superiority of the mobile bearing prosthesis concerning the Knee Society Score. Focussing on the ROM they found no difference between both groups. Kim et al investigated 116 patients with simultaneously bilateral TKR (fixed and mobile bearing) in one patient. After
a minimum follow-up of 6 years there were no statistically significant differences for one or the other design regarding ROM, Knee Score, Pain Score and patient satisfaction. In our series we found no statistically evident differences concerning ROM in Flexion for both groups (p=0.08). Mean ROM in the RP group was 107° for flexion (SD 25.4°) and 112° (SD 14.5°) in the fixed bearing group. In our study we measured patient satisfaction with the WOMAC-Score, which focuses on pain, stiffness of the joint and function. We found for both groups nearly similar values for as well the three subgroups as the total WOMAC Score (RP: 23.06; fixed: 22.57). This demonstrates that in our series no type of design is superior to the other in regard of subjective patient parameters.

We could show in the current study that there are no statistically significant differences for two-year follow-up results between rotating platform and fixed platform in computer assisted TKR concerning WOMAC and Knee Society Score and Biodex® measurement. Except ligamentous stability was better in patients with rotating platform as well in extension and in flexion.

References

The effect of sequential soft tissue release in TKR – A computer aided model

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Introduction: The cornerstone of total knee replacement is to achieve a stable, well aligned knee over the full range of movement with symmetrical extension and flexion gaps. Numerous ligament balancing techniques and soft tissue release sequences have been published, which are still discussed controversially.

Recently, computer assisted surgery has been introduced in TKR and allows highly precise intraoperative angular and tibiofemoral gap measurements.

In this in vitro cadaver study we proposed to elucidate the relationship between a standardized sequential medial soft tissue release, the resulting a.p. leg axis after total knee replacement and the resulting change of the medial and lateral tibiofemoral gap in extension and flexion.

Materials and Methods: We used 10 fresh, not formalin fixed anatomic full body cadavers for our testing. All legs were without deformities, without previous operations concerning ipsilateral foot, knee and hip, but full range of movement of the ipsilateral hip and knee. The navigation system used in this study was Ci® CT-free navigation system (DePuy® I-Orthopaedics, Munich, Germany).

Surgical technique: Knee replacement surgery was performed using the PFC Sigma® standard specialist-2® instruments (DePuy, Int. Ltd., Leeds, UK). A first navigation controlled measuring of the physiological a.p. leg alignment as well in extension as in 90 degrees flexion was carried out and taken as reference. After implanting the trial component in the CAS technique the coronal angulation in full extension and 90° flexion was visualized by the
navigation system before any soft tissue release. After each release step, the surgeon removed the trial components and used a tensor device (Balansys®, Mathys®, Bern, Switzerland) which was set to 150 N in extension and 90N in flexion, to measure the coronal angle. The ligament release technique was carried out according to the recommendation of Matsueda et al. (1999) (1).

Statistical analysis was performed using the unpaired T-Test and Box and whisker plots.

**Results**: The difference of the a.p. limb axis for each release step was statistically significant as well for full extension and for 90° flexion (p<0.001). After the 6 cm release and release of the MCL the increase of coronal angle was found to be strongest in contrast to the previous release step (6 cm: range: 1.2° – 3.7°, p<0.0001; MCL: range: 1° – 3°, p<0.0001). Massive changes in the coronal angles were found in 90° flexion for the 6 cm release (1.5° – 5.9, p<0.0001), the release of MCL (1.1° – 5.7°, p<0.0001) and the release of the entire PCL (1.1° – 3.5°, p<0.0001).

For the medial gap we found significant progression in the gap distance for each release step except the 4 cm release. In extension the highest increase compared to the previous release step was found for the 6 cm release (0.7-1.5mm, p<0.0001) and the release of the entire cruciate ligament (2-2.7mm, p<0.0001).

In 90° flexion all differences of the release steps were statistically significant (p<0.0001). Massive progression of the medial gap in flexion was found after the 6cm release (1.1 – 2.4 mm, mean 1.2 mm, p<0.0001), the release of the medial half of the posterior cruciate ligament (2.3 – 2.7mm, mean 2.5 mm, p<0.0001) and the release of the entire posterior cruciate ligament (4.3 – 4.5 mm, mean 4.4 mm, p<0.004).

Only little increase of the lateral tibiofemoral gap was seen during the release sequence for extension and flexion. Mean overall changes (before release to release of the entire PCL) was 2.3 mm in extension and 2.3 mm in 90° flexion. After release of the entire PCL the lateral gap opened only 0.1 mm compared to the previous release step.

**Discussion**: The current literature delivers many reports about different soft tissue releases, their necessity and the clinical results of different techniques, but lacks experimental setups dealing with this matter. Only some papers have been published focussing on the relationship between different soft tissue release techniques and their influence on the leg axis and the correction of deformity.
In our study the release of the entire posterior cruciate ligament resulted in a significant increase of the flexion gap (mean 4.4 mm compared to the previous release step) as in extension (mean 2.5 mm compared to the previous release step). This supports the findings of Krackow et al. (2) who reported that a sacrifice of the PCL led to a 4 mm increase of the flexion gap, but only little average increase for the extension gap of the same knee. In a magnetic resonance imaging study Freeman could show the behaviour of PCL in Flexion and Extension. His findings strengthens the hypothesis that PCL is tightened in 90° flexion but not in full extension. In a cadaver study Mihalko et al. (3) could demonstrate a similar effect. They found a significantly larger flexion gap than extension gap after releasing the PCL.

In the current cadaver study we could show the significant sequential increase of a defined medial soft tissue release sequence. To our knowledge this is the first study using a common navigation system for measuring as well a.p. limb axis and changes of the tibiofemoral gaps. The highest influence on the leg axis has the 6 cm release and the release of MCL in extension and the release of MCL and entire PCL in 90° flexion. Equal findings have been made for increase of the medial tibiofemoral gap: the 6 cm release and the release of the PCL result in the highest change of gap size, whereas flexion gap is superior to extension gap.

References
Influence of everted and subluxed patella in ligament balancing of TKR

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Introduction: Total knee arthroplasty (TKA) has proved to be a reliable treatment of primary and secondary osteoarthritis of the knee with a highly satisfactory outcome in more than 80 percent of patients. Recently, computer assisted surgery has been introduced in TKA. These systems provide the opportunity to improve the accuracy of component orientation and restoration of the mechanical limb axis. Using the computer aided technique, intraoperative angular and distance measurements have become available with an accuracy of less than one degree or one millimeter.

A cornerstone of TKR is soft tissue handling. The ligament balancing is responsible for stability of the implanted prosthesis over the full range of motion and proposed to have great influence on the long term results. For positioning ligament balancing tools, patella has to be either everted or subluxed.

It was therefore the aim of this study to determine the influence of everted and subluxed patella to the a.p. leg alignment 1) in extension and 2) in 90 degrees flexion under control of navigation and compare the findings.

Methods: In a cadaver specimen experiment we investigated subvastus, midvastus and medial parapatellar approach as standard approaches in TKA. The navigation system used in this study was Ci® CT-free navigation system (BrainLAB®/DePuy®, Munich, Germany/Warshaw, USA), which is based on an optical tracking unit and infrared light.

All knees were from full body cadavers which were not formalin fixed and not older than 36 hours. Inclusion criteria was preoperative leg alignment in
between plus/minus 3 degrees varus-valgus, full range of movement of the ipsilateral hip and the operated knee, no previous operations of the operated leg, absence of osteoarthritis in the patient history.

After median skin incision two reference arrays with passive marker spheres were rigidly attached to the femoral and the tibial bone. A first navigation controlled measuring of the physiological a.p. leg alignment as well in extension as in 90 degrees flexion was carried out. Then subvastus, midvastus or medial parapatellar approach, but no further soft tissue release were performed in five knees each. Resection of distal and dorsal femur and tibia was performed with use of navigation. Then each leg was brought to full extension and patella was first subluxed. A tensor device (Balansys®, Mathys®, Bern, Switzerland) was put into the extension gap and spreaded with 150 N for as well the medial as the lateral compartment. Then the leg axis was measured by the navigation system. Similar setup was used in all cases. The same procedure was carried out with patella everted. In a second step, the knees were flexed to 90 degrees and measuring was done again with subluxed and everted patella and the spreader set to 90 N in flexion according to the recommendation from Mathys®, Bern, Switzerland. The difference from the physiological situation was digitized and deviation from the previous position was calculated.

**Results:** With everted patella, the difference of leg axis compared to physiological situation was as follows: Subvastus approach: Plus 1.02 degrees (SD 0.53°) valgus, midvastus approach: Plus 1.7 degrees (SD 0.33°) valgus, medial parapatellar approach: Plus 2.88 degrees (SD 0.37°) valgus.

Performing the approaches with subluxed patella in extension, the deviation from the physiological situation showed less valgization than everted patella: subvastus approach: Plus 0.42 degrees (SD 0.29°) valgus, midvastus approach: Plus 1.16 degrees (SD 0.27°) valgus, medial parapatellar approach: Plus 2.28 degrees (SD 0.46°) valgus.

In 90 degrees flexion the subluxed patella led to a nearly equal valgization as in full extension. Subvastus approch: Plus 0.44 degrees (SD 0.3°) valgus, midvastus approach: Plus 1.5 degrees (SD 0.68°) valgus, medial parapatellar approach: Plus 2.68 degrees (0.43°) valgus.

For everted patella in a 90 degrees flexed knee resulted these findings: Subvastus approach: Plus 1.02 degrees (0.58°) valgus, midvastus approach: Plus 1.96 degrees (SD 0.61) valgus, medial parapatellar approach: Plus 3.06 degrees (SD 0.41°) valgus.
Discussion: To the best of our knowledge this is the first navigation controlled study to assess the different influence of everted and subluxed patella during ligament balancing in total knee arthroplasty. Most articles attempting to describe the balancing techniques to gain a stable and perfectly balanced knee, lack a systematic schedule for treating patella during soft tissue handling. As our results demonstrate, the everted patella influences the ligament tension of the medial and lateral collateral ligament as well in full extension as in flexion and the a.p. leg axis deviates towards valgus direction. If the surgeon everts the patella and relies on this falsified situation, rotation of femoral component might be incorrect and lead to further problems within the patellofemoral joint.

Our findings demonstrate that an everted patella leads to a stronger deviation of the leg axis to valgus direction as well in full extension as in 90 degrees flexion compared to patella subluxed. These findings lead to the hypothesis that ligament balancing should be carried out with patella subluxed. With everted patella the leg axis in extension tends to plus 1,02 degrees valgus. This effect increases to plus 2,88 degrees in medial parapatellar approach. Compared to subluxed patella, this effect is amplified to about 0,5 degrees as well in extension as in 90 degrees flexion. Although this seems to be only a slight difference, this issue may falsify the release steps in soft tissue management and strengthens other slight imperfections in achieving a stable and well aligned knee arthroplasty. In addition the goal of sufficiently balanced and aligned knee may fail.

According to our cadaveric study, ligament balancing should be carried out with subluxed patella to avoid further valgus deviation of a.p. leg axis through the medial pressure of everted patella. The surgeon has to keep in mind the different influence of subluxed and everted patella and that they are dominant in medial parapatellar approach. When using ligament situation to rotate femoral component instead of bony landmarks the patella influence has to be carefully considered during surgery.
Short-term clinical results of image-guided periacetabular osteotomy

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Introduction: Periacetabular osteotomy (PAO) is a joint-preserving treatment for the correction of acetabular dysplasia. Several different types of PAO have been described in the literature, and in general, it is considered a difficult procedure to perform. Recently described variations of PAO \cite{1,2} using a transtrochanteric approach are possibly easier to perform because the approach is familiar to most adult hip surgeons and provides full visualization of the posterior column and acetabulum. This abstract describes the short-term clinical results of computer-assisted Kingston PAO.

Methods: Adult patients with symptomatic acetabular dysplasia were considered for PAO. Preoperative radiographs and CT scans were obtained; patients with significant degenerative changes were excluded from the study. Twenty-two procedures on twenty-one patients have been performed since May 2001. Perioperative data on correction, complications, clinical outcome measures (WOMAC and SF36), and radiographs were collected for all patients. A total of fifteen patients are scheduled for one-year postoperative CT scanning before the CAOS symposium; we hope to present an analysis of these scans in a separate abstract.

The Kingston PAO was previously described by Mayman \cite{1}; we briefly review the procedure here. A computer model of the pelvis was generated from a CT scan for planning purposes. Intraoperatively, an osteotomy of the greater trochanter was performed to enhance the anterior exposure. The superior pubic rami osteotomy was performed conventionally using fluoroscopic guidance. The posterior and superior osteotomies were performed using image guidance. The pelvis was registered to the computer model using shape-based registration, and the osteotomies were marked using Steinmann pins drilled under image guidance. The acetabular fragment was
rotated into the corrected position and fixed with pelvic reconstruction plates. We do not currently track the acetabular fragment because of the difficulty attaching a reference body to the fragment and maintaining line-of-sight between the tracking system and reference body while the fragment is manipulated.

**Results:** The registration produced guidance that was clearly incorrect in one case and the procedure was completed using fluoroscopic guidance; all other cases were successfully performed using image guidance. Two cases of trochanteric pull-off were revised without complication. In one case, a delayed union of the pubic rami osteotomy was bone grafted after which it healed normally. One case of radiographic, but not clinical, heterotropic ossification occurred in a patient with contraindication to prophylaxis.

We had available preoperative and postoperative (one year or more) center-edge (CE) angles from weight-bearing X-rays for twelve cases. The average CE angle was 13 degrees preoperatively (range -10 to 22) and 29 degrees postoperatively (range 6 to 40). The average increase in CE angle was 16 degrees (range 0 to 24). A complete set of preoperative measurements will be available for the CAOS symposium.

We were able to measure postoperative (one year or more) CE angles for twenty cases (including the ones from the previous paragraph). The average CE angle was 28 degrees (range 6 to 40).

We have been able to follow nine patients out to two-years postoperative. At two-years, their average raw WOMAC score was 27.9 (range 4-55), and their average SF36 physical component score (SF36PCS) was 47.3 (range 22-71). Four patients had improved WOMAC and SF36PCS scores compared to preoperative scores; the average improvement in WOMAC was 26.8 (6, 26, 26, and 49) and the average improvement in SF36PCS was 22.3 (7, 13, 31, and 38). One patient had improved WOMAC (from 58 to 39) but worsened SF36PCS (from 49 to 35); this patient was recovering from a PAO on the other hip during this two-year period, which would affect the quality of life scores. One patient had worsened WOMAC (from 33 to 41) but improved SF36PCS (from 36 to 43). One patient had worsened WOMAC (from 45 to 55) and SF36PCS (from 27 to 22) scores. Two patients had no preoperative scores; their two-year WOMAC scores were 11 and 29, and their two-year SF36PCS scores were 32 and 59.

**Discussion:** The one case where both quality of life scores declined occurred in a patient with poor preoperative quality of life scores; this was consistent with Ko [2] who found poor preoperative function to be the only factor they studied that was associated with poor outcome. The use of image guidance
was especially helpful during the first several cases. The transtrochanteric approach allows an experienced hip surgeon to perform the osteotomy under direct visualization even if image guidance fails. This advantage is offset by the need for a trochanteric osteotomy and a large incision compared to a Ganz osteotomy. We are investigating ways of tracking the acetabular fragment relative to the femur and pelvis. This might allow us to follow the preoperative plan with greater accuracy and to confirm adequate coverage of the femoral head.

References


One-year clinical results of image-guided and conventional Oxford unicompartmental knee replacement

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Introduction: Several research groups have provided evidence that image-guided techniques can improve the implantation accuracy of unicompartmental knee prostheses but it remains unclear if this increase in accuracy leads to superior clinical results. This abstract describes some results of a prospective study to evaluate quality of life measures for patients who have undergone image-guided and conventional UKR.

Methods: A total of 50 knees have been enrolled in this study that started in January 2003, with 30 knees scheduled to receive image-guided UKR and 20 knees scheduled for conventional UKR. We used the Biomet Oxford Phase 3 UKR prosthesis, and the surgeries were performed by a surgeon familiar with the prosthesis (Rudan). The image-guided cases were performed using the Fluoroguide system (IGO Technologies; Kingston, Ontario, Canada). The surgical protocol was described in [1], and a brief summary is provided here. The Fluoroguide system uses a tracked and calibrated fluoroscope to provide navigational information. A tracked reference body was fixed to the distal femur. AP fluoroscopic images were taken of the proximal and distal ends of the femur, and a lateral image was taken of the distal end. The leg was positioned 90 degrees in flexion and holes for the tibial saw-guide nails were drilled using a tracked and calibrated surgical drill; the axis of the drill was superimposed on the AP and lateral fluoroscopic images for guidance purposes. The standard holes for the femoral cutting guide were drilled; the axis of the drill hole was towards the center of the femoral head in the AP
view and parallel to the cortex in the lateral view. The standard instruments were used to perform the bone cuts.

We collected preoperative and postoperative WOMAC and SF36 surveys at regular intervals. We are scheduling one-year postoperative weight-bearing radiographs for all patients.

**Results:** We anticipate having one-year postoperative results for 15 image-guided and 15 conventional knees before the CAOS symposium. We describe the results we currently have in the remainder of this section.

A total of 7 image-guided and 4 conventional knees have had the femoral component alignment measured on postoperative weight-bearing radiographs by an observer blinded to the type (image-guided or conventional) of surgery performed. The number of measurements is too small to be statistically meaningful but the results were 0 degrees average varus/valgus error (range 5 degrees valgus to 3 degrees varus) and 0 degrees average flexion/extension error (range 6 degrees flexion to 3 degrees extension) for the image-guided cases, and 0 degrees average varus/valgus error (range 3 degrees valgus to 3.5 degrees varus) and 0.5 degrees average flexion error (range 7 degrees flexion to 6.5 degrees extension) for the conventional cases. The measurements were made as shown in the manufacturer’s guide of surgical technique [2]. The alignment of the tibial components are still being measured.

A total of 6 image-guided and 4 conventional cases have one-year WOMAC scores; the average raw WOMAC score was 11 (range 6-20) for the image-guided cases and 17 (range 0-52) for the conventional cases. The average improvement from preoperative was 46 (range 36-59) for the image-guided cases and 34 (range 21-41) for the three of the conventional cases (one patient did not have a preoperative score).

A total of 5 image-guided and 4 conventional knees have one-year SF36 physical component scores; the average raw SF36PCS score was 57 (range 45 – 81) for the image-guided cases and 63 (range 24 – 92) for the conventional cases. The average improvement from preoperative was 20 (range –5 – 40) for the image-guided cases and 23 (range –10 – 53) for the conventional cases.

One case of image-guided surgery required revision of the tibial tray and replacement of the bearing.

**Discussion:** There were no obvious differences between the image-guided and conventional cases performed by an experienced surgeon. The number of cases is still too small to draw statistically meaningful conclusions, but the
number of cases available for analysis will increase between now and the CAOS symposium.

Fluoroscopic image-guidance of UKR is generally easy to perform and requires only one reference body to be fixed to the patient. We prefer this method of guidance to CT-based and morphing-based methods because neither registration nor surface digitization of the bone is required. One possible weakness of our fluoroscopic method is that the location of the components is determined in the conventional fashion, whereas it would be possible to preoperatively plan the component locations using CT-based methods.

References

Stress distribution visualization on pre- and post-operative virtual hip joint

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Introduction: With the increase in computer power, more and more effort is being dedicated for building more realistic computational and graphical models to be used in clinical applications. This effort is important but is not sufficient in itself since clinicians need tools that can effectively help them in performing the regular tasks they are used to perform on biomedical images. Resulting biomedical datasets can be multi-dimensional and are usually very large, which makes them difficult to explore and understand [1]. Therefore there is a need for intuitive representations for end users to deal with this increasing complexity. At the same time, medical images do not describe functional aspects of the patient body that are interesting for diagnosis. For example, in orthopaedics, mechanical parameters like pressure on cartilages and tension on ligaments can be correlated to pain around a joint. To obtain that information, one possible solution is performing a biomechanical simulation of the joint.

In this paper, we present a case study using a spreadsheet-like interface for exploring biomedical datasets generated by a biomechanical model of the hip. The case we analyze here is an osteotomy corrective surgery that reorients the femoral body in relation to the femoral neck, somewhat like the intertrochanteric osteotomy described by Imhäuser [2]. That is a procedure recommended by most authors as a surgical treatment of severe slipped capital femoral epiphysis. Then we compare estimated contact area of the pre- and post-operative hips from a threshold of the computed stress.

Methods: Spreadsheet-like interfaces are a generalization of conventional spreadsheets where cells can contain graphical objects such as images, volumes, or animations or even widgets to interact with data. In this class of
visualization systems, screen space is spent on operands rather than operators, which are usually more interesting to the end user [3]. They also benefit from the fundamental properties of spreadsheets where it is easy to organize, compare, analyze and perform operation on data. Our spreadsheet framework consists basically of: Cells, operators and dependencies. Cells are the basic data elements. They can contain numbers, images, curves, vectors, matrices or widgets for interactive cells. The cells are organized in a tabular layout, which makes them easy to browse. Operators are applied to cells or ranges of cells and define the dependencies between the cells. A firing algorithm controls dependencies as in conventional spreadsheets and automatically updates the cells to reflect changes.

The data we use come from the biomechanical simulation of the human hip joint. Separated software [4], based on a conceptual joint model is used for hip simulation. The model is based on a hybrid approach. A kinematical component defines the bony rigid motion from measures on the static and dynamic MRI, while a biomechanical component computes soft connective tissues deformation, and allows estimating force exchange and consequent stress on those soft structures. Soft parts are discretized such that a generalized mass-spring system can process the deformations. Special considerations had to be taken into account to adapt traditional mass-spring system to medical applications. The most important is the correct biomechanical behavior of the biomaterials. In a previous work [5], we describe how we configure our springs lattice such that our virtual ligaments and cartilages have a predictable elasticity, defined by the Young’s Modulus (E) of the material.

**Results:** A right hip model has then been built to illustrate a use case where the joint congruity is analyzed. The elements present in our hip are: The femur and the pelvis bones; the femoral head and the pelvis cup cartilages; the ischiofemoral ligament; the acetabular rim (labrum). The bones and the labrum are considered rigid, and the elasticity for the cartilages and ligament is defined to be 10 kPa. It is softer than the mean value found in the literature, but it allows our simulation to converge faster, while the stress distribution remains coherent. In addition, fibers orientation is taken into account for the ligament, in a way that it is anisotropic. The motion we performed is 90° of flexion plus total internal rotation, a key motion in orthopaedics.

To simulate the osteotomy operation, we deformed the 3D femur moving the distal extremity internally on the frontal plan, such that the hypothetic patient has to abduct his hip to keep the knee at its place. We represent this abduction as a reorientation of the femoral head – and consequently of the whole femur – such that the new anatomical axis of the femur keeps aligned.
with the original one. Then we applied the same motion on the osteotomized joint that we had applied on the original. We could observe that the stress distribution on the cartilage surfaces, and consequently, the contact areas change.

A template comparing pre- and post-operative virtual hip joint. The contact area is estimated based on the stress calculated on the cartilage surfaces. A stress threshold was defined in A2 and used to determine the contact area on the animation in B2. Other views were derived (C2 and D2) and a graph of the contact area history is shown in E2. The row 2 was then copy-pasted into rows 3 to 5. Rows 2 and 4 represent simulated pre-operative situation for different threshold values. Rows 4 and 5 represent simulated post-operative situation.
Discussion: We present a case study combining our spreadsheet-like interface and our hip joint simulator to analyze the congruency of a 3D virtual hip before and after an osteotomy of Imhäuser.

The geometric data we used come from a healthy patient. Thus, it is normal that analyzing the results we obtained, one can see that the joint congruency was better before the operation. Anyway, the operation we performed has the goal of showing how we can assess the surgery in the planning phase and not actually improve congruency. We believe that with such tools for preliminary surgery planning clinicians to gain time and precision on diagnosis.

References
A computer assisted surgical technique for total knee arthroplasty revision

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Introduction: Total Knee Arthroplasty Revision (TKA Revision) is a skill-demanding intervention due to the complexities that exist after the removal of the failed prosthesis: Bone deficiencies and lack of anatomical references make it difficult to understand the normal knee kinematic and adequately plan the intervention.

On the other side accurate soft tissue balancing, proper restoration of limb alignment and joint line height are necessary to achieve a successful outcome. Since main landmarks are not available, the surgeon uses some secondary parameters that if contemporarily considered provide precise indications for implant positioning.

Using computer assisted navigation systems can be potentially very helpful since they allow the contemporary control of several parameters.

On the other side, most of existing navigated techniques for TKA Revision use navigation systems developed for primary TKA [1] [2], using imprecise data and disregarding those useful indications provided by secondary parameters.

A computer assisted technique for TKA Revision is presented. It is based on the use of a navigation system, RTKANav consisting of a commercial optical localizer (Polaris Northern Digital Inc.), a dedicated software specifically done for TKA Revision and some navigated tools developed for this application. Qualitative early results obtained using this navigated technique on two patients by an expert surgeon are reported.

Methods: The surgery starts performing surgical incision and fixing navigation markers to the femur and the tibia.
After prosthesis removal, the surgeon detects several anatomical landmarks (12 points) for the computer system to construct the 3-dimensional representation of the patient’s lower limb, by registering in space critical biomechanical landmarks.

After reaming the medullary canal of both tibia and femur, two dedicated navigated tools developed to acquire the canals directions are inserted into the bones. These tools are made of two main parts: A plane with a rod in the middle reproducing the relationship between the component distal cutting plane and its stem (i.e. perpendicular in the tibial tool and 85° lateral in the femoral one). Positioning these tools with the rod inside the canals and with the plane tangent to the most prominent point of each bone, provide the system with information on the distal femoral cut and tibial cut orientations and allows the surgeon to correctly position the two cutting guides. The appropriate cutting level is determined by the surgeon through the analysis of the bone quality.

On the system interface, the patient anatomy model is represented with dots and lines corresponding to the acquired landmarks and data derived from it (femoral and tibial mechanical axes, transepicondylar line); angles between the mechanical axes can be controlled and monitored at any time.

To correctly perform soft tissue balance, space between the tibial navigated plane and the femoral one with the knee in extension (extension space) and the distance between the tibial navigated plane and the femoral stem insertion (flexion space) with the ligament correctly tightened are estimated using a custom-made spacer. During these acquisitions, graphical tools indicate to the surgeon if the current gap is rectangular or not allowing him to estimate the possible need of ligament release. Moreover, during flexion space acquisition the actual relationship between the femoral component position and the transepicondylar line is reported; this way the surgeon can choose the surgical technique he prefers to adopt to determine correct intra-extra rotation of the femoral component.

Once the two spaces have been acquired, the planning phase begins.

Even if during acquisition phase some specific points cannot be identified (e.g. one or both the epicondyles), since for each prosthetic component several criteria to set each degree of freedom are considered and compared, the system is always able to suggest an intervention plan.

A range of acceptability for the joint line level is determined related to the medial and lateral epicondyle height, the patella pole and the fibular head. The final joint line height is set considering the determined interval and the
measured extension space, providing also indications about the tibial polyethylene insert size and if any femoral augmentation is needed. The IE rotation of the femoral component is set considering the transepicondylar line or the femoral neck axis and the flexion space. The femoral components size is determined considering the prosthesis properties, the distance between the navigated stem and the anterior femoral shaft and the flexion space. On tibial side, the component size is set considering the estimation of the tibial plateau done through points acquisition; IE rotation is determined related to the tibial tuberosity position.

The system provides the surgeon with tools to analyze and modify the proposed plan monitoring the behavior of the residual joint gap in flexion and in extension.

Once refined the intervention plan, the system provides the surgeon with tools to navigate the cutting guides to reproduce the plan on the patient. The final position of the tibial and femoral implants can be checked by displaying the postoperative leg alignment and residual joint gap.

**Results:** Till now the presented technique was used on two patients by an expert surgeon. Qualitative results on surgeons’ feelings were collected through a questionnaire after the intervention. System automatic planning showed to be very satisfactory for the surgeon on the femoral side and not very reliable on the tibial side concerning the component size. Implemented criteria to assess the need of ligament release and the possibility to check different implant solutions monitoring several parameters, especially the residual joint gap in flexion and in extension were considered crucial for a successful outcome. Final limb alignment evaluated with postoperative X-rays, was satisfactory in both cases.

**Discussion:** A computer assisted technique based on the use of a navigation system specifically done for TKA Revision was presented. Computer guidance showed early promising results providing the surgeon with useful indications to achieve a satisfactory prosthesis implant. Future works concern system validation assessing system accuracy and comparing the navigated technique with the traditional one.

**References**

Ankle tortion would cause varus alignment of the tibia using extramedullary guide in total knee arthroplasty: The necessity of computer navigation system

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**Introduction**: Proper lower extremity alignment is an important factor for the long-term success of total knee arthroplasty (TKA). It has been reported that varus malalignment is associated with higher failure rates and positioning of femoral and tibial components should be in less than 3 degrees of error. Surgeons use intramedullary and extramedullary alignment guide (conventional methods) to obtain the correct alignment, however, some authors reported cutting the tibia in varus malalignment is common with extramedullary alignment guide. One of the disadvantages of using extramedullary alignment guide is that the alignment is easily affected by the ankle joint condition. Since the distal tibia has external torsion, there is rotational mismatch between the proximal tibia and the distal tibia (ankle joint). We hypothesized that this rotational mismatch would cause malalignment. Even if the distal end of the guide is placed right front of the center of the ankle joint, the position of the guide would be lateralized when the distal tibia is externally rotated. This study evaluated the effect of the rotational mismatch between the proximal tibia and the ankle joint on predicted postoperative coronal alignment of the tibia, in order to clarify the limitation of the accuracy of the extramedullary guide.

**Methods**: Thirty-four osteoarthritic knees with varus deformity in 33 patients who were evaluated using CT scans before TKA. We informed them the risk
of exposure to radiation and spending time for this study, and informed consent was obtained. They had no history of surgery and flexion deformities were 10 degrees or less to avoid an error of the measurement from malpositioning of the knee. The study group consisted of 6 men and 27 women. Twenty-nine patients had osteoarthritis, and five patients had rheumatoid arthritis. The mean patient age was 73.4 ± 6.7 (60 – 84) years. The mean maximum flexion angle was 112.2 ± 28.1 (40 – 140) degrees. Scanning direction was aligned to be perpendicular to the fixed tibial shaft axis. CT scans were taken at the knee and the ankle joints with 2 mm thickness. We analyzed the CT scans data by reconstructing three-dimensional bone using the computer software (Real INTAGE Ver.2.0, KGT, Inc. Tokyo). The anteroposterior (AP) axis of the ankle joint was defined as the line perpendicular to the anterior cortex of the talus that was approximately straight line. The slice level of the proximal tibia was selected at 8 mm distal level from the lateral tibial plateau. Five different AP axes of the proximal tibia were evaluated. The axis 1 was connecting the posterior notch and the medial border of the patellar tendon and the axis 2 was connecting the posterior notch and the medial 1/3 of the patellar tendon. The clinical epicondylar axis (CEA) was defined as a line connecting the most prominent point of the medial and lateral epicondyle of the femur, and the longest parallel line to the CEA was drawn on the proximal tibia. The axis 3 was perpendicular to the longest parallel line to the CEA and passed the midpoint of the parallel line. The axis 4 was connecting the midpoint of the longest parallel line to the CEA and the medial border of the patellar tendon. The axis 5 was connecting the midpoint of the longest parallel line to the CEA and the medial 1/3 of the patellar tendon. With using these five axes of the proximal tibia, we measured the difference of the rotational angle (the twisting angle) between the AP axis of the ankle joint and the AP axis of the proximal tibia (+: AP axis of the ankle joint where external rotation angle compared to the AP axis of the proximal tibia). We established spatial coordinates to evaluate the effect of the twisting angle on predicted postoperative coronal alignment of the tibia. The presumed tibial alignment was calculated when the extramedullary guide was used with these AP axes (five axes of the proximal tibia and one axis of the ankle joint). The distal end of the extramedullary guide was placed in front of the center of the ankle joint (on the line of the extended AP axis of the ankle joint), and the proximal end was placed on the line of the extended AP axis of the proximal tibia, while the guide was parallel to the tibial mechanical axis in the sagittal plane. The twisting angle, and the predicted tibial coronal alignment was calculated in both cases when the tibia is cut with or without 7 degrees of posterior slope.
Table 1

<table>
<thead>
<tr>
<th>Tibial AP axis (external rot.)</th>
<th>Twisting angle 7 degrees slope</th>
<th>Varus alignment 0 degrees slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 17.7 ± 7.5 (1.0–32.0)</td>
<td>4.6 ± 1.9 (0.2–8.2)</td>
<td>2.5 ± 1.1 (0.1–4.6)</td>
</tr>
<tr>
<td>(2) 8.9 ± 7.7 (-10.0–24.0)</td>
<td>2.3 ± 2.0 (-2.6–6.3)</td>
<td>1.3 ± 1.1 (-1.4–3.5)</td>
</tr>
<tr>
<td>(3) 3.3 ± 7.6 (-16.0–16.0)</td>
<td>0.9 ± 2.0 (-4.3–4.3)</td>
<td>0.5 ± 1.1 (-2.4–2.4)</td>
</tr>
<tr>
<td>(4) 18.5 ± 6.7 (-4.0–30.0)</td>
<td>4.9 ± 1.8 (-1.1–8.1)</td>
<td>2.7 ± 1.0 (-0.6–4.7)</td>
</tr>
<tr>
<td>(5) 4.9 ± 6.9 (-17.0–15.0)</td>
<td>1.3 ± 1.7 (-4.7–4.1)</td>
<td>0.7 ± 1.0 (-2.6–2.3)</td>
</tr>
</tbody>
</table>

Results: The twisting angle and the predicted tibial coronal alignment were shown in Table 1. The twisting angle was all positive in all axes, which means the ankle joint was externally rotated compared to the proximal tibia in the AP axes of the proximal tibia. The predicted tibial coronal alignment was all varus alignment in all axes. The twisting angle and the predicted tibial coronal alignment was smallest with the AP axis 3, which was perpendicular to the longest parallel line to CEA and passed the midpoint of it.

Discussion: The results of this study suggest that varus alignment could occur due to the rotational mismatch between all the proximal tibia and ankle joints even when the distal end of extramedullary guide was correctly placed adapting to the AP axis of ankle. It is almost impossible to accurately detect the 3-D center of the ankle joint intraoperatively, and this is the limitation of the extramedullary guide. The use of the navigation system would overcome the shortcoming of the conventional alignment rod method.
Special demands for pedicle screw insertion in dynamic stabilization of the lumbar spine. Clinical accuracy of manual technique – CT based navigation technique and fluoroscopic navigation technique

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Introduction: Misplacement of pedicle is associated with potential risks, like iatrogenic damage to neurological structures or failure of biomechanical stability and well known to a different extent dependent on spinal level, experience and surgery technique. In spinal fusion systems the dorsal implant has no more function after bony fusion or cage in growth. In contrast the demand on biomechanical stability an optimal screw position is much higher in dynamic dorsal spinal stabilization systems. Because of the designated segmental movement on the one hand and expected long-term endurance of the systems there is a higher demand in screw position.

For fusion systems different studies could show that pedicle screws were applied more accurately and safely by using a computer-assisted surgery system than by operating without navigation support. The classification of accuracy of screw placement in these studies are focused to pedicle perforation and neurological complications. For a dynamic spinal implant, with a higher demand to the biomechanical long-term stability, additional factors of screw position are important.

Methods: We performed in 29 patients a dynamic stabilization of the lumbar spine using the Dynesys™ Spinal System (Zimmer, Warsaw). In each patient preoperative CT scan with pedicle parallel reconstruction was available. 44 pedicle screws were inserted manually, 46 with fluoro-navigation, 40 with...
CT based navigation. Each screw position was checked postoperatively using CT scan with multiplanar reconstruction. The graduation of misplacement was classified considering correct entrance point, intrapedicular position, cortical perforation, convergence and contact to facet joint. Intraoperative control of pedicle awling and screw placement with fluoroscopy in lateral view was used for all cases.

**Results:** There were no neurological complications related to the screws position and no significant misplacement of the inserted screws in all groups. In the navigated cases there was no pedicle perforation over 2 mm, in the manual group 2. The overall placement in our own classification related to the dynamic system was better in the navigated cases with a slight benefit for CT based navigation. A statistical difference was not observed between the different groups concerning mean operation time and blood loss. Intraoperative X-ray exposure was less in the navigation groups.

**Discussion:** The study demonstrated that pedicle screws are inserted more safely and accurately with computer navigation, comparable to results of navigated fusion systems. The tendency for better results for CT based navigation may improve the results especially in dynamic stabilization systems in the lumbar spine, more than in fusion systems. The technical investment and intraoperative work is higher in fluoro-navigation than in CT based. So in all cases the CT data are available we prefer CT based navigation with a real 3-D control of screw placement. To what extent the higher accuracy with navigation can improve the mid- and long-term results of dynamic stabilization systems for the lumbar spine must be proven in further monitoring of these patients.

**References**

Non image based navigation for minimal invasive THR – A feasibility study of cup ans tem navigation

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Introduction: Different techniques are described for minimally invasive techniques for total joint replacement. Less muscular trauma is expected and should lead to less pain, less functional disturbance and faster rehabilitation. Nevertheless reduced overview and higher intraoperative soft tissue tension may lead to worse implant position than in conventional approaches. A tendency to vertical cup placement and eccentric reaming of the acetabulum is reported. The excellent results of conventional THR should not be risked using minimal invasive approaches.

Therefore promising results in navigated conventional THR, reported from different groups with image based and non-image based navigation systems, may improve minimal invasive THR and prevent approach related pitfalls. A real 3-D registration of the acetabulum and femur with fluoroscopy is limited. Anatomically based non-image based navigation seems to be more suggestive.

Methods: We did a feasibility study using a well-established non-image based navigation system for conventional THR in supine position, for minimally invasive THR in lateral position with the standard navigation instruments.

A pelvic reference coordinate system was digitized in flip technique, which means digitizing necessary points in supine position after fixing the pelvic reference base, and turn the patient in lateral position afterwards. All relevant data for control of the center of rotation, cup inclination and anteversion, leg length and stem position are acquired intraoperatively by probing anatomical landmarks and surfaces.

We used an anterolateral approach (OCM-approach), a cementless anatomical adapted stem (Optan, Zimmer, Warsaw, Indiana) an alternative
was a pressfit cup (Trilogy, Zimmer, Warsaw, Indiana) and in 3 cases a screwing cup (ACA, Zimmer, Warsaw, Indiana). For navigation the standard navigation instruments were used.

**Results:** Component placement under navigation control was possible in all cases and improved the results especially in restoration of center of rotation and cup position in comparison to our conventional experience with this minimally invasive approach additional surgery time is about 20 minutes.

Leg length control in lateral position was very accurate using the navigation system. For stem positioning the benefit was not so relevant using the quiet benign anatomical adapted stem system. No navigation related complication has been observed. Instrument adaptation is not necessary but desirable.

**Discussion:** Minimally invasive THR is more and more common. The reduce overview and especially in lateral position, intraoperative control of component positioning is limited and potentially leads to non optimal implant position with bad function and early loosening.

Reliable and reproducible cup and stem positioning with navigation is reported in different studies for conventional and MIS approaches. The combination of the two innovative procedures are suitable. CT based navigation systems give real 3D information, but they are time-consuming and expensive and not necessary for standard THR. Fluoro-navigation for minimally invasive THR is in our opinion elaborate and dependent on accuracy of exact plane of acquired X-rays. The easy to use non-image based navigation gives good information about instrument position during bone preparation and implant positioning and improves implant position in reduced overview in MIS THR. Influence of functional outcome and long-term results are still absent.

**References**

Navigation guided high tibial osteotomy (HTO) – is it worth the effort?

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Introduction: High tibial osteotomy is an acknowledged surgical procedure in the treatment and prevention of unicompartamental (medial) osteoarthritis of the knee worth to think of even having in mind the good results of knee arthroplasty. It is well known that long term results of high tibial osteotomy depend strongly on quality of correction (postoperative leg alignment) and accuracy of surgical procedure. Unfortunately planning based on full-leg X-rays is both difficult and not exact due to problems like extension deficit and malposition of the leg. Intraoperative correction is also poorly quantifiable with procedures like the cable-method. Therefore this study should investigate whether navigation is suitable for solving these problems.

Methods: Between June 2003 and January 2005 we performed 27 high tibial osteotomies in open wedge technique with plate osteosynthesis. Preoperative planning was based on plain knee and full leg X-rays, surgery aimed at a postoperative valgus of 3 degrees, this is to bring the load line of the leg to the so called Fujisawa-point slightly lateral to the eminentia intercondylica. For intraoperative measure the orthopilot-system (Aesculap) was used. This system is based on CT-free infrared acquisition of kinematic joint centers (hip, knee, ankle) and percutaneous palpation of different landmarks. Two additional stab-incisions for fixation of two rigid bodies (femoral and tibial) are necessary. Surgery was performed in the way described by Staubli. After osteotomy the gap was opened as far as necessary to gain the intended correction angle resulting in a leg axis of 3 degrees valgus. Osteotomy was stabilized with a titanium tomofix-plate and angle-stable screws allowing partial weight-bearing at once after surgery and full weight bearing after six weeks. After surgery and prior to patient’s discharge another full-leg X-ray was gained and the postoperative leg axis related to intraoperative measure and preoperative planning.
Results: From 27 patients 15 were male and 12 female aged between 28 and 65 years. Indication for high tibial osteotomy was idiopathic or secondary varus deformity with a maximum of eleven degrees. No specific complications due to navigation could be found. With navigation operation time was prolonged not more than ten minutes. In all patients postoperative leg axis was 3 plus/minus 1 degree valgus and thus related very exactly to intraoperative measure provided by the navigation system.

Discussion: Having in mind the good results of navigation in knee arthroplastic surgery it seemed logical to use navigation also for surgery concerned with correction of leg axis. According to the results described above using the orthopilot-navigation system for high tibial osteotomy pitfalls of preoperative planning can be avoided. Not only varus deformity but also extension deficit can be addressed intraoperatively. It is well known that without navigation in most cases after high tibial osteotomy there results an undercorrection which is an essential reason for bad clinical results. With our early results navigation for high tibial osteotomy seems to be a reliable and safe procedure that needs no computed tomography and no intraoperative fluoroscopy. Navigation itself is simple and in this study without specific complications. Connection with open wedge osteotomy seems to be ideal, but it should also work with closed wedge surgery. Prolongation of operation time can be neglected regarding the benefit assumed for better long-term results. More data should be achieved to confirm these first experiences, but it seems that using navigation for surgical correction of leg axis especially for high tibial osteotomy makes sense and is not wasting time.
The impact of fixation type and location on tracker stability in navigated THA – A cadaver study

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Introduction: In navigated total hip arthroplasty it is necessary to track the pelvis as well as the femur by means of fixing rigid bodies directly to the bony structures. To allow an exact tracking throughout the procedure, it has to be guaranteed that the connection between tracker and bone remains translationally and rotationally stable. For this purpose, bi-cortical screws with a rotation locking mechanism or two to three pins connected together like the ones from the Stryker imageless navigation system (STRYKER Leibinger, Freiburg, Germany) are used. This cadaver study was performed to compare intraoperative stability of different tracker fixation options consisting of an anchoring screw with a rotational stabilizer and pairs of pins of different diameters connected with clamps. These devices were tested at different locations of the femur.

Methods: To simulate an intraoperative setting three human cadavers were placed in supine position on an OR table with a reference tracker in the area of the greater trochanter. As test fixation devices K-wires (3.2 mm), Steinman’s nails (3 and 4 mm), Apex-pins (3 and 4 mm) and a standard screw were used. They were positioned medially in the proximal third of the femur, ventrally in the middle third and laterally distal. In six different leg positions their spatial positions were detected with a navigation system.

Multivariate analysis of variance (general linear model) was used to compare the association of shifting and deflection and the independent variables. Pin, leg position, and pin fixation method were handled as independent variables. In addition a post-hoc Dunnett-T3 analysis was performed to test the pair-
Results: The multivariate analysis of variance showed highly significant effects on pin (p<0.001), pin fixation method (p<0.001) and leg movement (p<0.001). The Dunnett T3 analysis showed that the six pins do differ in terms of shifting and deflection. Differences between Pin K and Pins A3, A4, P and S3 were highly significant (p < 0.001). In the figure-four position all anchoring devices showed a substantial deflection (1.5-2.5°). With regard to the placement location, on the medial, proximal area a general tendency to higher deflection (> 0.5°) was detected in all six leg positions. Here the 3 mm Apex-pin pair showed the least stability (1 – 2.5°). In the lateral fixation all anchoring devices kept the tracker in a stable position. At the ventral side only the standard anchoring screw showed deflection (1.5 – 2.5°).

Discussion: It can be concluded that all anchoring system with two connected pins with the exception of 3 mm Apex pins have proven to be more stable than the single screw fixation with a rotational stabilizer. The insertion of two pins is less invasive than the introduction of the anchoring pin with the rotational protection. Fixation in the distal lateral area, where little muscular tension induced loads occur, is the region for anchor placement that can be recommended. Extreme positions like the figure four position during the process of navigation should be avoided.
Taylor spatial frame in limb reconstruction surgery – Review of 100 cases

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Introduction: The Taylor Spatial Frame is an external fixator which employs computer software to achieve deformity correction. The fixator consists of two rings interconnected by six telescopic struts to form a hexapod. This design incorporates a virtual hinge based on the Stewart Gough platform. Web based computer software is used to calculate adjustments to the strut lengths to allow correction of all 6 elements of a deformity simultaneously over any period. Frame adjustments are performed by the patient at home according to a computer-generated prescription sheet.

Method: We report the results of the Taylor Spatial Frame in 100 consecutive limb reconstruction cases. The mean age of patients was 40 years, all were tertiary referrals and 87 had undergone previous surgery for the same condition which had failed.

A range of conditions were treated: non-union (44), malunion (16), leg length discrepancy (14), deformity (13), and acute fractures (13). A unique solution was required for each condition. For example, non-unions could be treated with closed correction of deformity and distraction, or bone resection and transport. The system was used in the following situation: Closed non-union treatment (28), bone transport (12), acute fractures (12), deformity correction (28), lengthening (15), and arthrodesis (5). Anatomical location was tibia (77), femur (13), knee (3), ankle (4), humerus (2), and forearm (1).

Deformity was assessed from orthogonal radiographs using standard geometric calculations.

Results: The results showed the computerized system to be very accurate with complete correction of deformity in 93%. In lengthening procedures the
ability to perform very accurate serial adjustments produced very reliable cylindrical regenerate. Mean lengthening of 38 mm was achieved with a lengthening index of 0.58 mm/day. The computer allowed accurate correction of angular deformity simultaneous with the lengthening procedure.

In 12 patients bone resection and transport was performed. This was achieved with two frames assembled in a “stacked” fashion. The software allowed simultaneous accurate control of regenerate at one level with anatomical reduction of the docking site at the other site.

28 stiff non-unions, were treated closed with distraction and accurate correction of non-union deformity. This achieved union in an anatomical position without bone graft.

Mean treatment time was 169 days (range 43 to 401). There was complete compliance with patients performing their own adjustments according to the computer-generated prescription. Minor pin site problems were common (34 patients) but only 3 required debridement. Other problems included wire breakage (10), pain (3), peroneal nerve palsy (1) and DVT (1). 15 knees and 11 ankles developed stiffness which resolved.

**Discussion:** The introduction of computer assisted deformity correction is changing practice. The ability to reliably and accurately correct deformity in any plane over any given period of time is extending the indications for the use of external fixators in limb reconstruction. In addition the Taylor Spatial Frame may be used safely to treat acute fractures where other fixation techniques are associated with high complication rates.

We demonstrate the computer assisted hexapod external fixator incorporating a Stewart Gough Platform as an extremely accurate, versatile, effective and safe tool in limb reconstruction and trauma surgery.
Navigated measurement of the tibial rotation after ACL reconstruction

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Introduction: The control of success after ACL reconstructions can be estimated with the well established measurement of the anterior-posterior (ap) translation. Shortly the measurement of the pre- and postoperative tibial rotation became an important factor to evaluate the operative result. So far a direct computerized measurement tool is not available to determine the tibial rotation. Goal of our study was the development of a reproducible system for the measurement of the tibial rotation before and after ACL reconstruction with the help of a navigation system. A comparison between the manual measurement and the new navigated system was done.

Methods: A conventional fluoroscopy based navigation system (Brainlab, Vectorvision) was used as a measurement tool. In combination with an especially developed external software module on a conventional PC, data transfer of rotational movements of two defined axes became possible. Initially analog measurement of the tibial rotation in defined 30, 60 and 90 degrees of flexion with the help of a specially developed goniometer was done. Defined Internal and external rotation from 5 – 35 degrees were done in a total of 10 leg models. All testings were done on plastic whole leg models with existing collateral and ACL/PCL ligaments. Secondarily the navigation system was used for the same measurements on the plastic models with regular fixation of dynamic reference bases (DRB) close to the joint line. To be able to perform also tibial measurements potentially postoperatively without invasive markers, we also fixed in a second study the tibial DRB on an external applied immobilizing Vacoped claf boot. A comparison of the manually defined tibial rotations vs. the navigated
measurements with and without an internal and external tibial DRB was done and results statistically compared.

**Results:** Measurement of the tibial rotation with the navigation system was reproducible without technical problems. The results revealed the same measurements of analog and navigated tibial rotation. According to the specific degree of rotation at 30, 60 and 90 degrees of flexion, in all results comparing analog and navigated methods there were no significant deviations. In all cases the navigation module was able to reproduce the determined rotation. Also testings with the fixed DRB at a Vacoped boot, according to a noninvasive referencing showed the same results. No significant deviation of the measurements were found.

**Discussion:** Measurement of the tibial rotation for an outcome control of ACL reconstructions gained importance within the last years. However reproducible technical realization has so far been problematic. Our study did show that potentially a regular surgical navigation system can be used for this intention. Validate data transfer of the tibial rotation during the stages of a knee flexion became possible. However an intraoperative use can easily be done with regular invasive DRB’s, in the future a tool might be necessary to be able to control operative results of an ACL reconstruction also postoperatively in defined times. Thus a noninvasive DRB fixation is needed, and if possible also a rigid fixation can be achieved at the patients. So far our results showed that a noninvasive DRB fixation is at least at the tibia possible and rotational measurements adequate. So far cadaver studies have started to improve our findings before secondarily first clinical trials can be done.
Clinical use of virtual fluoroscopy in trauma surgery

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Objective: Mobile fluoroscopic devices are an integral part of the standard equipment used in orthopaedic surgery to provide real-time feedback of bone and surgical tool positions. One of the disadvantages of this technique include the need for continued radiation exposure for visual control.

Clinical Relevance: This paper describes a computer-assisted surgical navigation system based on fluoroscopic X-ray image calibration and 3D optical localizers (Fluologics system, Praxim, France). This system allows real-time navigation in several X-ray projections simultaneously, with the fluoroscope turned off and removed from the operating field. In Trauma surgery procedures such as osteosynthesis of Ilio sacral joint, pedicle screw placement in spine, distal locking of intramedullary nails or, extra-intra capsular femoral neck fractures fixation, safety and accuracy can be improved thanks to the multiplanar guidance, while radiation exposure of both patient and surgical staff can be significantly reduced [1][3].

Materials and Methods: A three-dimensional localizer (Polaris system; Northern Digital; Waterloo, Ontario; Canada) is used to track the position of surgical tools, patient reference and the image intensifier of the C-arm within the region of the operating table. Each component is equipped with passive markers that give the position and orientation of three distinct tools (patient reference frame; surgical tools; C-arm) with the help of a three-dimensional localizer. Data are passed on to a workstation computer (Fluologics system, Praxim, France). The C-arm used in this study is an OEC fluoroscope (OEC Medical system; Courtabeuf; France). To avoid image intensifier distortion, a calibration grid (equipped with passive markers) is fixed to the image intensifier. The surgeon acquires two single C-arm views from A-P and lateral positions. After correction of image intensifier distortions by the
computer, the views are then displayed on the workstation screen. A computer-generated projection of surgical tools is then displayed on each image and a real-time navigation is possible. This is equivalent to its representation under conventional constant fluoroscopic control. More than sixty clinical cases were done by using virtual fluoroscopy for ilio sacral joint screwing, pedicle screw placement [2], distal locking of intramedullary nails (femur and tibia) and extra-intra capsular femoral neck fractures fixation. A comparison of irradiation data and intervention durations with the same data collected during conventional procedures was done.

**Results:** The virtual fluoroscopy shows clearly that the system provides better accuracy and safety than conventional fluoroscopy. This affirmation is always true when analyzing the results by type of pathology. When we compare irradiation data with the same data collected during conventional procedures we can say that virtual fluoroscopy reduces significantly radiation exposure time by the 1/3 ratio. With a quick learning curve and clinical experience we can say that there are no statistical differences when we compared intervention durations with the same data collected during conventional procedures.

**Discussion and Conclusion:** Currently available computer-assisted orthopaedic systems are generally based on 3D image data sets that are acquired preoperatively with a Computed Tomography (CT) scanner. A fluoroscopy-based computer system can be seen as a complement to a CT-based computer system (CT scans provide full 3D image data, not fluoroscopic images) [4]. The advantages over CT-based systems are twofold: instant availability without preoperative preparation (no CT acquisition required) and up-to-date image data of patient anatomy (X-ray images used for navigation are acquired at the beginning of the surgical procedure). As compared to standard fluoroscopy, the fluoroscopy-based computer system allows real-time navigation in several X-ray projections simultaneously and reduces significantly radiation exposure of both patient and surgical staff [5]. Finally, the authors believe that this system can also greatly improve on surgical accuracy and safety of many applications in orthopaedics.

**References**


Clinical evaluation of CT-based navigation system for total knee arthroplasty

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Introduction: Optimal postoperative axial alignment of the lower extremity alignment is fundamental to achieving long-term survival of total knee arthroplasty (TKA). It has been reported that varus malalignment is associated with higher failure rates and positioning of femoral and tibial component should be in less than 3 degrees of errors [1]. In several large series of total knee implantation, the ideal position of the components was achieved in at best 70-80% of patients using intramedullary or extramedullary alignment rods [2]. Some clinical studies on computer-assisted knee arthroplasty systems have shown improved accuracy of implantation of the prosthesis [3,4]. Our laboratory study concluded that marked deviations from ideal alignment can be almost entirely avoided with CT-based navigation system using cadaveric specimens [5]. This study evaluated clinically quality of implantation using the CT-based navigation system in comparison with the conventional alignment rod system.

Methods: Fifty-eight primary TKAs in 55 patients were performed using the Nexgen Legacy Posterior Stabilized prosthesis (Zimmer, Warsaw, IN) between November 2002 and July 2004. Of these 58 knees, 21 were implanted using CT-based navigation system (Vector Vision Knee Brain LAB Inc., Heimstetten, Germany) and 37 were implanted using a conventional femoral intramedullary and tibial extramedullary alignment rod system. Standard medial parapatellar exposure was used for both groups. Each cutting guide was fixed to the bone with pins and bone cuts were performed with a saw blade. The operative time and the loss of blood were recorded. The Knee Society score was used to evaluate knee status. Student’s t-test was used to determine statistically significant differences between the
two systems with these parameters (significant: p<0.05). The quality of implantation was evaluated on the postoperative antero-posterior view of the whole leg radiograph. Weight-bearing ratio (WBR ideal: 40 to 60 %), mechanical femoral angle (MFA ideal: 88 to 92 degrees), mechanical tibial angle (MTA: 88 to 92 degrees) was measured. Fisher’s exact probability test was used to compare the quality of implantation between the two systems with these parameters (significant: p<0.05).

Results: Mean operative time with CT-based navigation system was 137±31 min (range, 110 – 230 min), and 123±32 min (range, 91 – 245 min) with conventional system (p=0.17). Mean loss of blood with CT-based navigation system was 610±206 ml (range, 312 – 991 ml), and 749±340 ml (range, 280 – 1530 ml) with conventional system (p=0.14). Mean Knee Society score with CT-based navigation system was 95.4 and 93.8 with conventional system (p=0.41). Ideal WBR, MFA and MTA was obtained in 95.2%, 100%, 95.2% with CT-based navigation system and 54.1%, 64.8%, 59.4% with conventional system (p=0.02, 0.005, 0.04).

Discussion: Our results demonstrated significant improvement of total knee implantation with CT-based navigation system in comparison with the conventional system. Whether CT is necessary for computer-assisted TKA is a matter for discussion. The image-free system finds the mechanical axis by intra-operative joint motion and bony landmarks. The advantage of the image-free system is that it does not require pre-operative imaging or planning. However its accuracy in defining the center of the joint is inferior to that of the CT-based navigation system, in which it can be seen directly on the CT images. One of the greatest advantages of the CT-based navigation system is that three-dimensional pre-operative planning, including sizing of the component and coverage of the bone, is possible in conjunction with three-dimensional alignment of the component. We prefer to use the CT-based navigation system enhanced with the function of CT-free navigation system.

References
Automatic detection of femoral neck axis for hip resurfacing surgeries

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**Introduction:** Hip resurfacing becomes more and more an alternative for the younger and active population that needs to undergo a THR\(^1\). Superior notching of the femoral neck while reaming as well as varus or too proximal mal-positioning of the head implant are the most critical hazards of this technique that leads to early post-operative fractures and making a THR necessary\(^2\), \(^3\). One reason for misplacement and such an adverse outcome are given by the conventional instruments that determine the alignment of the implant respectively the direction of the neck axis. They are inaccurate and not easy in handling. For this reasons it is essential to provide a solution that makes the procedure more accurate, reproducible, intuitive and as much independent of the surgeon’s experience as possible. An imageless navigation system, using multiple acquired landmarks to morph a model of the femurs anatomy and calculating the neck axis automatically, has already proven its accuracy and reliability in TKR and THR surgeries and can certainly assume this task\(^4\).

**Method:** The evaluation and final decision of three possible algorithms to determine the femoral neck axis are the main focus of this paper. After in detail the principle of all approaches will be explained, the validation method to find the most accurate and reliable one will be described:

Generic axis of morph (MORPH): the training model of the PDM contains a default neck and shaft axis. While morphing the model this default axis was scaled within certain borders to match as close as possible to the real situation.

Middle of points (MOP): As the primer point of the neck axis the calculated center of all the projected points in the coronal plane were used. Therefore all registered landmarks on the femoral neck were projected on the coronal plane which was defined by the center of rotation, the piriformis fossa and the
midpoint of both epicondyles. As the end point of the axis the center of rotation was chosen. Middle of planes (MIP): Based upon the medial planes between the anterior and posterior, respectively the superior and posterior landmarks, was the intersection line of the two medial planes used to calculate the neck axis. The first step of the validation was to define a reference neck- and shaft axis respectively a default CCD angle. Therefore ct-scans of all bones were made and loaded into the ct-based software enabling the user to adjust the neck and shaft axis. Different and experienced users, whereof 2 surgeons, planned the axis separately. The CCD angle and coordinates of each axis were documented and the average values were calculated to get the reference. Afterwards a ct-based gold standard registration, using a surface match algorithm, of each bone was performed and the coordinates of the reference axis were transformed into this coordinate system. From now the position of the reference star stayed the same and an imageless registration of the proximal femur was done with a prototype of the resurfacing VV Hip SR software. To do so the user acquired all neck areas and the femoral head with a pointer by scratching it over the surface. Then the pre-planned reference axis was transformed again from the ct-based into the imageless coordinate system, which enabled us to always have the reference axis and the test axis available in one software and image. Furthermore the deviations in incli-/declination and retro-/anteversion between test- and reference axis were calculated and logged by the software.

To get reproducible results 10 measurements of 2 artificial left and 2 right bones under good and bad conditions were done. As the data of 3 cases could not be taken into account, overall 77 of 80 trials were reported.

![Graph showing angle deviations between calculated angle by all 3 algorithms and the ct-based gold standard in °]
Results and Discussion: According to the predefined pass criteria (good $x < 4.0$ / acceptable $4.0 \leq x < 8.0$ / unacceptable $x \geq 8.0$) were all average values good or acceptable. In total the average deviation angles of the 3 approaches were generally better in the coronal ($\pm 4.9^\circ$ incl./declination) then in the axial plane ($\pm 6.8^\circ$ ante-/retroversion). Besides, in both planes higher accuracies were achieved by using the middle of planes algorithm (coronal: $4.2^\circ \pm 1.7$ / axial: $5.7^\circ \pm 3.2$) than by approaching via the MORPH (coronal: $5.1^\circ \pm 2.6$ / axial: $7.8^\circ \pm 4.6$) or MOP algorithm (coronal: $5.5^\circ \pm 3.0$ / axial: $6.8^\circ \pm 3.2$).

The two cross checks showed that on the one hand the calculated angle deviations under good and bad scenarios for all 3 algorithms were not affected by bad registration conditions. On the other hand did the left and right comparison clarify that the retro-/anteversion angle of the MORPH and MOP algorithm lead to unacceptable results at right femur bones. Average deviations in the axial plane under 4° were only achieved by the middle of planes algorithm (retro-/incl-angle: 3.7°).

Conclusions: Of all 3 approaches the middle of planes algorithm calculated the neck axis the most accurately and reliably; thus its use can be recommended for the resurfacing software. Still the results visualized that especially the ante-/retroverted angle deviation must be decreased. Thus can be concluded that a manual and landmark based angle planning by the operating surgeon is necessary. Good previous navigation experiences showed that a manual setting of target points in the axial plane such as the fossa piriformis leads to a good accuracy.

References

Heat generation and temperature distribution in human cortical bone drilling

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Introduction: The stability of orthopaedic fixation devices depends partially on the quality of the host bone. One cause of necrosis is thought to be the generation of excessive heat during the surgical drilling procedure. In previous studies the rotational speed, feed rate, drilling geometry and bone mineral properties were varied in parametric analysis to determine the importance of each one on temperature rise and therefore on thermal damage. It was found that drill speed, feed rate and drill diameter had the most significant thermal impact while changes in drill helix angle, point angle and bone thermal properties had a relatively small effect. This paper presents the results obtained from heat transfer finite element modeling (FEM) simulation to predict the temperature rise and thermal injury in bone during a drilling operation.

Methods: Reviewing past articles and studies in bone drilling, the mechanizing parameters that have the most influence in the heat distribution were determined. A human femur model was adapted for use with the FEM simulation PC software (IDEAS). The model includes the thermal and mechanical characteristics of the material (bone). In order to simulate the heat produced in the drilling procedure, a hole was made in the model, and the temperature of the surface of this hole was defined. This temperature value represents the value of temperature that can be found in a real drilling experiment when the threshold for thermal damage is surpassed [4]. When the simulation is over, the volume of damaged bone can be extracted.

When mechanized cutting tools such as saws and drills are used, heat is produced which raises the temperature of both the tool and the material being cut. In orthopaedics and dental practices, high-speed tools are often applied to
bone, and heat from these operations may result in thermal necrosis [1,2]. Since the thermal necrosis generally has a negative impact on the outcome of a drilling procedure, bone temperature must be kept below the threshold that results in necrosis.

Results: The data obtained from the simulations shows that the use of the Finite Element Modeling can help surgeons and researchers who are developing bone tissue mechanizing equipment. In the experiments, three different levels of temperature are applied. The simulations have shown the behavior of the bone and, in cases of necrosis, the areas of the bone which will become dead tissue, and should be eliminated. In the modeling process of the femoral bone it is necessary to include the following parameters associated with the bone tissue properties: Young Modulus, density thermal conductivity, etc.

The temperature of the outer surface of the bone was 36.5°C. In the following example in Fig.1, temperatures of 50°C, 55°C and 60°C have been applied on the surface of the hole, in order to analyze the response of the model for each temperature, in terms of dilation, temperature distribution and tissue damage [3].

Discussion: It is shown that the Finite Element Modeling FEM is useful in representing the temperature maps, and in predicting the zones of possible
thermal damage in the bone tissue [3]. With this technique we can analyze and optimize the mechanizing process, in order to obtain good results, and to avoid the possible traumatic side effects that could appear if the process results are not satisfying.

References

Minimally invasive, computer-assisted TKR – The use of percutaneous 2-pin fixation

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Introduction: Accurate surgical navigation requires rigid fixation between the reference frames and the bones being tracked. When larger incisions are made, it is possible to fix these frames through the primary incision. However, these frames often compete with other surgical instruments in the surgical field. Further, less invasive surgical techniques preclude the use of the primary incision for reference frame fixation. Single-pin fixation systems have the potential to become rotationally unstable and their size requires larger incisions. In addition, the sleeves designed to confer rotational stability may injure the surrounding soft tissue. By contrast, 2-pin fixation has greater rotational stability and the insertion of each pin can be fully protected with a drill sleeve. Whether frame fixation is performed using single or two pin fixation, the risk of neurovascular injury and post-operative fracture is always a concern. The current study assesses the use of 2-pin percutaneous reference frame fixation for total knee arthroplasty.

Methods: 176 computer assisted total knee arthroplasties were performed (Smith-Nephew Genesis II). 70 procedures were performed using image-based virtual fluoroscopy (Medtronic Ion System) and 106 procedures were performed using image-free methods (BrainLAB CT-free knee). The procedure was performed by affixing reference frames percutaneously to the femur and tibia using 2-pin fixators. Drill sleeves were used to protect the soft tissue. The knee was flexed during femoral frame fixation to avoid tethering the quadriceps. After the 1st 10 cases, 4 mm tibial pins were used after pre-drilling with a 3.2 mm drill and 5 mm pins were used for the femur without pre-drilling. Hip and ankle data were acquired prior to elevating the tourniquet. Alignment and ligament balance were assessed and all bone cuts
were tracked using navigation. Post-operatively, limb alignment was assessed on full limb standing films.

**Results:** Of the 704 percutaneous pin sites, one pin site became infected and requiring antibiotic treatment. The tip of one 3 mm fixation pin broke on insertion and was left in situ. No 4 mm or 5 mm pins have broken. One femoral frame shifted and required reregistration. One tibial frame shifted after all of the components had been implanted and did not require reregistration. Both of these reference frames shifted at the fixator-frame junction. No pins loosened within the bone. There were no vascular or nerve injuries and no fractures. Alignment on long-leg radiographs were measured in the 167 limbs. The measurements demonstrated that femoral component alignment had a mean of 0.4 degrees of varus (Standard Deviation 1.0 degrees), tibial component alignment had a mean of 0.7 degrees of valgus (Standard Deviation 1.1 degrees) and overall alignment had a mean of 0.2 degrees of valgus (Standard Deviation 1.0 degrees).

**Discussion:** The use of percutaneously placed 2-pin fixators results in stable and safe fixation for reference frames used for surgical navigation of total knee arthroplasty and result in accurate limb alignment following computer-assisted TKR. Pre-drilling of the tibia with a sharp drill bit is recommended for the cortical bone of the tibia to prevent thermal injury to the bone and surrounding tissue.
Comparison of experience with CT-based and fluoroscopic-based surgical navigation for total hip arthroplasty

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Component malposition is associated with hip instability, increased wear, wear-associated osteolysis, and revision surgery for instability and lysis. Further, component malposition has become a more common problem associated with minimally-invasive surgical techniques. Surgical navigation for total hip arthroplasty offers the opportunity to reduce the incidence of these problems. Surgical navigation for THR can be performed using image-free or image-based methods. Image-based methods include preop CT-based and intraop-fluoroscopic methods. CT-based methods have the additional advantage of allowing for three-dimensional planning and prediction of impingement-free range of motion. The current study compares our experiences with CT and fluoroscopic methods of acetabular component navigation for total hip arthroplasty.

Methods: 91 THA were performed using fluoroscopic-based navigation (Medtronic ION system) and 146 THA were performed using CT-based navigation (BrainLAB CT-based hip navigation). 123 of the 146 THA performed using CT-based navigation had surgery performed using a tissue-preserving, superior capsulotomy technique with an average incision length of less than 8 cm. The fluoroscopic-based navigation was performed using multi-purpose navigation software prior to the development of and approval for hip-specific applications in the United States. The fluoroscopic software was used to measure acetabular component abduction during implantation based on an angle between the inter-teardrop line and the cup impactor handle. Using CT, the three dimensional position of the cup impactor was navigated.
Postoperative radiographs were used to measure cup abduction postoperatively.

**Results:** Cup position for the 91 fluoroscopically navigated cups averaged 40.8 degrees with a standard deviation of 2.4 degrees. The range was 35 for 50 degrees of cup abduction. Cup position for the 146 cups navigated using CT averaged 43.2 degrees with a standard deviation of 3.6 degrees. The range was 35 to 52 degrees.

**Discussion:** Fluoroscopic and CT-based navigation are both accurate methods of tracking cup position during surgery. Measurement of cup position on plane radiographs has limitations including the inaccuracies of cup abduction measurement introduced by pelvic malrotation around the transverse and longitudinal axes.

Fluoroscopic-based navigation has the advantage that this method is capable of navigating hips where CT images are poor (as in revision THR) and in cases of previous hip fusion (where routine CT registration methods are not possible). Fluoroscopic-based navigation also has the advantage that preop planning is not required. Fluoroscopic-based navigation has the disadvantage that the procedure is disrupted by the use of fluoroscopy during surgery. This is especially true of current fluoroscopic software developed for hip applications that require several images to establish the pelvic coordinate system.

CT-based navigation has the advantage of being more rapid to perform intraoperatively without the need for fluoroscopic equipment in the OR. CT-based methods also have the advantage that the three-dimensional nature of the deformity is better understood, the impingement-free range of motion can be predicted, and optimal component placement can be planned in detail.

In our experience, since both methods have different advantages and disadvantages, both methods have a role for navigation of total hip arthroplasty.

**References**

Tissue-preserving computer-assisted total hip arthroplasty: Faster recovery and lower complication rate without compromising accuracy of cup orientation

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Introduction: A new method of tissue-preserving computer-assisted total hip arthroplasty using a superior capsulotomy was developed with the goal of accelerating recovery while simultaneously maintaining or even reducing the already low perioperative complication rate associated with conventional total hip arthroplasty techniques [1,2]. The current study prospectively compares the results of a sequential series of THA performed using the tissue-preserving, superior capsulotomy exposure (study group) to a sequential series of conventional THA using a modified direct lateral exposure (control group).

Methods: 106 consecutive total hip arthroplasties performed using a tissue preserving technique through a superior capsulotomy (study group) were compared to 130 consecutive total hip arthroplasties performed using a modified direct lateral exposure (control group). All procedures were performed by the same surgeon at the same hospital using the same implants. In order to have a control group of similar complexity to the study group, 23 of the 130 consecutive control cases were excluded as they were deemed too complex to have been performed using the tissue preserving technique, leaving 107 hips for evaluation. Reasons for exclusion due to complexity were prior pelvic or femoral osteotomy with or without hardware (10 hips), deformities too severe to have been safely performed using the superior
capsulotomy technique (6), protrusio (4), prior vascularized fibula and hardware (1), achondroplasia (1), and prior ORIF with hardware (1). There was no statistically significant difference of the patients’ demographics between the two groups (Table 1).

The control group were all performed using a modified direct lateral exposure. For the study group, a novel tissue-preserving computer-assisted approach through a superior capsulotomy was used. The intra- and perioperative complications were recorded, and the clinical and radiographical results of both groups were evaluated preoperatively, postoperatively at 6 weeks and at 3 months. The study group patients were treated using a computer-assisted tissue-preserving superior capsulotomy technique. This method involves developing the interval between the piriformis which is reflected posterior and the gluteus minimus which is reflected anteriorly. The posterior capsule and short external rotators are preserved. The femur is prepared prior to excision of the femoral head. First, cylindrical reamers are placed into the femur through the trochanteric fossa and the the superior portion of the neck is removed to allow broaches to be fully seated. The femoral neck is then transected and the femoral head is excised. The hip is not dislocated. The acetabulum is then prepared using a tracked angled reamer and the acetabular component is inserted using a double-angled cup impactor that exits the incision superior to the greater trochanter. For both groups, cup insertion was performed using computer guidance. A fluoroscopy based system (Medtronics) was used for the control group, a CT-based navigation system (BrainLAB) was used for the study group.

Results: Neither group had a patient sustain a hip dislocation despite allowing unrestricted range of motion postoperatively. Neither group had an intraoperative femur fracture or deep venous thrombosis. Although there was a significant difference in cup orientation, the variability of cup abduction and the number of cup outliers did not differ. There were 2 surgical complications in the study group, one intraoperative greater trochanteric fracture, and one unrecognized displacement of the acetabular component during surgery requiring acute correction. There were 7 complications for the control group: 4 trochanteric wafer nonunions, one intraoperative and one postoperative trochanteric fracture, and one deep infection requiring incision and drainage. Assessment of post-operative function by Merle D’Aubigné scoring demonstrated a statistically significantly accelerated return to normal unaided gait at 1st follow-up in the study group as compared to the control group (Table 1).
### Summary of the demographic data, the clinical and radiographical results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Study group</th>
<th>Control group</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of hips</td>
<td>106</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>Age [years]</td>
<td>56 ± 12.3</td>
<td>54 ± 14.0</td>
<td>0.207</td>
</tr>
<tr>
<td></td>
<td>(20.1 – 84.6)</td>
<td>(27.7 – 84.2)</td>
<td></td>
</tr>
<tr>
<td>Gender [% male]</td>
<td>54.7</td>
<td>52.3</td>
<td>0.416</td>
</tr>
<tr>
<td>Side (R/L) [% right]</td>
<td>56.6</td>
<td>47.6</td>
<td>0.121</td>
</tr>
<tr>
<td>Bilateral [% bilateral hips]</td>
<td>15.1</td>
<td>22.4</td>
<td>0.115</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>171 ± 10.7</td>
<td>172 ± 10.4</td>
<td>0.596</td>
</tr>
<tr>
<td></td>
<td>(149 – 190)</td>
<td>(147 – 193)</td>
<td></td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>78.8 ± 18.0</td>
<td>81.6 ± 20.9</td>
<td>0.439</td>
</tr>
<tr>
<td></td>
<td>(45.4 – 129.5)</td>
<td>(44.1 – 136.4)</td>
<td></td>
</tr>
<tr>
<td>BMI [kgm⁻²]</td>
<td>26.7 ± 4.8</td>
<td>27.1 ± 5.3</td>
<td>0.672</td>
</tr>
<tr>
<td></td>
<td>(17.5 – 39.2)</td>
<td>(18.0 – 45.2)</td>
<td></td>
</tr>
<tr>
<td>Preoperative diagnosis [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Osteoarthritis</td>
<td>73</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Dysplasia</td>
<td>20</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Osteonecrosis</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>No. of hips with previous surgery [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic osteotomy</td>
<td>7 (6.6)</td>
<td>6 (5.6)</td>
<td>0.492</td>
</tr>
<tr>
<td>Femoral osteotomy</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>ORIF</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Surgical hip dislocation</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Core decompression</td>
<td>-</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cup abduction [°]</td>
<td>43.7 ± 4.0</td>
<td>40.8 ± 3.9</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>(35 – 56)</td>
<td>(26 – 54)</td>
<td></td>
</tr>
<tr>
<td>Variability of cup abduction [°], Standard deviation</td>
<td>4.0</td>
<td>3.9</td>
<td>0.891</td>
</tr>
<tr>
<td>Abduction outliers (&lt; 30° or &gt; 50°) [%]</td>
<td>4.7</td>
<td>5.9</td>
<td>0.506</td>
</tr>
<tr>
<td>Length of stay [d]</td>
<td>3.9 ± 1.0</td>
<td>4.5 ± 1.69</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>(2 – 10)</td>
<td>(2 – 13)</td>
<td></td>
</tr>
<tr>
<td>Disposition (home/rehabilitation) [%]</td>
<td>73.5</td>
<td>71.9</td>
<td>0.664</td>
</tr>
<tr>
<td>Complication rate [%]</td>
<td>1.8</td>
<td>6.5</td>
<td>0.087</td>
</tr>
<tr>
<td>Merle d'Aubigné preoperative</td>
<td>10.1 ± 1.6</td>
<td>10.5 ± 1.7</td>
<td>0.123</td>
</tr>
<tr>
<td></td>
<td>(5 – 14)</td>
<td>(6 – 14)</td>
<td></td>
</tr>
<tr>
<td>Merle d'Aubigné 1st follow up</td>
<td>15.2 ± 1.9</td>
<td>12.8 ± 1.8</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>(8 – 18)</td>
<td>(9 – 18)</td>
<td></td>
</tr>
<tr>
<td>Merle d'Aubigné 2nd follow up</td>
<td>17.0 ± 1.1</td>
<td>17.0 ± 1.3</td>
<td>0.450</td>
</tr>
<tr>
<td></td>
<td>(13 – 18)</td>
<td>(12 – 18)</td>
<td></td>
</tr>
</tbody>
</table>

**Discussion:** Perioperative complications can occur with any surgical exposure for total hip arthroplasty but have been shown to be more frequent with some minimally invasive methods without surgical navigation [3-5]. If
minimally invasive techniques accelerate recovery in a majority of patients but also result in an increased rate of complications and reoperation, the practice of those minimally invasive techniques may not be justified. The tissue-preserving technique described here was specifically designed to allow rapid transition to a conventional exposure if necessary and designed to allow direct visualization and protection of the abductor muscles while preserving the short rotators and posterior capsule. The hip is not dislocated during surgery since this act of displacement requires destabilization of the joint by release or disruption of the surrounding tissues.

Computer navigation plays a crucial role in this whole concept. Cup insertion in lateral decubitus position is difficult and often results in malpositioning of the acetabular component. In this study, with the help of image guidance, the acetabular component could be inserted with a similar accuracy and without more cup abduction outliers even with a limited field of view for the new approach.

While more technically demanding, the technique can be performed in the same or less time than the conventional direct lateral exposure. The finding of only one reoperation in this group combined with an absence of dislocations and intraoperative femur fractures is encouraging. As compared to a conventional direct lateral exposure, the computer-assisted technique clearly accelerates recovery, maintains accurate cup orientation and shows promise in decreasing, rather than increasing the incidence of peri-operative complications.

References

Variations in acetabular anatomy: Application to a pelvic atlas-based image-free navigation system

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Introduction: In total hip replacement (THR), it is important to know the thickness of the acetabulum, and the medial wall in particular. This information can guide the surgeon during reaming, drilling for anchoring holes and placement of screws. Surgeons typically rely on the four-quadrant theory1 as a qualitative indicator for the thickness of the acetabular wall.

The purpose of this study is to quantify the acetabular thickness in both males and females with a method that can be used with atlas-based image-free navigation systems.

Methods: Models derived from CT scans of the pelvis from 20 males and 22 females undergoing THR were selected as the base population of our statistical atlas. The population spans a wide range in weight (M: 64–118 kg, F: 56-93 kg), height (M: 162–190 cm, F: 157-178 cm), and BMI (M: 23–34, F: 19–38). For the purposes of our study, we assume that the opposing hip from the THR can be categorized as “healthy” and correspondingly used these hemi-pelves to build the atlas. Measurements of acetabular thickness and diameter were performed for each patient surface model and the mean models of the male and female pelvic atlases.

For each hemi-pelvis surface, we defined a sub-surface containing the wall of the acetabulum, a sub-surface containing the entire acetabulum (the wall plus the fossa), the anterior superior iliac spine (ASIS) landmark, and a set of points defining the rim of the acetabulum. We automatically performed a least squares fit of a sphere to the acetabulum vertices (excluding the fossa) to determine the diameter and center point of the acetabulum. The rim points were then used to define a plane. The coordinate system for the data is...
located at the center of the sphere and oriented by a vector from the center to the ASIS point, a vector normal to the plane and a third orthogonal vector (determined by the cross product of the first two vectors).

For each vertex on the acetabular sub-surfaces, rays were projected through the model radially from the center of the acetabulum. The distance between the location where the ray exited the model and the vertex was recorded as the thickness at that vertex. The data were then normalized by the diameter of the sphere fit to the acetabulum. The results are projected onto the plane fitted to the acetabular rim. The results can then be easily binned by position for statistical analysis.

Figure 1  Distribution of normalized thickness (thickness/diameter) for a male and female statistical atlas of the left hemi-pelvis

**Results:** The average diameter of the female acetabulum was 50.1 mm +/- 4.0 mm. The average diameter of the male acetabulum was 53.6 mm +/- 2.6 mm. The diameter of the acetabula in the mean models of the statistical atlases is 44.6 mm and 50.0 mm for female and male respectively.

The normalized thicknesses were binned in 4 ways: As 4 quadrants, as 16 wedges, as 4 quadrants further divided into 3 radius ranges (rim, mid and center)
, and as 16 wedges similarly divided into radius ranges. There was no statistically significant difference (p < 0.05) between the male and female thickness maps for any of these binning schemes.

The general shape of the thickness distributions for males and females is consistent with previously published reports. These results are consistent with the four quadrant classification in that the posterior quadrants are, in general, thicker than the anterior quadrants [Posterior Superior: 0.57 +/- 0.49 (female atlas), 0.68 +/- 0.52 (male atlas); Anterior Superior: 0.26 +/- 0.10
(female atlas), 0.29+/-0.12 (male atlas); Anterior Inferior: 0.29+/-0.20
(female atlas), 0.37 +/-0.21 (male atlas); Posterior Inferior: 0.41+/-0.18
(female atlas), 0.43+/-0.23 (male atlas)].

**Discussion**: The quadrant definition, while characterizing the thickness, does not adequately describe the variation. This is demonstrated by the large standard deviation in the posterior superior quadrant. The large standard deviation tells us that there is a wide range in the observed thickness values in this quadrant. The thickness maps are better characterized as a vertical band of the normalized thickness in excess of 50% running posteriorly to the fossa (Figure 1). These maps are similar to Noble's\(^3\).

With this technique, atlas-based image-free navigation systems can generate patient-specific acetabular thickness maps utilizing many of the same landmarks and points required to establish the navigational reference. This approach reduces the large standard deviations in the distribution of acetabular thickness observed when applying the conventional quadrant approach.

**References**

Sex: Does It matter (in the construction of a statistical atlas of the hemi-pelvis)?

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Introduction: Anatomically, there are recognized differences between the male and female pelves beyond dimension, e.g., shape of the pelvic inlet (oval vs. heart-shaped), flare of the ilia, verticality of the pelvic wall, thickness of the bone, relative spacing and orientation of the acetabula, and so on. Statistical atlases are hoped to provide accurate models for image-free navigation systems. It has not been shown whether there is a benefit in utilizing sex-specific atlases. We examine whether combining male and female data into a single atlas hinders our ability to construct a best-fitting model from a subset of the available data.

Methods: The atlas population consists of 20 male and 20 female patients undergoing THR. The population spans a wide range in weight (M: 64 – 118 kg, F: 56 – 93 kg), height (M: 162 – 190 cm, F: 157 – 178 cm), and BMI (M: 23 – 34, F: 19 – 38). For the purposes of our study, we assume that the opposing hip from the THR can be categorized as “healthy” and correspondingly use these hemi-pelves to build the atlases. Four atlases are built: one female-only, one male-only and two combined male and female atlases. The female-only, male-only and one combined atlas are built with data from 19 patients (saving one hemi-pelvis for the leave-one-out tests). The larger combined atlas is built with data from 38 patients so that both a female and male hemi-pelvis can be reconstructed in the analysis. Hemi-pelvis surface models defined as triangle meshes are derived from volumetric CT scans. We use a multi-resolution method to determine the correspondence between models. The first step in the construction is a fuzzy correspondence of the models at low resolution utilizing Chui and Rangarajan’s TPS-RPM...
algorithm. After that we refine the correspondence by more precisely locating the vertices on the mapped surface with respect to the vertices of the initial surface. Once the surfaces are mapped, they are re-interpolated to a high-resolution state using radial basis functions (RBF). We then use principal component analysis (PCA) to build the statistical atlas. New hemi-pelvis surface models can be constructed as linear combinations of the resulting principal components added to the mean by projecting data onto the eigenspace of the atlas using a subset of the principal components.

The ability to reconstruct an arbitrary hemi-pelvis from the atlases was examined using the leave-one-out technique. We reconstructed male and female models from the four atlases. Evaluation of the results is based upon distance measurements between surfaces as defined and calculated utilizing the MESH application. Maximum, mean and RMS distances between models were calculated for varying numbers of principal components.

**Results:** To analyze the data, we plotted the number of eigenvectors used in the reconstruction against the observed distance metric for the reconstruction of a hemi-pelvis from a specified atlas.

As expected, increasing the number of eigenvectors utilized to reconstruct a model reduces the mean and RMS distances between the original surface model and the reconstructed approximation. However, the trend is slight and we observed very little difference beyond the first 5 eigenvectors for atlases based on populations of 19. These first 5 eigenvectors account for roughly 70% of the variation in the male-only atlas and 80% in the female-only atlas as measured by the sum of the eigenvalues. In the male-only atlas, increasing the number of eigenvectors to 13 to capture 90% of the variation reduces the mean distance from 1.5 mm to approximately 1.25 mm and the RMS distance from 2.0 mm to approximately 1.5 mm. For the combined atlas built with 38 patients, the variation of distance measurements with increasing number of principal components was similar – the mean and RMS distances decrease slightly with increasing numbers of eigenvectors. The magnitude of the distance metrics, for comparable numbers of eigenvectors, is less for the atlas built with 38 models than the other combined atlas.

The results of reconstructing a male hemi-pelvis from the female-only atlas and a female hemi-pelvis from the male-only atlas are more interesting because they result in significantly poorer fits. In fact, the mean and RMS distances between the original female pelvis and reconstructed female surface from the male-only atlas are greater than a factor of 4 times the mean and RMS distances when compared against a reconstructed hemi-pelvis from the female-only atlas (Fig. 1). This suggests that our male pelvis population does not adequately describe the possible variation in female pelves. The male
hemi-pelvis reconstructed from the female-only atlas is not quite as striking: the mean and RMS distances are roughly a factor of 2 times the distances when compared against a reconstructed male hemi-pelvis from the male-only atlas. The combined atlases produce comparable results as reconstructing same sex hemi-pelves from single sex atlases but utilizing additional eigenvectors.

**Discussion:** The validity of any statistical atlas depends upon the population of input data from which it is built. The atlas can represent only the features that exist in the basis population. The benefit in building distinct atlases based on sex is that the variations due to sex are accounted for so that fewer principal components are needed to describe the resulting surface model with equal accuracy. We observed that greater accuracy is achieved when the reconstructed models are based on same sex atlases rather than opposite sex atlases. Comparable accuracy can be achieved with combined atlases, but using more principal components.

**References**

Comparison between robotic-assisted system and manual implantation of primary cementless total hip arthroplasty; A short-term result

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Introduction: ROBODOC system (Integrated Surgical Systems, Davis, California) is the first active robot that was designed to reduce potential human errors in performing cementless total hip arthroplasty (THA). Although there are several reports that have compared ROBODOC surgery with conventional manual operation, there is no consensus whether it is really useful or not. The purpose of this study is to compare robotic-assisted implantation of total hip arthroplasty with conventional manual implantation and to know the safety and effectiveness of the system.

Methods: 153 primary cementless THA were performed on 135 patients who had secondary osteoarthritis. We performed robot assisted THA for 78 hips (72 patients) using ROBODOC system, and conventional manual THA for 75 hips (63 patients). Follow-up periods ranged from 24 – 37 months (average 27). The average age was 58 years for each group. There were no significant differences between the two groups with regard to the distribution of patient age, gender, weight, height, and follow-up periods. Preoperatively, we planned the position and the size of the VerSys FM Taper stem (Zimmer, Warsaw, USA) three-dimensionally on the ORTHODOC workstation (Integrated Surgical Systems) for both groups. At the operation, posterolateral approach was used. Full weight-bearing was permitted as early as possible after the operation.
Results: The average duration of the surgery was significantly longer in the robotic milling group (121 minutes) than in the hand-rasping group (108 minutes) (p < 0.05). However, the average blood loss during operation was significantly less in the robotic milling group (559 ml) than in the hand-rasping group (666 ml) (p<0.05). In the hand-rasping group, there were five intraoperative femoral fractures (6.7%). Dislocation was seen in one (1.3%), thigh pain in four (4.0%) postoperatively. In the robotic milling group, there were no intraoperative femoral fractures. Dislocation was seen in two (2.6%), thigh pain in one (1.3%), and knee pain, associated with pin insertion, in two cases (2.6%) postoperatively.

Preoperatively, there were no significant differences in the Japanese Orthopedic Association (JOA) hip scores between the two groups (robotic milling group 48 points, hand-rasping group 51 points). Six months postoperatively, it was significantly better in the robotic milling group (92 points, 88 points) (p<0.01). At twenty-four months, the score was still significantly better in the robotic milling group (96 points, 94 points) (p<0.05).

Plain radiographs at two years showed bone ingrowth fixation for all the stems and cups. However, there were more stress shielding of proximal femur (Engh’s grade 3 or more) in the hand-rasping group (19 hips, 25.3%) than robotic milling group (9 hips, 11.5%) (p<0.05).

Discussion: Robotic milling THA had less operative bleeding, less intraoperative femoral fractures, better clinical scores, and less stress shielding of the proximal femur although the operation time was longer than conventional hand-rasping THA. We hypothesize the reason why robotic milling group had less stress shielding was that precise milling of the femoral canal by the robot enabled proximal fixation of the stem.

Short term follow up clinical results show that ROBODOC assisted THA is safe and effective.

References
Preoperative versus intraoperative assessment of landmarks in navigated TKA. A regression and correlation analysis

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Introduction: Today, CAS and navigation becomes increasingly popular in orthopaedic surgery, especially in total hip and total knee arthroplasty. The advantages of CAS and navigation are directly linked to the correct and reproducible intraoperative performance of the user. However, for preoperative planning and intraoperative interpretation during navigated TKA it is essential to know if the anatomy (landmarks) of a knee is reflected equally in both, the preoperative radiological image (e.g. X-ray or CT-scan) and during the intraoperative navigation setup. Our report focuses on a regression and correlation analysis of landmarks (axis) that have been assessed both pre- and intraoperatively during a controlled and randomized trial on navigated TKA.

Methods: For the CONVERNA study (conventional versus navigated TKA, study protocol accepted by the local institutional review board (IRB)), all patients admitted to our hospital for primary TKA have been studied prospectively since March 2003. According to the preoperative axial CT image of the distal femur, the posterior condyle axis (PCA) and the transepicondylar axis (TEA) were defined by the radiologist: The most prominent points of the medial and lateral condyle were connected to the TEA, the PCA was defined as the tangent at the posterior condyles. Then the “Condylar Twist Angle” (CTA) between theses two axes was measured.
During the randomized trial, every second operation was performed with the intra-operative use of a navigation system (VectorVision2, BainLAB-Company, Munich, Germany, Software 1.1, CT free). During the operations, the surgeon defined both the medial and lateral epicondyle at the distal femur. The software then connected these two points to the TEA. For definition of the PCA the medial and lateral condyle was palpated with the pointer, collecting a cloud of surface points representing the medial and lateral condyle. Then the system connected the two most dorsal points of the cloud of points to the PCA. Again, the CTA was measured as angle between PCA and TEA.

**Results:** The average preoperative CTA on the CT scan was 3.8 +/- 2.3°. During the operations, the average angle measured by the navigation system was 3.2 +/- 2.8°. The statistical analysis (Evapak for Windows, version 3.0) revealed that there was no correlation ($r = 0.095$) between the pre- and intraoperative data (Table 1).

**Discussion:** Statistically, there is no possibility of collecting the same angles and axes when using the two different methods (CT vs. navigation) on the same knee. It is not possible to copy the preoperative anatomical situation
exactly with the virtual intraoperative data. The reason for this are firstly inter- and intraobserver errors in both methods (CT/Navigation). Secondly, a standardized method for measuring and performing the preoperative CT scan is very hard to achieve. Only with a 3D model of the complete distal femur an assessment will be correct. However, a 3D CT scan requires a lot of radiation. It might be difficult to collect statistically valid data due to ethical reasons (radiation exposure of the patient). In the study presented, the local ethic committee (IRB) accepted the study protocol just by using the technique of Waidelich et al [1] with only 3 CT-scans at the examined leg for assessment of rotation and the axes and angles mentioned above.

References
ACL reconstruction with Orthopilot System: Correlations between the computer data and the X-rays measurements. A study with 50 cases

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The aim of the study is to prove the reliability of the computer during the ACL procedure.

The surgical procedure is a classical arthroscopic ACL reconstruction. We used the Orthopilot-System with an infra-red camera made by Polaris system. The computer needs the fixation of two rigid bodies, one on the tibia and one on the femur. We use now active rigid bodies on the tibia and on the femur, and we use also passive sensors to palpate the different external and internal points. We begin to record several external points on the tibia and some internal points in the knee around the intercondylar notch and the axial face of the lateral condyle. The tibial tunnel is drilled with a special guide which is viewed by the camera of the computer. The position of the tibial tunnel is recorded in the frontal and sagittal plane. The angulation of the tibial tunnel is also recorded in the two planes, and the femoral tunnel is drilled with a special guide. We use two guides: the conventional guide first and the CAO guide in a second time.

All the points and the data are recorded by the computer.

In our study, we have two aims: In the first study, we research the reliability of the computer, we compare the computer data with measures realized on the post-op X-rays. In the second study we compare the traditional femoral guide and the CAO femoral guide.

For the first study we measure on the post-op X-rays: The position of the tibial tunnel in the frontal plane, in the sagittal plane, the angulation of the tibial tunnel in the frontal and in the sagittal plane, the distance of the center
of the femoral tunnel to the over the top position on the lateral condyle. All the X-rays are realized in the same conditions, by the same person and the measurements are realized twice. The X-rays enlargement is always the same (1:1). We have two views: Frontal view and antero-posterior view. We also use a statistic study to treat the different data. For the second study we compare during the procedure the position of the femoral wire put with the traditional guide (Phasis) and the position of the wire put with the help of the computer. We record the data and we compare the results.

For the first study we have a very good statistical correlation between the computer data and the X-ray measurements. All the data are correlated with p<0.001. The position of the tibial tunnel is always in a good position, the center of the tunnel is at 44% of the width of the tibial in the frontal plane and 39% of the depth in the sagittal plane. The angulations of the tunnel are changeable and depend on each case, but there is a correlation between the computer data and the X-rays measure. The position of the center of the femoral tunnel with regard to the over the top position is in female cases at 4.7 mm in mean and at 5.3 mm in mean in male cases. We have also a very good correlation between the computer data and the X-rays measure. For the second study, we obtain the same position of the wire with the two guides in 97% of the cases.

This study proves that the Orthopilot System is reliable to perform an ACL reconstruction and there is no difference between the conventional procedure and the CAO procedure with the position of the tibial tunnel and femoral tunnel, when we use a procedure out-in to drill the femoral tunnel. There are no studies actually who compare in ACL reconstruction the computer data and the X-rays measure. There is some difficulties to obtain very good and reproductive X-rays after surgery and a learning curve is necessary for the radiologist.

The CAO procedure gives us a lot of information about the isometry of the ligament, the conflict with the intercondylar notch and does not increase the time of the procedure too much. Actually we perform 300 ACL reconstructions per year and 75 with the computer. We find no clinical difference actually but we think that the computer is a good help in difficult cases and perhaps if the surgeon is a young surgeon or with a short experience with this type of surgical procedure.

References

1. J.-C. Panisset, D. Saragaglia, Place de la navigation dans la chirurgie du ligament croisé antérieur Ligaments croisés du genou (Cahier N°86) (page 42), Elsevier
Adjustable constraints – A novel method for positioning 8-in-1 cutting guides in computer assisted orthopaedic surgery

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Introduction: Cutting guides are frequently used to prepare bony surfaces for implants in orthopaedic surgery. A single guide template can contain several cutting surfaces so that the finished bone surface conforms to the inner implant geometry. Femoral templates like those used in total knee arthroplasty (TKA), for example, typically contain four or five (4in1 or 5in1) cutting guide surfaces. Recently, 8in1 cutting guides have been introduced, which permit the surgeon to perform all five planar cuts plus all three notch cuts using only one guide template [1].

Although incorporating many cutting planes within a single template helps to maintain the congruency of the bone cuts, positioning such templates in surgery can be illusive. This is due in part to the many degrees of freedom (DOF) that must be adjusted simultaneously (5 DOF for a 5in1 and 6 DOF for an 8in1). Moreover, these templates typically cover most of the exposed femoral bone surface, making it difficult to adjust the relative position between the guide and the underlying bone.

Several solutions have already been developed for assisted cutting guide positioning in navigated surgery. Freehand positioning is the most common means used because of its inherent speed and simplicity, though this technique is usually effective and repeatable in the hands of an experienced surgeon.
Other solutions typically use mechanical systems that have a base element which is first fixed to the bone [2]. Adjustment screws are then used to adjust the position of the template relative to the base before fixing the guide to the base or bone. Although these systems can offer improved precision over conventional or free-hand positioning techniques, they can also present several drawbacks. Firstly, many designs require fixing a base in regions that are clear of the cutting area, thus requiring larger incisions. Secondly, fixing a base can mean adding extra steps, time, and complexity. Thirdly, the design of the adjustment mechanisms can be large, complex, and costly to manufacture and sterilize.

Our goal was to develop a positioning system for complex cutting guides that has the advantages of precision, speed, and simplicity. We propose a solution using variable constraints that can be adjusted in surgery to conform to the shape of the patient’s bone.

**Methods:** We demonstrate our approach with the Universal Knee Instrument(R) (UKI, Precimed Inc. USA), a versatile 8in1 TKA guide designed to perform all femoral cuts with a single jig. The protocol has been developed on the open platform Surgetics Station(R) (Praxim-medivision, France), which uses image-free BoneMorphing(R) technology to intraoperatively reconstruct the bone surface geometry [3].

We integrated an array of “adjustable constraints” into the UKI by machining a number of threaded holes directly through the template (Figure 1). Two anterior screws adjust primarily axial rotation and flexion, while two distal ones control varus/valgus and proximal/distal positioning. Anteroposterior positioning is fixed by a mechanical constraint on the anterior arm which prevents femoral notching, and mediolateral positioning is done free-hand using centerlines rendered on the navigation interface. In total, this configuration thus has 1 fixed and 4 variable constraints (1+4 constraint mode).

The steps of the positioning algorithm are:

1. Implant planning
2. Position of cutting planes
3. Position of cutting guide
4. Axes of adjustment screws
5. Intersection of axes with bone surface
6. Optimal screw length (select from database)
7. Screw adjustment distance from reference surface
Once the surgeon plans the optimal implant size and position intraoperatively based on the mechanical axis, knee balancing in flexion and extension, and BoneMorphing acquisitions, the system indicates which screw length is optimal so as to minimize the screw length protruding from the outer guide surface. The system then calculates the required screw adjustment from the guide reference surface, from the bone intersection along the screw axis. The surgeon/assistant can then preadjust each screw using a special graduated screwdriver such that when the template is positioned on the bone, it already corresponds to the desired position. The guide position is then “fine-tuned” once it is placed on the bone surface, by tracking its position relative to the femur using a planar probe rigidly inserted into one of the cutting slots. The navigation interface assists this step by displaying graphically in real time which screw to turn in which direction, and by how many turns, in order to bring the guide to the desired position.

![Figure 1](image1.png)

**Figure 1** (Left) Virtual models of the bone and UKI template with adjustment screws, (right) schematic diagram showing screws positioned in between cutting planes

**Results and Discussion:** To test the adjustable constraint configuration and freehand navigation, we first tried the system on sawbones with several subjects before carrying out a cadaver test at the HSS. In our initial prototype we incorporated 10 different screw positions to determine empirically which
combination of positions worked best for stability and ergonomics. The sawbone and cadaver experiments showed that preadjusting alone positioned the UKI within 1 – 2º and 1 – 2 mm from the desired position, though the final position could always be brought within 1º/mm during the fine tuning step.

Surprisingly, freehand navigation of the UKI using only the 1 fixed constraint for stabilization proved to be fast and accurate in the hands of an experienced surgeon skilled in manipulating several DOF at a time. However, this method is often difficult for most surgeons and the (1+4) adjustable constraint mode seemed to offer better stability and reproducibility.

In addition, stability of the guide during final pinning is improved due to the distribution/orthogonality of the positioning constraints. The screws can be left in place during sawing as they do not intersect any of the cutting guide-slots (Figure 1), permitting quick transition from positioning to cutting.

In conclusion, we demonstrate that it is possible to precisely adjust the position of an 8 in 1 cutting block without any primary fixation on the bone, considerably simplifying the instrumentation and making the global navigation process very fast.

References
Bone morphing vs. freehand localization of anatomical landmarks: Consequences on the reproducibility of TKA

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Introduction: During total knee arthroplasty (TKA), the positioning of each implant relative to the bone is a combination of 3 rotations (flexum, varus-valgus, axial rotation) and 3 translations (antero-posterior, medio-lateral, distal cut height). These parameters are optimized based on implant specific criteria (tibial slope, tangency to anterior cortex, external rotation, etc…). An optimization loop is performed in order to reach the ideal position of both femoral and tibial implants.

The input parameters of this optimization are the mechanical axis, anatomical landmarks, and the 3D surface model. In an image-free navigation system, these are acquired either from kinematic acquisitions (hip center) or by direct digitization of landmark points on the bone surface using a pointer. 3D surface models can be obtained with 3D to 3D elastic registration of sparse point clouds acquired intra-operatively as in the Bone Morphing® technology (Praxim-Medivision, La Tronche, France) [1].

The main objective of this study is to assess the reproducibility of 3D based implant planning in navigated TKA procedures. Some of the most currently used landmarks in TKA [2] can be recomputed after bone morphing or directly digitized with a pointer. In a second part of the study, we compared, for the two methods the reproducibility of the positioning parameters directly influenced by these landmarks.
Methods: A test application has been developed on the Surgetics Station based on a TKA application with additional steps for the digitalization of specific landmarks. Two trained users have performed a total of 30 tests on the same sawbone. The femoral and tibial planning proposed by the system was recorded for each test. For a pertinent analysis, landmarks and planning were expressed in a common anatomical reference frame that had been acquired prior to the experiments using the current per-operative method.

The second goal of this study was to compare the reproducibility of one positioning parameter using points derived from the 3D model or points acquired on the bone surface. We decided to isolate the antero-posterior translation of the tibial and femoral components, and the tibia medio-lateral sizing. These parameters are normally optimized simultaneously. Therefore it was first necessary to define a unique implant position relative to the bone. Then, on every test, the error with respect to the ideal criteria was computed using the 3D model and the single points of the current acquisition as the inputs. For example, a criterion for femoral antero-posterior translation can be the tangency of the implant to the anterior cortex. The criterion to be minimized is therefore the distance of the implant to the anterior cortex. The expert positioning of the femoral implant had been injected into the trials and the distance of the implant to the femoral anterior cortex was measured using the bone morphing or a single point on the anterior sulcus of the femur.

Table 1  Bone Morphing vs. Freehand localisation of anatomical landmarks: comparison of standard deviation (n=20) for the positioning parameters directly influenced by these landmarks

<table>
<thead>
<tr>
<th>Information derived from the 3D model after Bone-Morphing.</th>
<th>Free-hand digitalized landmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibial resection level (Tibia worn condyle)</td>
<td>Not recomputed</td>
</tr>
<tr>
<td>Tangency to the femoral anterior cortex</td>
<td>0.06</td>
</tr>
<tr>
<td>Tibia anterior tangency</td>
<td>1.3</td>
</tr>
<tr>
<td>Tibia Medio-Lateral Size</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Results: For one of the users, the sizing algorithm recommended two different implant sizes (size 2 and 3, n = 20), while for the other, there was no intra-operator sizing variation for the femoral and tibial implant (size 2, n=10). Considering the discrete property of implant sizing, it shows a good reproducibility. Standard deviations of the six positioning parameters showed
very good reproducibility within 1° or 1 mm except for the axial rotation (1.84 for the femur and 1.02 for the tibia). The reliability of anatomical landmarks for determination of axial rotation has already been discussed in [3] and [4]. Concerning the second issue, the Table shows the direct influence of landmarks on the positioning parameters, comparing the standard deviation for all 30 cases in function of the landmarks origin.

**Discussion:** Some free-hand anatomical landmarks show good reproducibility in the interesting direction but others can lead to hazardous implant positioning parameters. It has to be taken into account when designing a CAOS system. The bone morphing can be used to recompute some particular anatomical information. However, if the search is done in one anatomical direction (medial, posterior or distal), particular attention should be given to the choice of the landmarks determining the anatomical axis.

The surgeons have to be aware of the critical importance of these steps in the overall procedure and efforts should be put in the user interface to help them to precisely identify these points. Bone morphing combined with the digitalization of reliable and reproducible landmarks, enables a reproducible positioning and sizing of the implant. With a specific 3D model, it is possible to do a global planning where all the parameters can be optimized in the same time. Indeed, given a specific implant position on the bone, it is possible to compute the contour of the implant and therefore give information about tangency, and sizing. This cannot be done by digitalization of individual points. As the gap between the femur and tibia can be computed on each condyle at any degree of flexion, it is also possible to achieve dynamic ligament balancing.

**References**


A novel interface for ultrasound guided percutaneous pinning of fractured scaphoids

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Introduction: We propose a novel interface for minimally invasive percutaneous pinning of the scaphoid bone. The interface integrates and registers the pre-operatively generated 3D bone meshes, extracted from Computed Tomography (CT) images, with the intra-operatively tracked 2D Ultrasound (US) images. The interface is targeted to enhance the surgical guidance by using 3D visualization, while reducing the ionizing radiation exposure for patients and operating room staff.

Each year in North America, more than a quarter of a million new scaphoid fractures occur; accounting for nearly three-quarters of all wrist fractures [2]. Other than percutaneous pinning, common treatments for scaphoid fractures include open reduction surgical pinning and casting. Although casting is the most common treatment, it has complications [6] and has reported union rates of 88% [5]. Surgical pinning maintains an earlier return to function over casting, but has risks associated with invasive procedures; such as infection and damage to blood supply. By using intra-operative fluoroscopy to guide the surgical instruments, surgeons are able to insert the tools through a much smaller incision. Therefore, percutaneous pinning reduces the invasiveness associated with open reduction surgical pinning while maintaining its key advantage: The significant decrease in time to recovery over casting, or, at the very least, far faster return to function compared to long-term casting [1].
Despite its advantages, there are two main drawbacks with the use of intra-operative fluoroscopy in the percutaneous pinning of fractured scaphoids: a) two dimensional fluoroscopy images complicate the surgeon’s effort in 3D positioning, b) the repeated exposure of the surgical team to X-rays, an ionizing radiation. We propose to replace fluoroscopic imaging with intra-operative US to guide the surgeon’s positioning for this application.

**Methods:** In order to verify the interface, phantom tests were designed using a typical setup. First, using a GE LightSpeed diagnostic CT scanner, images were acquired from a Sawbones scaphoid phantom in the long-axis orientation; voxel resolution was 0.188 mm x 0.188 mm x 1.25 mm (interpolated to 0.625 mm). Using the marching-cubes technique, a meshed 3D CT model was formulated; then 30 landmark validation points were collected from the model.

![Figure 1](image)

*Figure 1  Registration results; the blue lines show the bone surfaces extracted from ultrasound images registered to the bone mesh surface*

The scaphoid phantom was then hard-mounted to a stainless steel jig equipped with a Dynamic Reference Body (DRB) mounted to remain clear of the water bath and to provide optical position tracking. The jig was then placed in a tub of room-temperature water and ultrasound images were taken.
US images were acquired using a 12 MHz, one-dimensional array GE Voluson transducer. The transducer carried an optical target that was followed by the optical camera; a Polaris optical tracker (Northern Digital Inc.). The reference of the optical target to the DRB allowed for the determination of its 3D spatial coordinates. Ultrasound images were captured through a frame-grabber, which was synchronized with the Polaris camera system. Furthermore, thirty landmark validation points, for ground truth error analysis, were collected using an optically tracked stylus.

Using a Matlab based Graphical User Interface (GUI), US images were segmented using an automatic algorithm. The segmented US images were then visually aligned with the CT model in 3D space, as in Figure 1.

Manual alignment involved matching two pairs of three points; each representing the same, arbitrary, landmarks on the CT mesh and the extracted 3D US surface. Visually acceptable manual alignments were then fine-tuned using the feature-based Iterative Closest Point (ICP) algorithm; only sub-patches of the model and US extracted bone surfaces were used for ICP-based registration as in [7].

**Results**: For all of the experiments, both virtual (from the computer model) and stylus validation points were collected that represented the same anatomical landmarks. After manual alignment and ICP-based registration, the mean values for the validation point clouds were compared. The difference of means test, along with its corresponding deviation, was calculated as the ground truth error for the registration technique; only translation errors are presented as future testing will determine rotational accuracies.

For manual alignment, the difference of means translational error between virtual and physical point clouds was 2.21 mm; the corresponding standard deviation was 0.0952 mm. The equivalent results for ICP based registration was 3.33 mm and 0.0866 mm, respectively.

**Conclusions**: We have developed and demonstrated that the proposed US-based, surgical guidance interface is capable to 2.21 mm accuracy in translational error; these results are comparable with other findings [3,4,7,9]. ICP based registration was less successful with an average worst case translational error of 3.33 mm. The scaphoids’ small size and featureless characteristics, along with ICP’s sensitivity to non-Gaussian noise [8], can account for the worse results as suggested in [7,9]. Further laboratory and clinical tests are currently underway.
References


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Introduction: Computer assisted technology enables the surgeon to measure and appraise what he really does during surgery. It is the very first time that we are able to monitor in real time knee behavior from extension to flexion. These measurements actually reflect tibial rotation about the femoral condyles and are also indicative of patellar tracking. Patients undergoing computer-assisted TKR using the Orthopilot (Aesculap/B.Braun, Tuttlingen) and PS Search Knee Evolution and Columbus Knees, were evaluated with four measurements of the femoro-tibial angles at 0, 30, 60 and 90 degrees of knee flexion before and after TKR. These measurements were compared to those of femoral component rotation.

Materials and Methods: A series of 25 patients underwent TKR for endstage osteoarthritis from January 27, 2003 to November 17, 2004. The series concerned 13 right and 12 left knees, 8 males and 17 females with an average age of 73.6 (+/- 8.1; 44 – 84). The BMI score was 29 (+/- 5.55; 21.6 – 42.7), KKS function was 35.8 (+/-17; 5 – 70) and KKS Knee score was 51.2 (+/-8.52; 30 – 73). Preoperatively we measured femoral mechanical angles on a long-leg film. We collected the varus/valgus femoro-tibial angles from knee extension to 30, 60, and 90 degrees of knee flexion. Whiteside’s
line was used to align the femoral component during the surgical procedure. No procedure required patellar resurfacing.

**Results:** Preoperatively 4 patients were in valgus 185.6 +/- 4.7 (range 191 – 182), one well aligned and 20 in varus 174.1 +/-3.45 (178 – 166)

Femoral mechanical angles were 90.7 +/-3.1 (84 - 98) on preoperative X-ray assessment.

Intraoperative femoro-tibial angles were -4.2 +/- 5.2 (-14 to 11) at 0 degrees, -2 +/- 3.6 (-11 to 6) in 30 degrees, -2.8 +/- 2.8 (-10 to 3) in 60 and -2 +/- 2.8 (-10 to 5) in 90 degrees before TKR and -0.08 +/-0.57 (-1 to 1) at 0, -0.2 +/-1.1 (-3 to 2) in 30, -0.68 +/-1.9 (-6 to 5) in 60 and -0.68 +/- 2.2 (-7 to 4) in 90 degrees after TKR.

From extension to 90 degrees of flexion, the femoro-tibial angle deformity had a tendency to decrease before TKR both for varus or valgus deformities. The femoral component was externally rotated with 2 +/-1.63 (0 to 7) degrees. Preoperative angle augmentations seem more difficult to correct.

**Discussion:** Using Whiteside’s line, we were close to the recommended femoral component orientation (1,2,3). Even in gross osteoarthritis, the majority of posterior condyles are still unworn (from extension to 90 degrees of flexion, the knee mechanical angle corrects from the initial deformity). This suggests that posterior condylar referencing may be more reliable than is commonly thought (4,5).

Long-leg alignment films may still be important for preoperative planning in view of knee anatomy variability. This study allows us to define the knee flexion arc before and after TKR. This series is small but this study can help the surgeon to foresee how femoral rotation should be adapted to each individual patient.

**References**

Varus and valgus stress before and after TKR. What is right?

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Introduction: Adjusting the soft tissue balance during TKR remains difficult even for experienced surgeons. Computer-assisted technology allows us to evaluate knee behavior in real time and gives us the opportunity to measure many unknown values of the pathological knee. A better understanding of the knee measurements would be helpful to accurately and predictably adjust TKR balance.

25 patients underwent computer assisted TKR using the Orthopilot (Aesculap/B.Braun, Tuttlingen) and PS Search Knee Evolution and Columbus Knees. We collected and stored four measurements of the extended knee before and after TKR.

Material and Method: A series of 25 patients underwent TKR for endstage osteoarthritis from January 27, 2003 to November 17, 2004. The series concerned 13 right and 12 left knees, 8 males and 17 females with an average age of 73.6 (+/- 8.1; 44 – 84). The BMI score was 29 (+/- 5.55; 21.6 – 42.7), KKS function was 35.8 (+/-17; 5 – 70) and KKS Knee score was 51.2 (+/- 8.52; 30 – 73). Preoperative X-ray planning including long-leg film, AP, lateral and skyline views was undertaken. All procedures were performed using the Orthopilot system, which enabled us to collect femoro-tibial angles stressed in varus and valgus by the surgeon in extension. Among these patients, only 6 had a medial or lateral release. All others had a medial approach and osteophyte removal.

Results: Preoperatively, 4 patients were in valgus 185.6 +/- 4.7 (191 to 182), one well aligned and 20 in varus 174.1 +/- 3.45 (178 to 166).
Preoperatively, the varus stress average angle was $5.13 \pm 3.44$ (0 to 11), valgus was $1.5 \pm 1.53$ (-4 to 4) and at the end of the surgery the varus stress average angle was $1.78 \pm 1.59$ (0 to 5) and valgus was $1.79 \pm 1.06$ (0 to 4). After 45 days, knee average flexion was $115\pm 10$; (90 to 126). Two patients had an early manipulation. One of them had an extension deficit of less than 5 degrees.

**Discussion:** This study showed that only 6 of the 25 patients needed extensive ligament release (24%).

Preoperatively valgus stress values were about three times higher than varus stress values (3,4). At the end of the surgical procedure, in the extended knee, varus and valgus were equivalent.

This work confirms previous studies showing that not all knees necessarily need an extensive release. We note that the medial approach is already in itself a partial release (5).

This work also confirms that a relative tight knee in extension doesn’t compromise flexion and extension results as long as attention is paid to the flexion gap (1,2).

**References**

Minimal access total knee arthroplasty using a miniature robot and a new side milling technique

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Introduction: In conventional or “open” total knee arthroplasty (TKA) the standard surgical (anterior/midline) approach uses a 25 – 30 cm skin incision extending proximally from just distal to the tibial tubercle, followed by a medial 20 – 30 cm parapatellar arthrotomy which extends superiorly through the quadriceps tendon [1]. Although the incision allows for lateral evertion and dislocation of the patella, dividing the quadriceps muscle can cause increased pain, blood loss, and time to ambulation, prolonged hospital stays and rehabilitation, and decreased range of motion and knee strength [2].

Surgeons are beginning to use “minimal access” or “minimally invasive” surgical (MIS) TKA techniques. Some preserve the quadriceps mechanism entirely, while others use a ~2 cm vastus medialis snip to facilitate patellar subluxation [2][3]. Femoral cuts are made from the anterior or medial side through a 6-14 cm “mobile” incision that is moved to expose different aspects of the joint by flexing and rotating the knee. Approaching the bone cuts obliquely or medially circumvents the need to evert the patella, thus reducing morbidity and trauma to the extensor mechanism, and improving post-operative knee function, recovery rate and pain.

A significant drawback to MIS TKA is the difficulty in attaining precise implant cuts and alignment with the reduced bone exposure. Currently, the bone cuts are carried out by pinning a downsized cutting-block onto the side of the knee. Because sawing accuracy diminishes quickly with extension of
the sawblade beyond the cutting-block, however, achieving accurate cuts is challenging and requires a high level of surgical experience [2].

Our goals are to develop a miniature robotic guide positioner that is (1) sufficiently light and compact that it can be mounted on the medial side of the knee, and (2) can precisely position a milling tool guide that can follow the “mobile window” for each of the five femoral cuts.

Figure 1  Mini-robotic milling guide positioner mounted on the medial side of the knee. The “G” shaped rigid body is used to calibrate the system and to verify the guide position before making a cut

Methods: We designed a 2 degree of freedom (DOF) fixation/adjustment system that is ~30 mm cubed, ~50 grams in weight, and attaches solely to the medial aspect of the femur with two threaded pins just proximal to the distal cut. To keep the design as compact as possible, we integrated a fine-tuning screw for adjusting only varus/valgus; internal/external rotation is lockable but rotates freely during navigation. The robot has two motorized DOF whose axes are arranged in parallel ~35 mm apart and are aligned perpendicularly to the profile of the implant cuts using the adjustment mechanism [4]. The first motor axis is fixed to the adjustment system while
the second attaches to a single saw or milling tool guide, allowing the guide to be positioned for all five implant cuts.

We encased both motors in a sealed autoclavable housing that is separable from the mechanical system containing the gears, bearings, etc., so that the motors only need to be connected to the robot during the five positioning phases. This prevents unexpected transfer of forces from the electrical cable to the fixation pins and tool guide. We incorporated a spring-loaded brake mechanism behind zero-backlash precision gears so that the guide can maintain its position during milling without the motors in place. Furthermore, since the brake sustains all of the applied loads during the cutting process, we were able to use very small motors weighing only 26 grams each. Thus, the system has sufficient power to move the cutting guide to the correct plane, but it is still backdrivable so it cannot cause serious harm to the patient or surgeon.

Bone cutting is performed from the anteromedial side through a small incision using a side-milling technique and a novel method of tool guidance. We designed a passive milling guide which allows the tool to both pivot and slide in the cutting plane. An additional rotational DOF about the milling tool axis improves the ergonomics of the guide, allowing the surgeon to angle their wrist at the most comfortable orientation.

**Results:** The navigation protocol has been integrated into the open platform SurgeticsStation® (Praxim-medivision, France), incorporating kinematic measurements of the mechanical axis, soft tissue balancing in flexion and extension, and image-free BoneMorphing reconstructions for intraoperative implant planning.

Experiments on synthetic bones (“Sawbones”) show that the repeatability in adjusting and locking the milling guide in varus/valgus and internal/external rotation is 0.1 – 0.2° standard deviation (SD, n=10, 2 subjects) in ~60 sec. We also measured the dual-motor unit positioning reproducibility by clamping a 0.01 mm resolution dial gauge to the adjustment base and measuring the guide surface location after randomly repositioning the motors. The resulting precision in the implant positioning plane was <0.01 mm SD (n=10).

**Discussion:** The 2DOF parallel robot architecture in combination with the passive 2DOF side-milling guide result in a kinematic positioning of the milling-tool entry point that is through a small MIS window of ~5cm for all five cuts (Figure 1). In addition, safety of the robotic guide is improved because the positioning motors can be mechanically separated from the guide during milling, and therefore no unexpected motions can occur as a result of
a controller malfunction. Moreover, the backdrivable system can be overpowered by the surgeon when the motors are attached during positioning or calibration. The modular system facilitates easy replacement in surgery and disposal of the autoclavable motors at the end of their lifespan.

We have also integrated the control of the electric milling motor into the navigation system to allow for advanced control techniques such as adjusting the milling motor speed as a function of the cutter position. This becomes particularly useful for the posterior cut, where critical soft tissues adjacent to the bone must not be harmed. We are currently performing a series of cadaver tests with new prototype milling guide, and will include a video of the experiments illustrating the surgical technique during the presentation.

References

Rotational alignment in total knee replacement using CT-less navigation

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Introduction: Since the restoration of mechanical axis alignment has been shown to be a major determinant of outcome in total knee arthroplasty (TKA), a frontal axial range of 180° ± 3° varus/valgus-deviation is known to increase long-term survival of prostheses (1). As a second factor influencing long-term survival and patient satisfaction after TKA, rotational alignment of components has come into focus (2). In recent literature, rotational malalignment of femoral and/or tibial components has been recognized to cause pain, reduced range of motion, instability and increased wear after TKA (3), if there is no evidence for classical implantation failures or other reasons for failure (e.g. inadequate frontal alignment/soft tissue balancing; infection). The aim of our study was to prove, whether the use of a CT-less navigation system may improve rotational alignment after total knee arthroplasty compared to non-navigated implantation technique.

Methods: A total number of 250 patients was enrolled into a prospective, comparative mono-center-study. Ninety patients received computer-assisted-orthopedic-surgery (CAOS) using the NAVITRACKTM-system. In 160 patients TKA was performed in conventional technique without a navigation system. Patients were operated by four orthopedic surgeons. Prior to surgery, patients gave written consent to participate in the study. All patients received the same type of prosthesis (INNEXTM, Zimmer Corp.). In not-navigated patients, surgeons used intramedullary tibial alignment, if bony tibial malformations were absent. Mechanical leg-axes as well as the partial-axes on femur and tibia were pre- and post-operatively identified using complete-leg-CT-scans. Further measurements (see below) were derived from coronary CT-scans and conventional X-ray. Since trans-epicondylary axis (TEA) – virtually perpendicular to mechanical leg-axis – approximates the knee-flexion-axis, TEA has earlier been used to determine femoral-component
alignment in TKA. Femoral component rotational alignment was defined by the posterior condylary angle (formed by condylary axis and TEA). Tibia-plateau position was measured from the angle formed by transverse tibia plateau axis relative to tibial tuberosity. Knee Society – and SF-36-Scores were collected pre- and post-operatively at 6 weeks / 6 months. Statistical analysis was performed by the chi-square-test.

**Results** (All values in mean SEM (range):

A mechanical-axis-range of $180^\circ \pm 3^\circ$ was achieved in 97.9\% of navigated, and in 76.8\% of the non-navigated patients. The tibial component was placed in a $2.1^\circ \pm 1.3^\circ$ varus-position in navigated patients. In the conventional patient group varus position was $1.8^\circ \pm 1.4^\circ$. A $0.8^\circ \pm 1.5^\circ$ femoral-valgus-position was found in navigated patients, respectively a $0.3^\circ \pm 2.7^\circ$ varus-position in the not-navigated. The internal rotation (relative to epicondylary axis) of the femoral component was $2.8^\circ \pm 1.0^\circ (0^\circ – 3.8^\circ)$ in the CAOS-group and $2.1^\circ \pm 1.5^\circ (0^\circ – 5.9^\circ)$ in the not-navigated. On the tibial side, the internal rotation of the plateau relative to tibial tuberosity was $20.5^\circ \pm 2.5^\circ (16.8^\circ – 24.8^\circ)$ in CAOS- and $22.2^\circ \pm 7.5^\circ (9.3^\circ – 43.2^\circ)$ in the conventionally treated patients. A significant reduction of outliers of mechanical-axis-ranges of $180^\circ \pm > 3^\circ$ was detected for the CAOS-group ($p=0.0015$, 6 weeks; $p=0.013$, 6 months). The analysis did not reveal differences in any SF-36 category between patient groups.

**Discussion:** CT-less navigation using NAVITRACKTM significantly reduced outliers in the reconstruction of a mechanical axis within the limits of $180^\circ \pm 3^\circ$ after TKR. NAVITRACKTM also reduce rotational malalignment of components, especially on the tibia. Since the use of NAVITRACKTM facilitates a visualization of bony landmarks it offers continuous alignment control during implantation. It may improve the survivorship of, as well as the functional outcome after TKR – if landmarks are registered correctly.

**References**

Validation studies of anatomical structure morphing

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Introduction: Anatomical structure morphing is the process of recovering the patient-specific 3D shape of the anatomy from digitized surface points. Models are typically obtained from preoperatively acquired CT scans, which may not always be available, or may not be a necessity if radiation-free and/or intraoperative solutions can be provided. Image-free procedures and hybrid procedures using statistical 3D shape models have been extensively researched [1, 2] to allow for accurate 3D visualization of bone structures that would improve the anatomical navigation for the surgeon. We have developed a stable method to construct a patient-specific model that provides an appropriate intraoperative 3D visualization [3]. We have successfully validated and published our methods using leave-one-out tests, and this paper presents the validation studies of our morphing technique carried out on two different cast proximal femur bones.

Methods: Our 3D statistical shape model based on principal component analysis was first constructed from a training database of bones. Since the application focus is on hip and knee surgery we chose to begin by concentrating on the proximal femur. 30 CT scans of the proximal femur were segmented, surface models of the bones were extracted and correspondence was established across the training population to construct a compact optimal model. Our previously developed statistical-based shape model infers the anatomical information in a robust way [3].

Two different cast proximal femurs were chosen for this study. High-resolution CT scans of the two bones were segmented and fine 3D surface
models of these bones were generated. The cast bones were fitted with fiducial markers to register the CT surface models into the tracked bones’ coordinate space.

During the experimental trials, the CT surface models were registered into the anatomy’s coordinate space by using paired-point registration and surface matching from an in-house optical-tracking navigation system, yielding a registration error of 0.2 mm for this experiment. The registered surface models were considered as “golden” references that were used for error measurements (computed using Mesh [4]) and validation of the predicted bone morph models.

![Bi-directional error: From golden reference to predicted shape (left) and from predicted shape to golden reference (right)](image)

Bi-directional error: From golden reference to predicted shape (left) and from predicted shape to golden reference (right)

Three anatomical landmarks (lesser trochanter, femoral notch, and greater trochanter) were first digitized using a calibrated navigated pointer to initialize the predicted morphed model in the tracked bones’ coordinate system. The pointer was then used to acquire additional bone surface points (24 – 26 points), spread over the surface of the cast bones. The morphing procedure was then employed to compute the morphed predicted model in the tracked bones’ coordinate space. Two different research scientists, to obtain stable estimates of the errors and to have an initial impression of the repeatability of our proposed method, each performed a series of 5 – 7 trials per bone.

Results: For the presentation of results, we shall consider the two bones as separate experiments.
For the first bone, the mean error over all 14 trials ranged from 1.65 mm to 2.24 mm. The average mean error was found to be 2.03 mm and the average median error was found to be 1.69 mm for both users’ combined results, over all trials, for 24 surface points per trial.

We did not notice a large observable discrepancy between the two users. The first user had a 1.94 mm average mean error and a 1.51 mm median error over 7 trials. The second user obtained an average mean error of 2.11 mm and 1.87 mm average median error over 7 trials.

For the second bone, the mean error over all 10 trials ranged from 2.56 mm to 3.66 mm. For the users’ combined results, the average mean error was observed to be 3.04 mm with an average median error of 2.86 mm, for 27 surface points.

For the series of experiments involving the second bone, we noticed a slightly larger discrepancy between the two users’ trials. The first user had a 2.80 mm average mean error and a 2.58 mm average median error. In contrast, the second user attained a 3.29 mm average mean error and a 3.14 mm average median error over 5 trials.

Discussion: In the clinical situation, considering what we have outlined in our results, given that the surgeon is able to accurately digitize a series of surface points of the anatomy, it can be seen that our bone morphing method can provide an accurate, and repeatable prediction of the patient’s anatomy without a priori information, as per a CT or MRI scan.

The error measurements that we have presented here, although in satisfactory experimental conditions, do not imply a lower-bound accuracy for our bone morphing method. Rather, they provide an accuracy limit given the training population size and given the bone morphing algorithm’s dependency on an accurate landmark digitization. It is to be expected, therefore, that an increase in population size would increase the accuracy of the method. Further, results could have been improved by acquiring more surface points, but this would have been too drawn out compared to a surgical situation, where it becomes less practical for the surgeon to acquire a large set of points using a tracked pointer.

This series of experimental trials demonstrated that in general, the bone morphing method performs well once initialized with accurate localization of the 3 landmark points. In a clinical situation, although the landmarks may be defined with flexibility (they should be fairly separated), there exists a challenge in localizing them due to limited surgical access and possibly high patient-to-patient variability. To this end, we intend on next implementing a
recursive registration step in the bone morphing calculation (by ICP or similar algorithm) so as to minimize our technique’s dependency on landmark selection. Further, we have also made initial steps on expanding the training population as well as exploring other means by which to intraoperatively obtain surface points from a given patient’s anatomy, for instance through use of ultrasound or fluoroscopy.

Our validation studies have demonstrated that indeed, we have a robust, accurate and stable bone morphing method and it suffices to refine the other components in our system to finally provide the surgeon with a reliable intraoperative visualization and navigation technique.

References

A natural and intuitive 3D planner for orthopaedic surgery

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Introduction: We describe a software system to assist in the planning of orthopaedic surgery. We have designed the system so that the surgeon can interact with it in a natural and intuitive manner. The system is intended to enable the surgeon to plan the reduction of a multi-fragment fracture of the femur within five minutes.

The system presents the surgeon with a 3D model of the fractured bone from CT data, and allows the surgeon to drag and rotate the 3D bone fragments on the computer screen. Interaction with the system is made more natural by providing a collision detection mechanism to prevent fragment interpenetration during manipulation, and by providing a “snap fit” mechanism to align fragments more closely after the fragments have been brought into approximate alignment by the surgeon.

After a plan has been built, the fragments will be tracked intraoperatively and compared to their intended positions in the surgical plan. This is ongoing work.

Methods: The surgeon is presented with two 3D models of the bone on the computer screen: one is a “fracture model” from CT data of the fractured bone; the other is a “template model” which approximates the unfractured bone. The template model can be obtained from the reflection of CT data of the unfractured opposing side, or from an atlas. The use of a template assists the surgeon by providing intuitive visual clues to the correct locations of the fragments.

The fracture model is made by segmenting the CT data into individual fragments. The segmentation is done by a separate computer program, which passes the fragments to the planner. The surgeon manipulates the fragments to drag them into their correct positions and orientations on the template.
model. The surgeon’s viewpoint, and the position and orientation of each fragment, can be manipulated in 3D with a mouse or trackball. At any point in the planning, the surgeon can view the fractured bone as a surface mesh model or as a digitally reconstructed radiograph.

The planner incorporates a collision detection mechanism to prevent the interpenetration of fragments during the planning. The collision detector [Ponamgi et al. 1995] keeps track of the closest points between the fragment being manipulated and every other (static) fragment, and prevents movements that result in interpenetration.

The planner incorporates a “snap fit” mechanism which brings into close alignment surfaces that the surgeon has aligned approximately. The snap fit mechanism determines matching surfaces between the fragment being manipulated and another fragment, and uses an Iterative Closest Point algorithm [Besl and McKay 1992] to more closely align the matching surfaces. The snap fit takes a few seconds to perform.

The planner will be used intraoperatively. Larger bone fragments will be registered and tracked by the attachment of dynamic reference bodies. The planner, which maintains a natural coordinate system for each fragment, will report the relative orientations and positions of the tracked fragments. The planner will also report the discrepancy between the planned positions and orientations and the tracked positions and orientations.

Results: This work is in progress. We have built many components of the prototype planner. Our next phase will be a usability study – involving several surgeons and residents – to determine the effectiveness of our 3D interface for surgical planning. Following that, we will integrate the planner with our intraoperative tracking system.

Discussion: Our goal is to have the surgeon complete the plan within five minutes. We believe that this can be achieved by careful design of the user interface. Our usability study will likely uncover techniques beyond those described above, which will improve the quality of the surgeon’s interaction with the system.

References
Individual optimization of the individual joint biometry in THR. Computer assisted positioning and selection of implant segments in a new modular THR implant system.

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Introduction: Navigation in total hip replacement (THR) is used routinely in many operation theaters nowadays. Two essential flaws of currently available systems have to be listed. One has to be addressed to the lack of collecting supplementary biometric data and consequently to use it for an optimized joint adjustment. In most cases navigation of the femoral stem in THR is reduced to leg length (z-axis of the body) and rotation around this axis (anteversion). Information about the stem position and rotation with respect to the other two coordinate axes is in general not available. In addition, interaction between the two joint partners – prosthetic acetabular hip cup and femoral stem – is not taken into consideration. A dislocating hip joint or poor biometric function can already be triggered, if a not more than a mere imperfection of the position of each implant adds up to a major geometric and functional insufficiency [1]. A navigation system should be able to detect such an unfavorable position of the firstly implanted prosthesis and correct this imperfection by modifying the position of the second implant.

Here the second essential flaw enters the stage. Even if these parameters could be navigated, currently available THR endoprostheses do not offer enough possibilities for geometric adaptation. For example, leg length and lateral offset are highly linked due to the design of currently available femoral stems and cannot corrected individually. Importantly enough, this shortcoming has a high impact on limping and dislocation tendencies [1].
A newly developed navigation and endoprostheses system for THR overcomes the addressed limitations and is being introduced in this presentation together with a report of clinical experiences.

**Methods:** Based on an existing image free system for cup navigation in THR functionality for stem navigation is added. Navigated parameters concerning the acetabular hip cup cover position and rotation with respect to all three axes of the coordinate system. The cup prosthesis is already established and widely used with a modern implant design.

The newly developed short stem has a modular concept. Its implantation in the proximal femoral metaphysis is designed to preserve the bone around the femoral neck. The new implant is divided in two parts according to the distinct function. The part that is responsible for primary stability and bony ingrowth is separate from the neck section. The latter is available in different caput-collum-diaphysis (CCD) and rotation angles and therefore addressing leg length, lateral and antero-posterior offset (influenced by rotation) independently. The metaphysis part is designed conical to prevent secondary sinking in. For improved ingrowth its designated bone contact area is additionally covered with a layer of calcium-phosphate. To assemble the femoral stem implant the independent neck section is inserted into a conical cavity at the proximal end of the metaphysic part.

Navigation of the femoral stem starts after the metaphysic part is in place and supports the surgeon to select the correct neck section and length of prosthetic head. The navigated parameters in this step are leg length, lateral and antero-posterior offset (influenced by rotation), as well as simulation of prosthetic impingement within a predefined range of motion of the hip joint.

**Results:** In tests it was proved to be one of biggest problems to develop a fixation for the femoral rigid body that was non-invasive as well as fix enough to resist the high impacts during femoral rasping. In its current form the system was successfully tested in laboratory and on cadavers, before it was introduced in clinical evaluation. Since the start of clinical evaluation a dozen surgeries have been performed so far. The relatively high number of parameters is still manageable due to reduced and intuitive information depicted on the navigation computer display. For the relatively complex selection of neck section a newly developed pointer-display interaction method was introduced.

During the surgeries the system proved to be reliable and comprehensible. Being currently at the beginning of the learning curve the additional time used for navigation is acceptable, but still one of the disadvantages of the
system. As a trend the additional time for this THR navigation seems to end up in roughly doubling the extra time for cup navigation only.

We found pelvic tilt and/or contractures of neighboring joints as the major uncertainty that biases the functional joint coordinate system [2].

**Discussion**: So far in THR many parameters can be tracked by navigation systems. However, options to influence these parameters by available endoprosthetic systems are very limited due to restricted implant design. Using the newly developed navigation and implant system we were able to overcome this problem and could also add more navigation functionality with respect to the harmony of the two joint partners. As the clinical key benefit of the system we perceived its ability to perfectly reconstruct the wanted hip geometry adapted to the individual biometry. The complexity of the modular stem prosthesis (metaphysic, neck and ball section) was much easier to comprehend by the use of the navigation system.

Preoperatively no additional imaging is necessary, intraoperatively extra time consumption seems to be promising for the use on a routine basis.

Even though the system was working well in the first cases and the early clinical outcome was very satisfying, a very important aspect affecting all THR navigation systems has to be addressed. As other groups found earlier, the individual pelvic tilt is not yet part of the navigational computation. In more elaborate systems like the proposed one this problem becomes obvious and if not respected it may lead to instable THR despite (or due to?) navigation.

**References**


Evolution in ligament balancing surgical technique for TKR. From historical gap measurement via today’s force controlled gap-balancing to tomorrow’s patients individual joint stability

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Introduction: Historical gap measurement in TKR with special focus on ligament stability is as old as modern TKR. Insall, Freeman and others have promoted this concept successfully1). In-vivo kinematics studies using fluoroscopic methods2) underline the importance of soft-tissue control in TKR. Gait laboratory studies3) show the clear influence of soft tissue balance on a patient’s gait pattern. On the other hand, the complexity of the surgical technique and the lack of quantitative data for the individual correct soft tissue-tension are limiting factors for the standardization of this concept.

Today’s force controlled gap-balancing uses surgical navigation, which allows precise 3D reconstruction of mechanical axes and the measurement of gap distances under defined tension. Since 2002 the authors have clinically used a force measuring device (ligament tensioner), which allows to apply controlled tension to the soft tissues4). Joint stability was defined to be 80 N per compartment in flexion and 100 N for each compartment in extension. This tension was used as a standard force to gain stability in flexion and extension.

The control of patient-individual joint stability during navigated TKR allows the application of non-standard ligament tension. Instead of applying a uniform tension, the differences in soft tissue properties of each patient are respected. The concept and first clinical results of this method are reported.
**Methods:** A ligament tensioner was developed to control the individual soft tissue stiffness. It communicates with the optical tracking system by means of dynamic referencing. Applied forces and resulting gap distances are recorded online. These data are used to mathematically determine and display to the surgeon the patient’s specific joint stability properties. The joint stability function is recorded, which is the relation between gap-displacement and soft-tissue tension. This function shows a viscoelastic part, an elastic part and a transition area between the two, where the individual joint-stability is defined as being at the end of the transition area. The joint stability functions are recorded for 90° of flexion and full extension. Femoral cuts and implant positioning are then based on calculated stability criteria. After implantation the joint stability is monitored over the range of motion. Twenty (20) TKRs were performed by the same surgeon using this technology. The approach involved a standard median incision and a medial parapatellar arthrotomy by evertting the patella.

**Results:** An individual joint stability function was found for each patient showing remarkable inter-individual differences. Patients related parameters such as individual viscoelastic and elastic tissue properties show an important difference. A clear stability criteria could be detected in all knees. Ligamentous deformities and laxities have an influence on the joint-stability function and could be quantitatively displayed. Applying the defined criterion, stability was achieved between 50 and 80 Newton per segment in most treated knee joints.

**Discussion:** Using navigation technology quantitative measurements of soft tissue mechanical characteristics can successfully be integrated into a standard TKR. Highly stable and proper soft-tissue-controlled knee function over the range of motion is achieved for all patients with no pre-existing severe ligament deformity using a standard rotating platform device. For strong ligament deformities a clear criterion is given to select an implant providing high intrinsic stability. The reported quantitative results may be characteristic for a standard median incision and a medial arthrotomy, and may be different for other types of incisions and tissue preparations. A limiting factor may still be certain asymmetric pre-stress in the lateral compartment due to the eversion of the patella. In order to generalize our findings a multicenter study needs to be performed, in particular to rule out the influence of different surgical preparation. Stability examinations over the range of motion with the replaced knee still partly show patient-individual local instabilities. This suggests that the procedure for patient-individual stability measurement, not only in extension and 90° flexion, but during the whole range of motion requires further development. To avoid such segments
of instability over the range of motion ligament corrections or the choice of a better suitable implant are possible solutions.

References
Robust registration in robotic assisted unicompartmental knee arthroplasty – The region-based point acquisition protocol

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Introduction: A major limiting factor for the accuracy in Computer Aided Surgery (CAS) is the system’s positional knowledge of the patient’s anatomy, derived through the process of registration. One of the commonly quoted measures of registration accuracy is the Root Mean Square (RMS) of the mapping residual error, which can be misleading. This paper defines a robust registration protocol, developed for the Acrobot® System for Unicompartmental Knee Arthroplasty (UKA), that ensures consistently accurate registration.

Methods: The aim of any registration method is to accurately establish the position of one co-ordinate system with respect to another. However, a robust registration method is one where this relationship can be derived with a high degree of confidence, irrespective of the current environmental conditions. For a registration algorithm which uses a set of points measured in one co-ordinate system and a surface measured in another co-ordinate system (such as the one used by the ACROBOT® System) the quality of both the point-set and the surface has a direct effect on registration outcome. The objective of this study is to define a robust point-touching protocol where point-set quality is used as a direct measure of registration outcome.

The quality of a point-set is defined in terms of three factors:
1. Accuracy of the points: Point accuracy is a representation of the extent to which the point-set fits the surfaces, and is affected by a number of factors, which include point collection inaccuracies, the accuracy of the digitizing method, and the quality of the registration surface. The latter is affected by the quality of the bone and the accuracy of the CT scanner, scanning process and segmentation.

2. Distribution of the points on the surface available for registration: Point distribution provides a direct measure of how accurately a set of points identifies a surface. Poor distribution would result in a poor representation of the surface, as a number of key features that give a surface its shape would not be located.

3. Number of points in the point-set: As point collection is time consuming, the number of points required for registration is important and should be minimized.

The “optimum point-set” should contain a minimum number of points while consistently producing an acceptable registration outcome in a minimum time, despite a high degree of noise in the readings. However, while the effect of a robust point-set can be described, a theoretical derivation for what constitutes a robust point-set is harder to provide. The regions described in Figure 1 are the result of extensive experimentation with a simulation platform and in vitro experimentation, where the performance of a number of manually and automatically assembled characteristic point-sets could be evaluated for a number of representative UKA surfaces. These regions include significant features that are characteristic for the shape to be registered, and allow important components of the error to be robustly bound.

The first three regions (I-III) are accessible through the conventional incision, while the fourth one (region IV) can only be accessed through two stab wounds, one for the femur and one for the tibia. These additional incisions are less than 5 millimeters in length, and do not require suturing.

An estimate for the overall point accuracy achieved for a specific intra-operative scenario can be derived by inspecting the RMS of the distance of each collected point to the mapped surface, combined with the spread of the residual error, for a robust point-set. A robust distribution of the points on the surface available for registration is guaranteed by a point acquisition protocol based on regions.

The number of points required to obtain an appropriate registration outcome is inversely proportional to the accuracy of the points. In the presence of significant noise in the readings (i.e. low point accuracy), collecting a large
number of points in key features has the effect of mitigating the effect of noise on registration outcome for a representative point-set. This method fails in the presence of systematic errors in the registration surface, which might be introduced during processing of the CT data. These areas of high uncertainty need to be identified and excluded from the surface prior to registration.

Therefore, a robust point acquisition protocol can be obtained by defining the point-set size required to ensure robust registration based on an estimation of achievable point accuracy and using the region-based acquisition process, with a proportion of the total point-set size in each region. In the case of the Acrobot® System, the region-based acquisition protocol, which is iterative in nature, is enforced intra-operatively by the Graphical User Interface (GUI), which visually guides the surgeon through the point collection process.

**Results:** The region-based point acquisition protocol, which has been clinically evaluated in a number of robotic assisted UKA procedures, was derived through simulation, and validated through plastic bone trials. Benchmark figures defining typical RMS error values for a specific degree of point accuracy and point-set size have been derived, alongside figures describing the relationship between point accuracy, point-set size and achievable registration accuracy.

Experimental results show that the region-based point touching protocol represents a viable means to assemble robust point-sets and can be used to enhance registration outcome.

![Figure 1](image)

*Figure 1  Registration regions for (a) the femur and (b) the tibia, suitable for UKA*
Discussion: The point acquisition protocol described can be used to increase the probability of obtaining good registration significantly. However, experimental results suggest that, because of the limited access resulting from a smaller incision, good point accuracy (i.e., better than 1 mm) is necessary for registration accuracy better than 2 degrees and 2 millimeters. This degree of point accuracy can be expected for a good surface model and an appropriate intra-operative setup, but poses an important constraint on the requirements for a system suitable for robotic assisted UKA, if a registration method based on anatomical features is to be used without the need for additional access.
Navigated versus hand-guided total knee arthroplasty

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Introduction: The success of total knee arthroplasty (TKA) mainly depends on correct alignment of the prosthesis. Although TKA is generally successful, severe failures like component loosening, instability, dislocation, fracture or infection occur in 5 – 8% and less severe failures such as patello-femoral pain or limited flexion in 20 – 40% of the implantations. Lately attention of the developers brought focus on Computer Aided Orthopaedic Surgery (CAOS). The use of navigation systems in clinical application in joint surgery requires evaluation of quality of implantation. The navigation systems have been introduced to clinical usage of arthroplastic surgery only very recently, that is why there are only few clinical studies available.

This prospective randomized study was designed to investigate precision of implantation according to navigation system and to non-navigated method. Furthermore clinical and subjective varieties should be identified.

Methods: 64 patients became subjects of the study. The patients were randomly divided into two groups; Group N patients underwent TKA using Stryker Knee Navigation System (Stryker Leibinger, Software Vs 1.01); Group C patients underwent conventional TKA without navigation. All patients received Duracon® total knee prosthesis. Each patient went through three series of X-ray; preoperatively, prior to discharge, and three months after the surgery as well as CT-scan of the operated knee ten days after the surgery. Following parameters have been presented on those pictures; mechanical tibio-femoral angle, femoral valgus angle, femoral joint angle, tibial joint angle, femoral flexion angle, tibial slope angle, Insall-Salvati Index, patella-tilt angle, as well as rotation of components. Clinical and subjective parameters were evaluated by means of Knee Society Score (KSS) and Western Ontario and McMaster University Osteoarthritis Index (WOMAC). Intraoperatively time of the surgery has been measured.
Results: The preoperative radiological, clinical and subjective results in both groups proved to be comparable. Significant differences were achieved in rotational alignment of femoral component [Mean: Group N –0.41° (±2.44°), Group C 1.09° (±2.81°); p=0.03] and flexion angle of the femoral component [Mean: Group N 0.65° (±2.64°), Group C 4.07° (±5.12°); p=0.008] and tibial slope [Mean: Group N 3.07° (±2.59°), Group C 4.91° (±3.27°); p=0.018]. Non-significant differences were achieved in mechanical axis [Mean: Group N 0.29° (±2.44°), Group M 0.13° (±3.18°)], patella-tilt angle [Mean: Group N 3.87° (±3.56°), Group M 5.61° (±3.54°)]. Mean time of the surgery in Group N with 115’ (±16’) was 32’ significantly longer than in Group M [Mean 83’ (±15’)].

Neither in early clinical (KSS) nor in subjective (WOMAC) outcome and in the remaining radiological parameters any differences have been detected.

Discussion: Major clinical problems can be related to poor femoral component positioning. Internal rotation of the femoral component leads to maltracking of the patella and femoral lift-off [2]. The findings of this study indicate that there is less rotational malalignment with the use of navigation system, which should decrease these complications. Navigation systems allow better alignment of the tibial and femoral components in sagittal plane. Especially changes in tibial slope have a major effect on soft-tissue balancing and on the range of motion.

Our results of comparing the alignment of the mechanical axes confirmed that using this Navigation System is advantageous. The standard deviation in Group N was less and there were two outliers in Group C (first 11° valgus and second 8° varus). These findings were also reported in another study [3].

Patella tilt angle of 5° was described by Grelsamer et al. as limit of normal. Patients with more than 5° have symptoms suggesting patellofemoral malalignment. The mean of patella tilt in Group N with 3.87° is in the safe zone, Group C with 5.61° is over the describe border. The main disadvantage of the navigation system is 32 minutes longer surgical time.

References
Open architecture haptics simulator for robot-assisted surgery

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Introduction: In this paper the general structure of a surgical simulator with open architecture is detailed. The simulator is thought to be used for surgical training and biomedical research. The main characteristics of this simulator are the capacity of connecting different haptic devices (open haptics) depending on the surgical operation that is being simulated, and the possibility of having different mathematical models for the modelling of soft deformable objects. Furthermore the simulator includes previous works on the mapping and indexing of workspaces that facilitates the work of the surgeon. This simulator could also be used in telesurgery to verify the surgeon’s actions before the telerobot executes these orders.

General scheme of the open haptics simulator
Methods: In the paper, the architecture of the developed simulator is explained, specifying the implemented model of deformable objects. Models of deformable objects can be classified as being kinematically or physically-based. Kinematics models do not consider the effects of the mass, forces or other physical properties during deformation, so they are not used in surgical simulators. Physics-based models can incorporate material properties.

A model of the Mitsubishi PA-10 robot of 6 d.o.f. has been considered as virtual robot, and two different masters have been used as interfaces: A serial master, the 6 d.o.f. PHANTOM, and a parallel one, the Magister-P.

Results: This section shows the used procedure to make a series of experiments to test the behavior of the simulator. The results show the capacity of the simulator to deal as much with solid rigid bodies as with soft deformable objects. Experimental graphics show the Z component of the tool position of the end effector and the Z component of the force sensed by the operator under several scenarios. These experiments have been made using the next simulation parameters: Simulation step time (0.001 sec), first order integrator, constant force reflection factor (0.1).

Discussion: An open architecture surgical simulator for experimentation and training of surgeons has been presented. The developed architecture allows using any haptic device that has its I/O Master Arm module (including the PHANTOM). Other advance teleoperation techniques that have been implemented on the simulator can be applied to improve the behaviour in surgical operations. Nevertheless, particularities on telesurgery invite us to improve the functionality of the simulator.

As a conclusion, an architecture including advanced techniques in teleoperation has been developed to obtain an open surgical simulator where several surgical operations can be simulated.

References
Using anatomical models and fast rendering algorithms for C-arm pose recovery and cone-beam tomographic reconstruction of bone anatomy

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Introduction: C-arms are being increasingly used for the purpose of 3D reconstruction of anatomy, especially that of bone. They are relatively inexpensive in comparison with CT and can be used intra-operatively. Rotational cone-beam data is obtained by controlled rotation of the “C” about one of its axes. The X-ray source travels nominally along a circular path with the detector positioned diametrically opposite. Precise knowledge of this rotation geometry is vital in obtaining accurate cone-beam 3D reconstructions. Unlike a CT gantry, C-arms are prone to inadmissible rotational and translational errors in detector position and orientation. In addition, there is also non-uniformity in the angles at which projections are obtained due to the acceleration and deceleration phase of the C-arm.

Traditionally, pose is recovered by performing a pre-scan of a calibration phantom that contains fiducials whose positions are precisely known. A homogenous transformation mapping is then estimated for each pose, by detecting the fiducials on the corresponding projected image. While these methods [1,2] have been shown to work well, they assume that the C-arm is capable of accurate reproduction of its positions through the sweep. Often this calibration is performed only once every few months during which period the C-arm is likely to deviate considerably from its path.
In this paper we present a method that uses images of a tetrahedral model of the subject bone to estimate the actual pose of the C-arm given its nominal poses. The tetrahedral mesh can be extracted from a CT scan of the patient, or instantiated from a statistical database (an atlas) of the anatomy through deformable registration. The latter case does not require pre-scanning of the patient. We demonstrate the potential of our method through comparison of tomographic reconstructions from the nominal poses, and the poses computed using the model. In addition, we introduce the use of a fast algorithm for rendering deformable tetrahedral models, which improves the runtime of the pose estimation by a factor of 10 to 15.

**Methods:** We created a model of a pelvis bone from a CT study of a prostate radiation therapy patient. The model is a tetrahedral mesh, built using a finite element mesher [3]. Each cell of the mesh is associated with a density function, which is a 2nd order Bernstein polynomial. Similar models had been used to create a statistical atlas of bone anatomy [4].

We developed two algorithms to generate simulated X-ray projections (DRRs) of the tetrahedral model. Both use a closed form expression of the line integral of Bernstein polynomials. One computes it on the computer's CPU, in a traditional programming approach. The other is a novel algorithm that uses the computer’s graphics processing unit (GPU) to compute the same integrals. We embedded the algorithms into a camera calibration module, which works by maximizing the mutual information between the reference image, whose nominal camera pose is given, and DRRs of the model. We use the Downhill Simplex algorithm to search through the space of camera pose parameters.

Tomographic reconstruction is then performed by using a very short-scan cone-beam reconstruction algorithm [5]. In order to cover the entire field of view (FOV) of the target object we obtained projections over a sweep of 180° + cone-angle.

**Results:** We generated a simulated 216-degree ideal C-arm trajectory in increments of 1 degree. We applied a known perturbation in the orientation of the detector. The perturbation included varying error of up to ±1° in the gantry angle (alpha), and up to ±2° gantry wobble error (tao). We created a series of reference projections (256 x 256 pixels) of the bone model along the perturbed trajectory, and then ran the calibration module. Both the CPU-based and the GPU-based calibration algorithms recovered the perturbation to a precision smaller than 0.1 degree.
We compared the execution time of the GPU-based calibration algorithm to a CPU-based implementation of the DRR generator. We ran the GPU-based method on a Windows workstation, with a 2.4 GHz CPU and NVIDIA GeForce 6800 GT graphics card. It takes between 70 and 82 seconds to compute the calibration for a single view. The CPU-based algorithm on the same machine is 10 to 15 times slower.

We created 3 tomographic reconstructions (see Fig. 1) of the model from a second projection series with 512 x 512 pixels (and the same perturbed C-arm trajectory as the first series): one with the known actual trajectory, a second from the nominal trajectory, and a third from the estimated camera poses obtained through calibration.

**Discussion:** We have shown that mutual information between 2D DRRs of 3D objects can be used as a similarity measure to recover errors in the orientation of a C-arm. Knowing a more precise pose significantly improves the accuracy of reconstructed tomographic images.

We developed a fast algorithm for rendering a tetrahedral mesh with polynomial density functions. The quality of the DRRs is sufficient to create a tomographic reconstruction of the rendered model. The algorithm can also
be used in conjunction with deformations of the model, for example, when
the model is instantiated from a statistical atlas. Our work on creating an atlas
of the full pelvis bones and using it for deformable 2D-3D registration is in
progress.

We have shown that a simple optimization algorithm can be used to find the
perturbation parameters with a high precision. Work is in progress on
extending our perturbation model from rotation only to translation and focal
length of the imaging system. A better optimization framework should enable
to reduce the number of DRRs generated during the parameter-space search,
and thus the time for calibration.

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**References**

X-ray imaging chains for three-dimensional reconstruction”, Computerized

Barth, and R. Graumann, “3D reconstruction from projection matrices in a carm
based 3D-angiography system,” First International Conference: Medical Imaging

generation from segmented medical images”, IEEE International Symposium on

Anatomical Atlases and Intensity-Based Registration”, presented at Medical
Image Computing and Computer-Assisted Interventions (MICCAI 2000),
Pittsburgh, PA, 2000, p. 531-540.

Beam Data Using Prior CT Information”. MICCAI (2) 2003: 134-141
A new orthopaedic implant management tool for computer assisted planning, navigation and simulation: From implant CAD files to a standardized XML-based implant database

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Introduction: There is a wide variety of different plates, screws and nails used in trauma surgery. However, scaled visualization and tracking of these devices and their corresponding surgical instruments is currently only possible with fluoroscopy [3], which requires radiation exposure. Current CAS systems often simplify the shapes of implants or instruments, but it is likely that more realistic rendering and additional navigation information will improve the functionality of navigation systems [4].

A novel concept has been developed to provide this functionality. This concept centers around a virtual implant database [1] that contains both geometric and calibration information of each of its trauma implants and instruments. This should enable the realistic navigation of various implants through a common interface [2] and could be used with any navigation application.
Currently a database has been established that contains various virtual representations of osteosynthesis implants and anchoring devices for fracture reduction and fixation, as well as images of various prostheses for total joint replacement (knee and hip). This database can be browsed for details on any stored virtual implant. The provided interface supports planning and navigation parameters of LISS and LC-DCP Plates and also implemented searching functionalities (search by implant size, manufacturer, bone part, implant type).

The system has been successfully tested with various CAOS applications [1, 5] and the aims were to evaluate integration issues, network access, speed and usability.

Nevertheless, the implant information is not static because periodically, manufacturers proceed to implant revision, remove some implants or add new ones. Following this continuously updated process and keeping CAS systems up-to-date is a fastidious task if done manually. This leads to an additional cost to system development and some inevitable errors can be generated due to the huge amount of information to process.

*Figure: Implant management tool overview*
To overcome these limitations and to improve the current implant management process in CAS, we have designed and developed, on top of our existing Virtual Implant Database, a graphical administration tool which aims to help surgeons, implant manufacturers and CAS system providers to easily administrate the implant database.

In respect of the confidentiality and security issues required by medical data, the tool has been designed with additional security mechanisms and with ergonomic considerations: no database or SQL knowledge is needed from the end-users.

Our laboratory tests give successful results and some improvements are planned in order to make more exhaustive tests with surgeons, manufacturers and CAS system providers.

**Methods:** To achieve the goals mentioned above, we adopted the following methodology:

1. All the implants are designed in a database containing tables and their relationships, which handle implant planning and navigation parameters and also various virtual representations of osteosynthesis implants and anchoring devices.
2. An application programming interface (API) is provided between the database and the client applications and acts as a communication channel [2]. This layer provides main functionalities to *connect* to the database, *search* implants, preview of the implants parameters including 2D image and implant 3D model, *Insert- Update- Delete* and *Backup* Implants.
3. A well-defined CAS compliant XML Implant file is generated from the implant CAD files. The first part of our XML file describes the general parameters common to all implants and the second part describes the specific parameters depending on implant type.
4. A customized xml engine (*XMLImplantReader* and *XMLImplantWriter*) has been developed and helps in XML Implant files loading. An advanced graphic user interface (GUI) allows the end-users (CAS system providers, hospitals, manufacturers) to manage implants. Our system workflow is organized in three stages: The user carries out actions while clicking buttons in the interface. These actions are reformulated in SQL requests in the interface layer. The requests are then sent to the database server which treats them and returns the result of the requests.

**Results:** We have successfully achieved the initial goals of the implant management tool. We developed a graphic-based application which, in a semi-automatic manner helps surgeons, implant manufacturers and CAS
system developers to continuously keep their systems up-to-date for clinical use. By doing this we also developed a new XML Implant standard which eases inter-operability, data sharing and provides a close link between manufacturers, CAS system providers and surgeons. The main functionalities provided are:

- Add implant
- Delete implant
- Update implant
- Preview implant parameters
- Backup implants
- Advanced search.

We have extended our existing implant interface to support XML files manipulation: Load implants files via `XMLImplantFileReader` and backup implants from database via `XMLImplantFileWriter`.

**Conclusion and Discussion:** Our proposed solution is a new application that addresses the current limitations and fills the gaps between the hospitals’ available CAS system implants and the implants provided by the manufacturers. Some laboratory tests have been successfully achieved to test the system’s usability and efficiency. Compared to existing solutions our approach has many advantages: Data reusability, security mechanisms, a robust database system, client/server architecture, ease of use.

Some improvements are planned to allow for a fully automated implant XML file generation directly from CAD files received from implants manufacturers. Also we need to make more exhaustive tests and continue to improve the XML implant scheme.

Currently our application can work locally and with a remote database server via a local network. Additional improvements are planned to make it work via secure internet tunnels.

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**References**


Hip resurfacing with computer navigation. Initial experience at the Royal Bournemouth Hospital, UK

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Introduction: Hip Resurfacing is now established as a treatment option for young active patients with osteoarthritis in the UK. Initially regarded as experimental, the emerging results of resurfacing in the medium term are excellent (1). The large bearing metal on metal articulation allows for a large range of motion with a reduced risk of dislocation, as well as reduced wear and potential longevity of the implant. The patients may return to both manual labour and active sports. This level of postoperative function has resulted in patients actively seeking surgeons to perform this procedure, encouraging this change in hip surgery practice. In the future potential revision hip surgery may be easier, with the femoral canal being untouched by the femoral component.

However there is slow uptake of hip resurfacing by some surgeons, as the operative procedure is significantly different from a routine hip replacement with often a slow and difficult learning curve, as well as concern regarding potential complications. Potential failure from femoral neck fracture, which is a small but highly significant risk, may follow notching of the femoral neck. This may occur upon preparing the femoral head after inserting the femoral head/neck guide-wire. The placement of the femoral head/neck guide-wire is a concern for even experienced surgeons routinely, and in difficult cases of femoral head/neck deformity this is especially so.

Methods: At The Royal Bournemouth Hospital, UK, for the first time a preliminary series of Durom hip resurfacings (Zimmer), based on the successful Metasul bearing (2), were implanted using a computer image guidance system (Medtronic). The aim of computer navigation is to optimally place the femoral prosthesis in the correct degree of valgus with good underlying bone coverage, without either notching the femoral neck or
oversizing the femoral component. Preoperative CT scanning was not required.

A standard posterior approach is used to the hip, with division of the tendon of gluteus maximus as well as the short external rotators. Two pins are then inserted longitudinally along the posterolateral border of the proximal femur, and the navigation reference frame with four passive marker spheres applied.

An image intensifier machine (with a calibration target over the base plate) is draped and brought over the patient. The computer navigation consul with the camera is located at the foot end of the patient out of the laminar flow. Image intensifier pictures of an AP and lateral view of the femoral head and neck, with the navigation reference frame in place, are obtainable and checked. The orientation and distances of the femoral head and neck are now precisely known, via the computer navigation system instantaneously. This is done quickly and easily.

The computer consol screen in this position has excellent visualization by the operating surgeon for guide-wire placement. A 2.5 mm guide-wire is then applied to the surface of the femoral head, through a navigated drill guide. The predicted direction of passage, into the femoral head and neck, of the guide-wire is then shown on the computer console, as well as the potential femoral bone cuts. Then with slight adjustment of the guide-wire in both the AP and lateral planes with the navigated drill guide and the guidance system, the wire is safely passed with ease into the femoral head/neck when the projected path is felt to be correct by the surgeon.

The femoral head is now prepared safely for the femoral component of the resurfacing, with both minimal risk of femoral neck fracture and correct alignment ensured.

**Results**: 6 cases of computer navigated Durom hip resurfacings were performed in October 2004. There were 3 men and 3 women, with a mean age of 49. This preliminary series was successful, with no complications and good component alignment and patient outcomes.

**Discussion**: Computer navigation systems have an important role to play in hip resurfacing with respect to femoral head/neck preparation, as demonstrated from our preliminary study. This series shows the use of computer navigation in hip resurfacing to be both safe and simple with a quick learning curve, and faster and more accurate in the process of guide-wire placement in the femoral head/neck as compared to conventional jigs.

Femoral neck fractures may even be potentially eliminated.
Beaule (2) showed for hip resurfacing that a mean femoral stem-shaft angle of <130° in the coronal plane, had an increase in the relative risk of an adverse outcome. The use of computer navigation to ensure accurate placement of the femoral component, should minimize such adverse outcomes.

In the future, computer navigation systems in hip resurfacing may allow:

- *Safer* hip resurfacing, with reduced rates of femoral neck fractures
- *Improved* patient outcomes
- The *training* of junior surgeons in hip resurfacing
- The surgeon to operate *independently* initially
- The surgeon to operate on *difficult* cases subsequently
- The development of *minimally invasive* hip resurfacing
- The development of *specialist* centers for teaching and difficult cases.

**References**

Computer assisted double osteotomy for severe genu varum. First results about 11 cases

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The aim of this study was to assess the radiological results of computer-assisted double osteotomy (femoral and tibial) for severe genu varum deformities. Between August 2001 and November 2004 we performed 11 computer double osteotomies among 157 osteotomies performed during the same period, that is 7%.

Material and Methods: We operated on 4 females and 7 males. The mean age was of 48.5 years (20 – 62) and the right side was involved in 7 cases (4 left side). One patient had no gonarthrosis but only an unsightly deformity. The other ten were graded according to the modified Ahlback classification. We recorded 6 stage 3, 3 stage 4 and 1 stage 5. The mean preoperative varus was 167.5°± 2.16° (164 – 170°).

Orthopilot was used to perform computer-assisted surgery. The first step was to insert percutaneously the rigid-bodies on the distal end of the femur and on the proximal end of the tibia. Then, we located the center of the hip, the center of the knee and the center of the ankle to obtain the mechanical axis of the lower leg. A closing distal femoral osteotomy of 5 or 6 degrees was performed to start the operative procedure and was fixed with an AO T-plate. Then we performed an opening proximal tibial osteotomy to complete the procedure. The desired mechanical axis was checked on the computer and the osteotomy was fixed with a TCP wedge (Biosorb\textsuperscript{R}) and an AO LCP T-plate.

The aim of the procedure was to obtain a mechanical axis of 182°±2°. All the patients had a long leg X-ray at 3 months postoperatively.
Results: We had no complications. The mean peroperative computer-assisted mechanical axis was 168.1°±2.21 (164 – 170°) that is the same as the preoperative axis. After the procedure, the computer mechanical axis was 182.7°±1.1° (182 – 184). 3 months after the operation the weight bearing long leg X-ray showed a mean mechanical axis of 180.8°±1.6° (177 – 182°). The preoperative goal was reached in all the cases but one (91% of the cases). No cases had an oblique joint line.

Discussion: High tibial osteotomy is a good surgical procedure to treat gonarthrosis with genu varum deformity (1, 2, 3). Nevertheless, in some cases with severe genu varum (more than 10 degrees of deformity), the overcorrection needed to have a good result (usually from 3 to 6° of valgus) leads to an oblique joint line. Since an osteotomy is usually considered as a waiting treatment, the need to have a TKA in a second step must be an important concern. In case of a severely oblique joint line (more than 5°) it will be very difficult to perform a well balanced TKA. To avoid this complication we prefer to do a double osteotomy involving the femur and the tibia. Still, it is a very demanding technique and the risk to have too much of an overcorrection or an undercorrection is not rare. On the basis of our experience with computer-assisted TKA (4) and HTO (5), we thought of using Orthopilot to navigate this procedure.

Conclusion: Computer-assisted double osteotomy for severe genu varum is a safe, accurate and reproducible technique. It simplifies the procedure which is a very demanding technique when performed without any assistance. The development of this procedure is very important to avoid the severely oblique joint lines which are very difficult to revise with total knee prosthesis.

References
Mutual information based musculo-skeletal tumor marking, an anatomically based approach

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Introduction: Defining precise resection lines for musculo-skeletal tumors is very important for the clinical outcome and survival time of patients. Understanding the tumor surface is difficult and error prone using multimodal image modalities. To get a better understanding of the tumor volume we generated a software for tumor marking based on normalized mutual information.

Methods: We took open source software on a standard PC to develop and test our software. The first step using the software is to define a tumor axis centered horizontally in one visualization window, the second window is used for marking in planes perpendicular to the tumor axis. Each window holds 2D coordinates to ensure in-plane calculations. Four matrices updated by user interactions enable synchronization of the two windows taking one 3D coordinate per point as a calculation base. Marking the tumor starts with four points representing a circular closed splines within the perpendicular planes, the number of marking points can be increased to achieve better precision. Navigation is possible sliding along and rotating around the axis. Finally the splines can be taken to set a variable number of points for triangulation purposes. Choosing a flexible number of points per plane enables sufficient triangulations reducing calculation time before optimization.

Results: We were able to address the problem of fast tumor segmentation using our software due to the fact that many of the musculo-skeletal tumors are axis symmetric. Testing a couple of volumes showed that segmentation could be done very efficiently. We had a benefit from using spline functions even with asymmetric tumor segmentations. Specific times could not be
measured because of the different tumor sizes. Switching between different modalities always using the same scale, origin and direction of the coordinate system was very comfortable in terms of image comparison.

**Discussion:** Using mutual information for multimodal volume registration eliminates time consuming image comparison. The used marking system, based on a tumor axis definition combined with spline functions helps segmenting tumors efficiently. Problems may arise from the used rigid transformation, which can not compensate structural soft tissue changes during scan time and intraoperatively. We believe that the implemented software is the right step toward safer tumor surgery.

**References**

A novel approach for biomechanical cup positioning in THR

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Introduction: Today, imageless definition of cup orientation (inclination and anteversion) with respect to the pelvic plane is a very common approach [1],[2]. In most cases, the position of the cup refers to the actual (preoperative) position of the joint center represented by the facies lunata or rather what is left of it. However, especially in the case of severe dysplasia and revision surgery, a more complex analysis and planning of the cup positioning seem to be indicated. This includes the consideration of the remaining bone stock for refixation of the revision implant including the remaining thickness of the acetabulum (prevention of a perforation into the lower pelvis), the potential need for corrections of biomechanical conditions, the implant geometry and “philosophy” as well as other anatomic and surgical aspects. Many, often contradictory, factors influence the determination of the optimal position. In the context of the MINARO project [3] a new approach for imageless revision cup navigation has been investigated.

Methods: Starting from considerations of Blumentritt et al. [4] purely based on planar a.p.-X-ray projections and empirical data, we developed a methodology of spatial analysis. In a first step a set of characteristic anatomic and functional landmarks have to be palpated transcutaneously as well as within the operating site using an optical localizer system. The centers of the affected as well as of the contralateral hip are identified by direct palpation or intraoperative motion analysis respectively. Moreover, A-mode ultrasound is used to determine the acetabular wall thickness towards the lower pelvis. Last but not least, the surrounding acetabular bone stock is digitized. Depending on the individual priorities and needs, the surgeon may define weighting factors concerning e.g. leg length or preservation of bone stock. Based on
these data a genetic algorithm is used to compute an optimal cup position to be proposed to the surgeon. Different aspects of this approach have been validated on bone models.

**Results:** In a first study we investigated the sensitivity of the algorithm with respect to errors induced by soft tissue in the course of the transcutaneous digitization of the different portions of the iliac crest. We found, that digitization errors of up to 30 mm resulted in a cup displacement of up to 2 mm only. In a second study we investigated the accuracy and reproducibility of the mirroring of the contralateral hip center. On 6 test persons we identified the pelvic plane and the sagittal plane by transcutaneous palpation as well as both hip joint centers by motion analysis. In these cases, the DRBs have been fixed on the legs by elastic tapes. Average deviation of hip centers was about 47 mm. Using synthetic bone models with rigid fixation of the DRB the same method resulted in maximum deviations of about 2.5 mm. Hence, accuracy of the non-invasive motion analysis of the contralateral hip is insufficient for the definition of the affected hip center, however it can be used as a starting point for the optimization process. Repeated digitization and optimization showed a reproducibility of cup positioning better than 7 mm. Results of ongoing cadaver studies will be presented.

**Discussion:** Apart from inclination and anteversion, the optimal positioning of the cup has to be taken into account in THR. Based on a biomechanical model approach and an minimal invasive imageless digitization of the individual anatomy, an optimal position can be calculated, taking into account the individual biomechanical as well as anatomical situation.

**References**


Computer assisted optimization of correction osteotomies on lower extremities

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Introduction: Correction osteotomies can be considered as an alternative to total arthroplasties in case of biomechanical deficits of extremities [1]. However, in clinical routine, the correct spatial identification of individual deformities, the determination of optimal cutting planes and amount repositioning (translation and rotation of n fragments) required as well as its transfer into the operating site turns out to be a problem.

Methods: The main problem in the determination of the spatial deformities is the identification of torsion (especially for a single cut osteotomy). One task is to provide a rather independent reproducible description of the deformity. Therefore we introduce an anatomic model which is individually adapted based on intraoperative calibrated fluoroscopic images and kinematic data acquisition. Using the individualized model, the surgeon has to define conventional correction parameters such as translation, derotation, angulation and difference in leg length. Moreover, additional boundary conditions have to be defined (e.g. bone contact surface, steepness of the cut, surgical approach, …). Based on this information, optimal solutions for exact location and orientation of the osteotomies, the repositioning and the osteosynthesis are calculated. Different optimization algorithms have been evaluated regarding computing time and accuracy of the desired correction. Subsequently, execution of the planned osteotomies, repositioning and osteosynthesis are supported by a freehand navigation module.

Results: In an initial study, the deformity parameters of bone models have been identified. Results have been compared with conventional methods as used in forensic medicine based on mechanical measurement devices. The
tests have been repeated 6 times with 3 test users. For all parameters standard deviation was lower than for the conventional method (e.g. angulation 1.4°, rotation 1.1°, translation 6 mm, leg length difference 2 mm). A second ex vivo study confirmed these results.

In the third study, we virtually simulated 400 complex deformities generated by different combinations of single as well as multiple cut osteotomies on an undeformed bone. In all cases, the optimization algorithm found an optimal combination of osteotomies and repositioning within less than 10 seconds for single cut osteotomies and less than 1 minute for a wedge osteotomy even in complex cases.

Discussion: We developed a new approach for the intraoperative identification of deformities of lower extremities including torsion. It became obvious that the conventional description parameters for a spatial calculation of the cutting surfaces were insufficient, because they used different frames of references and showed dependencies among each other. Based on the spatial modeling of the deformed bone different types of osteotomies can be simulated and an automatic optimization can be performed. Further investigations will include effects of this optimization on the clinical outcome.

References
About the benefit of intraoperative 3D-imaging in repairing displaced intraarticular calcaneal fractures – Results of a comparative study

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**Introduction**: Open reduction and internal fixation of displaced intraarticular calcaneal fractures have become more popular, though the functional outcome after operative treatment of severe fractures is not always satisfying (1). The purpose of this study was to investigate whether intraoperative use of ISO-C-3D® as a 3D-imaging device can potentially increase the accuracy of the operative procedure.

**Materials and Methods**: In a prospective clinical study the benefit of intraoperative use of ISO-C-3D® in the process of restoring displaced intraarticular fractures is analyzed (2). Preoperative CT-scans and intraoperative multiplanary reconstructions were evaluated with regard to reconstruction of articular surfaces and positioning of implants.

Patients with displaced intraarticular calcaneal fractures who were treated with ORIF using an extended lateral approach and the AO calcaneal plate between July 2001 and December 2002 were included in our study (3). Multiplanary reconstructions were made directly after fixation, immediate revision was performed when necessary. Fractures and results of reconstruction were classified according to Sanders (4) and Zwipp (5).

Patients of the control-group were treated similarly between January 1999 and June 2001; for these operations a conventional image converter was used intraoperatively.

**Results**: 54 patients with 60 intra-articular fractures were treated with ORIF using the ISO-C-3D® intraoperatively, 59 patients with 62 fractures were
included in the control-group. We found 9 type-II-fractures (control-group: n=16), 32 type-III-fractures (c: n=35) and 19 type-IV-fractures (c: n=11) using the Sanders’ classification system. Using Zwipp’s scoring system 8.6 ± 1.4 was the mean value among patients of the ISO-C-3D®-group, 8.2 ± 1.8 as mean value of the control group (p=0.20; n.s). Using the ISO-C-3D® anatomic or near-anatomic reduction was achieved in 80% (reduction of articular incongruity: x=2mm or less), among the control-group in 82.3% (p=0.74; n.s.). Malpositioning of implants was found only in 5% using ISO-C-3D®, while we found a significantly higher rate of malpositioned implants using a conventional image converter (29%, p=0.0004).

Discussion: Our data suggest that due to the possibility of immediate revision malpositioning of implants can be avoided in almost any case. No evidence could be found that intraoperative use of ISO-C-3D® leads to a better anatomic repair. There was no significant increase in time concerning duration of the operating procedure. Furthermore postoperative CT-scan becomes unnecessary. Severe fractures of the os calcis (type-IV-fractures according to Sanders) remain a therapeutic dilemma.

References

3-D planning and virtual X-ray evaluation in revision hip arthroplasty for instability

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Introduction: Recent trends indicate a steady increase in the number of revision total hip arthroplasty procedures being performed. Although many factors may have a role in postoperative instability, component malposition is the major contributor. Improvements in diagnostic tools and instrumentation, including computer assisted navigation systems, may allow surgeons to visualize the surgical anatomy both preoperatively and intraoperatively and improve component position after both primary and revision total hip arthroplasty. The use of 3-D planning and a new computer assisted X-ray measurement tool in the management of unstable revision hip arthroplasty is presented.

Clinical application: In our institution, a CT based navigation system (HipNav)\(^1\) is used for preoperative planning and intraoperative navigation of primary total hip arthroplasty. In addition, we have developed a computer assisted X-ray measurement system (Xalign)\(^2\) that allows 3-D anatomical measurement of acetabular component orientation using preoperative CT/postoperative X-ray matching algorithm. This can be applied to a series of X-rays from the pre- and postoperative periods and can be used in conjunction with hip navigation systems (e.g. HipNav). We used both HipNav and Xalign for preoperative stability assessment, planning of revision surgery and postoperative assessment for a case of recurrent dislocation of the hip in an 85-year old lady.

A CT scan of the existing unstable joint was acquired and segmented to allow determination of component position, potential component loosening, and remaining acetabular bone stock using the HipNav planner. The anterior pelvic plane (APP) was defined in the CT scan image of the pelvis. Next, the
acetabular implant was segmented from the CT scan and a corresponding 3-D computer model of the implant was manually positioned and oriented so that it matched the segmented implant position. Similarly the femoral implant model was matched to the femoral component in the CT scan.

The acetabular component was positioned preoperatively in the desired position and then the range of motion simulator was used to test the stability of the revised joint by simulating certain leg positions. Positions of impingement were recorded and cup orientation was modified until optimal position was achieved. The surgery was carried out using the conventional surgical technique with no intraoperative navigation. However the 3-D views of the acetabulum were created at the end of planning that corresponds to the surgeon’s intraoperative perspective to aid the surgeon in aligning the cup.

Results: Preoperatively the system measured the position of the acetabular component in the unstable hip and showed an abduction angle of 59° and anteversion angle of 70°. This system also significantly improved the visualization of the acetabular defect compared to radiographs and allowed
the segmentation and 3-D visualization of screws and clearly showed their integrity rejecting the preoperative suspicion that one of the screws was broken. The patient underwent revision of the acetabular component with femoral head exchange, as the femoral component was not loose. A Tantalum disc was utilized with a supplemental bone graft for the small deficiency of the acetabular medial wall. The postoperative radiograph was analyzed using the computer assisted X-ray measurement system and this measured an abduction angle of 39 degrees and an anteversion angle of 14 degrees.

**Conclusion:** 3-D planning and virtual X-ray can be useful tools in revision hip arthroplasty especially for instability. It can help in understanding the causes of instability and aid revision planning by optimizing cup orientation and reducing the risk of impingement. This technique could be used as a training tool for surgeons to practice in a relaxed environment on obtaining optimal cup position and range of motion avoiding impingement. The virtual X-ray can be used as a tool for postoperative analysis of cup position and study possible impingement.

**References**


Gap balancing in robot assisted total knee arthroplasty

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Introduction: In spite of the accurate alignment of component in robot assisted total knee arthroplasty (TKA), there have been no reports concerning the soft tissue balancing. Therefore, we conducted this study to evaluate the balance of the flexion and the extension gap, PCL balance, and the rotational patterns of knee in robot assisted TKAs during operation.

Materials: Robot assisted 50 TKAs were enrolled into this study. The posterior cruciate ligament was retained and NexGen CR TKAs were implanted for arthroplasty. Robot (ROBODOC®) assisted TKAs were carried out in two steps, CT-based preoperative planning using ORTHODOC® and robot assisted surgery. For good postoperative flexion, we placed the femoral component in a way resulting in a flexion gap 2 mm larger than the extension gap.

After milling of the femur and the tibia with the surgical robot, soft tissue release was performed until the balancer/tensor device on 60 lbs/inch showed ≤3 degrees difference between medial and lateral gap in extension and measured the extension gap. Once the satisfactory extension gap had been achieved, the knee was flexed 90° and the flexion gap was measured with the balancer/tensor device on the same force. After insertion of trials, the knee was then taken through a range of motion from 0 to 120 degrees. The proper PCL tension and posterior roll back without lift off of trials was graded as a “good” PCL balance; the lift off with tight PCL tension, “tight” > 3mm greater flexion gap than the extension gap with nonfunctioning PCL, “loose”. We also evaluated the rotational patterns of knee using visual inspection.

Results: Mean extension gap on the medial and lateral side was 21.4 ± 1.4 mm and mean flexion gap was ± 1.4 mm. The extension gap symmetry
was 0.8 ± 0.4° and the flexion gap symmetry 0.8 ± 0.9°. There was no case of >3° extension or flexion gap asymmetry. However, flexion-extension gap mismatch more than 3 mm was observed in one case.

The PCL balance showed good results in 46, tight in 3, and loose in 1 case. The PCL was partially released from tibial attachment in tight 3 cases. However, 30 out of 50 knees showed the normal axial rotation patterns and the reminder showed no or reverse axial rotation.

**Conclusion:** The use of surgical robot in TKA could achieve balanced flexion and extension gap without medio-lateral or flexion-extension gap mismatch. Most of TKAs with surgical robot showed excellent PCL balances and normal axial rotations. Therefore, the surgical robot was helpful for obtaining balanced soft tissue tension and a more reliable normal kinematic pattern.

**References**

Computer-assisted ankle joint arthroplasty using bioengineered autografts

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Introduction: Recent research in bioengineered cartilage has opened the door to new clinical treatments of joint lesions (e.g. [1, 2, 3]). Common to all therapies with in vitro engineered autografts is the need for optimal fit of the implant, for this is crucial to its successful integration into the joint. Computer Assisted Surgery (CAS) techniques have the potential both to ensure the required accuracy and simplify the therapy. They are prime candidates for filling the gap between basic research in cartilage engineering and its successful clinical application. As a pilot project in this field, the ongoing study aims at assembling a set of methods to realize and prove the feasibility of CAS ankle joint arthroplasty using bioengineered autografts. The ankle joint was chosen as a first target because of the lack of suitable alternatives: Post-traumatic osteoarthritis can be diagnosed in patients as young as 20 years, where classic therapies like total ankle joint arthroplasty or arthrodesis have considerable side effects (long-term outcome expectation, loss of mobility).

Methods: At the Universitätsklinikum Freiburg, Germany, one case of post-traumatic osteoarthritis has been treated with a bioengineered implant. The intervention was conducted in two steps: One for arthrotomy and defect moulding, a second for implanting the bio-engineered construct. Between the two operations several weeks were needed to proliferate autologuous chondrocytes and have them integrated into a cancellous bone construct shaped after the defect mould. Albeit clinically successful, this procedure
does not lend itself well to routine application: The two-step operation, the long period of treatment and the high cost of individually constructed autografts make it a time-consuming and costly alternative to classical therapies. CAS technologies, however, can potentially deal with all major challenges of the target therapy. The revised procedure consists of planning based on CT image data (the autograft shape can be deducted from a parameterizable model rather than individually developed), harvesting of mesenchymal stem cells by needle biopsy, constructing the autograft according to planning and conducting one single intervention for the arthrotomy and construct implantation. The defect debridement has to be accurate enough to fit the pre-constructed graft; proving this accuracy is a main goal of the ongoing work in this field.

**Results:** Two aspects of computer assisted ankle joint arthroplasty were chosen for first studies: operating technique and implant shape. Targeting the anterior approach to ankle joint arthrotomy, a navigable chisel was designed with two blades angled at 90°. Tests in a preliminary experiment on one human cadaveric foot showed sufficiently smooth lateral surfaces for press-fitting an implant; the rear face of the defect will require a navigated milling device. A software was further developed which allows interactive determination of the ankle joint axis in a CT volume without segmentation. In lateral view, a series of points is selected on the joint surfaces of distal Tibia and/or proximal Talus. From these points, the joint axis is calculated; a minimum of 18 points is sufficient to give a result, at least 50 points are recommended to ensure sufficient accuracy. The actual accuracy of axis calculation depends on the number of points selected and on their distribution over the joint. A known joint axis is a basis for later construct shape definition and any studies requiring the comparison of different joints.

**Discussion:** The feasibility of computer assisted ankle joint arthroplasty using bio-engineered autografts is being studied. First steps towards this goal have been made by defining a suitable operation technique and a concept for obtaining the data used for computer assistance. By developing and testing a navigable chisel for ankle joint arthrotomy the operation technique could successfully be prepared. Defining the shape of ankle joint grafts is a rather complex task; unlike hip joints, where the assumption of a spherical shape is already very close to reality, there is no obvious model corresponding to the upper ankle joint. An intuitive approximation is a cut from a rotational symmetric shape based on a joint surface profile. More sophisticated shape descriptions could involve statistical modeling techniques such as Principal Component Analysis PCA [4]. Common to all shape models is the need for a general way to define sections of the distal Tibia and the proximal Talus
which are to be covered by the model. Determining the pivoting axis of the upper ankle joint is an important prerequisite to modeling the anatomical structure in this region. The choice of an interactive software for this task has the big advantage of doing without a segmented joint surface, which would be prohibitively time consuming to get in clinical practice. From the results obtained with this method can be said so far that it was sufficient for a first trial; its accuracy and robustness will further have to be verified. Together with the results concerning the operating technique and CAS tools it has the potential to lead to the proof of feasibility of the target therapy.

References

Functional impact of navigation assisted minimally invasive total knee arthroplasty

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Introduction and Purpose: Navigation assisted minimally invasive total knee arthroplasty (NA-MIS TKA) using a limited mid-vastus approach without patellar eversion has been proved to help not only in reducing postoperative pain and promoting a rapid and easy recovery in the early postoperative period but also in producing more accurate leg and prosthesis alignment than conventional total knee arthroplasty. Whether those early postoperative functional impacts of NA MIS TKA will continue until several months after index arthroplasty is still unclear and not known. The purpose of this study was to evaluate later functional impact of NA MIS TKA after several months follow-up and to compare them with those of regular conventional TKA.

Materials and Methods: We evaluated the functional results of 91 NA-MIS TKA and compared them with those of 50 regular conventional TKA. Among them, 26 patients underwent simultaneous bilateral TKA (one side knee for NA-MIS TKA, the other side knee for regular conventional TKA). There was no significant difference of preoperative patient’s demographics between 2 groups in terms of diagnosis, degree of deformity, HSS score, knee society score and range of motions. Mean follow-up duration was 8.6 months ranging from 3 to 21 months in the NA-MIS group and 7.0 months ranging from 3 to 19 months in the regular conventional group. The hospital for special surgery (HSS) score, WOMAC score, knee society score, and range of motion (ROM) were evaluated. The patient’s own preference was assessed in the case of 26 simultaneous bilateral TKA.
Results: Mean HSS score was graded 91 points in the NA-MIS group and 88 points in the regular conventional group with a significant difference (P=0.02). Mean WOMAC score also showed significant differences with respect to total score (p=0.039) and pain score (p=0.05). Knee society pain and function score showed no significant differences between the two groups. The statistically significant difference also existed in mean ROM (p=0.03). In simultaneous bilateral TKA, the NA-MIS group showed better results in term of HSS score (p=0.04), knee society function (p=0.02), knee society pain (p=0.006), and ROM (p=0.014). NA-MIS TKA was more frequently preferred (17/26) by the patients (p=0.04). These results showed a statistically significant difference.

Conclusion: NA MIS TKA showed continuing functional impact in terms of pain and range of motion even after several months postoperatively and was a lot more frequently preferred by the patients.

References

CAOS assessment of tibial rotation in total knee arthroplasty

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Introduction: An important kinematic feature of the knee joint is axial rotation that occurs through the range of motion. After total knee arthroplasty, fluoroscopic video kinematic studies have demonstrated that while some cases demonstrate the expected internal rotation with knee flexion, others will actually exhibit paradoxical external rotation with knee flexion. Computer assisted surgical navigation (CAOS) offers a unique opportunity to evaluate tibial rotation along with numerous other parameters such as mechanical alignment, joint flexion, ligamentous balance, and tibial axis alignment in flexion. This report retrospectively reviewed tibial rotation documented before and after total knee arthroplasty in a group of patients where the “tibial cut first” method was utilized. A new method of tibial component positioning is described.

Methods: A group of 85 patients underwent primary total knee arthroplasty utilizing the tibial cut first technique. Implants utilized were either the LCS mobile bearing prosthesis or the Nexgen LPS Flex prosthesis. The Medtronic Universal imageless navigation system was used in all cases with dynamic reference base markers attached to either the medial proximal tibia or the distal medial femur over the medial epicondyle. The tibial rotation was defined mathematically by the relationship of the anterior posterior femoral axis which is perpendicular to the transepicondylar axis and measuring the vector to the midpoint prominence of the tibial tubercle. More recently, the Medtronic imageless reference added the femoral anterior posterior axis of Whiteside as an additional mark to determine femoral rotation eliminating the need for the transepicondylar axis.

Tibial component placement was centered on an initial mark on the proximal tibia that was a continuation from the femoral AP axis with the knee held in extension. This was adjusted to make the spine cam relationship optimal and centered with motion. In general the mark matched the optimal position, and
a new navigated instrument for tray positioning seeks to match this position which is determined at the beginning of the procedure. Because of the assumed inaccuracy of the transepicondylar axis referencing, all rotational measurements from the computer were considered to be relative. Axial rotation as a nominal measurement was determined at full extension and at 90° flexion and moved either external or internal to the femoral transepicondylar axis. The position of this rotation and the amount was then remeasured after the prosthetic implantation. Finally, the direction of rotation was determined after implantation to determine if this had altered. Standard descriptive statistical analysis was performed.

**Results:** The overall baseline measurement of tibial rotation from 0 degrees to 90 degrees flexion before TKA was 4.1 degrees +/- 8.9 of tibial internal rotation (95% CI: 1.9 degrees; Range – 18 degrees external rotation to 23 degrees internal rotation). The amount of tibial rotation from 0 degrees to 90 degrees flexion after TKA was 3 degrees +/- 7 of tibial internal rotation (95% CI: 1.7 degrees; Range – 18.5 degrees external rotation to 20 degrees internal rotation). Of the overall baseline group, 41% demonstrated tibial external rotation with flexion while the remainder had tibial internal rotation. After TKA, 37% had tibial external rotation with flexion while the rest had internal rotation. When comparing the nominal rotation at 0 degrees before and after TKA, it was noted that the tibial rotation point at 0 degrees moved more externally in 40% and more internally in the rest but the mean change for the overall group was 2.6 degrees of internal rotation. Finally, in 23% of cases there was a change in the direction in tibial rotation from the baseline measurement to the final measurement after total knee arthroplasty. For the new instrumented tibial tray, matching the baseline anterior-posterior tibial axis position at 0 degrees flexion seemed to provide the correct placement leading to final implantation.

**Discussion:** After TKA, alterations from the rotation of the normal knee may be related to anterior cruciate deficiency, prosthetic geometry, and differences in surgical technique in individual patients. Stiehl et al. have studied in vivo weight bearing kinematics of mobile bearing TKAs using the tibial cut first method as used in this study and assessed the amount of screw-home rotation evident with gait1. Maximum internal rotation with flexion was 9.6 degrees while the maximum external rotation with flexion was 6.2 degrees. The average tibial rotation for 20 patients was internal rotation of 0.5 degrees with knee flexion but 40% of TKAs demonstrated tibial external rotation with knee flexion.

The results of this study were similar to the fluoroscopic studies in that roughly 40% of TKAs demonstrated tibial external rotation with knee flexion.
flexion. However, the range of rotation was much greater in the CAOS studied patients which could be as much as 20 degrees. We would suggest that the lack of weight bearing forces in the CAOS TKAs could explain much of this difference. The occurrence of tibial rotation after total knee arthroplasty would appear to be quite variable and we could find no factors that predict which patients will externally rotate with flexion. From the computed tomographic studies of Berger et al., the transtibial axis is defined as a line bisecting the sagittal plane centers of the tibial medial and lateral condyles. The anterior posterior line perpendicular to the transtibial axis is roughly 18 degrees medial to the tibial tubercle center, and closely coincides with the femoral transepicondylar axis if it were translated distally in the coronal plane². Thus, there is a strong reason to couple the femoral anterior-posterior axis with the anterior-posterior tibial axis, and to utilize these points as references in a CAOS system. Preliminary experience with an instrumented tibial tray trial would suggest that matching this placement with the initial computer referencing anterior posterior tibial axis provides a viable option for image guided tibial tray placement. This may have greater application in minimally invasive surgical approaches.

References

Validation of fluoroscopic registration in surgical navigation of total hip arthroplasty

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Introduction: Computer assisted navigation (CAOS) in the performance of total hip arthroplasty requires registration and determination of critical performance measures such as acetabular component orientation, hip offset and leg length determination that are related to patient outcomes. Currently, the anterior pelvic plane (APP) is the most accepted pelvic reference plane. From the beginning, computed tomography has been believed to be the most accurate and reliable imaging modality to define prosthetic positioning. However, other methods have been sought in attempts to reduce resource expenditure and to minimize surgical times. Fluoroscopic referencing represents an alternative method where all referencing may be done in the operating room at the time of the index arthroplasty. This study compared the accuracy, reproducibility and repeatability of this method with a gold standard, NIST traceable coordinate measuring machine and with computed tomographic referencing.

Methods: The system evaluated was a Medtronic Stealth Treon platform (Medtronic, Lewisville, CO). A cadaveric pelvis for this study was then selected where a modular acetabular component was securely fixed in the appropriate position determined by conventional freehand guides with a target of 45 degrees inclination and 17.5 degrees anteversion. Testing of the cadaveric pelvis was done using a fluoroscopic registration module (Medtronic Fluoroscopic Hip). In each case, the prescribed referencing was accomplished using the software protocol of the system. This cup position was then assessed using a validated computed tomography protocol. A similar reference frame with the APP defined by two anterior superior iliac spines and the pubic symphysis was determined1,2. A metrologic
investigation using a NIST traceable, Brown and Sharpe coordinate measuring machine was performed on the pelvis, again using the same APP landmarks.

**Results:** For the cadaveric pelvis, the APP was determined using the symphysis pubis as the inferior landmark. The mean CMM abduction measurement of the acetabular cup position was 46.023 (SD=1.075; range 43.318 to 46.844 degrees). The mean CMM anteversion measurement of the acetabular cup position was 15.787 (SD=0.411; range 15.068 to 16.384) degrees. Computer tomographic measurement of the cadaveric pelvis revealed the abduction was 42.2 degrees with abduction of 12.4 degrees when measuring the APP from the ASISs and the pubic tubercles and 17.0 degrees when measuring from the ASISs and pubic symphysis.

One surgeon performed a repeatability study of the cadaveric pelvis using the fluoroscopic referencing (n=8). The mean abduction was 42.8 degrees (SD=1.5; range 39.5 to 44.5). The mean anteversion was 17.5 (SD=3.0; range 14.5 to 22.5). Three surgeons performed a reproducibility using fluoroscopic referencing (n=24). The mean overall group abduction was 48.5 (SD=0.9; range 46 to 50). The mean overall group anteversion was 17.8 (SD=2.5; range 13.5 to 23.5). All measures were within a predefined acceptability range of +/- 5 degrees.

**Discussion:** This study utilized two different ground truth baseline studies including a bench coordinate measuring machine analysis and a validated computed tomography protocol for determining acetabular component position. We are confident that these measures provide an accurate portrayal of the actual acetabular component position in the cadaveric pelvis. The accuracy and reproducibility of the fluoroscopic referencing method was found to be suitable for determination of cup position in the surgical setting. Anteversion measurements were more variable for the fluoroscopic method and could relate to the difficulty for the surgeon in predictably picking the anatomical points of the pubic symphysis from the fluoroscopic image. An important issue that arises is the fact that subtle differences in establishing the APP will affect the final cup position. In fact the cadaveric pelvic computed tomography revealed an increase of 5 degrees in anteversion following pubic symphysis referencing as opposed to the method where the pubic tubercles are used. This may be explained by the fact that the pubic symphysis may be about 5 millimeters more posterior in the anterior pelvic plane leading to a change of about 5 degrees in the component anteversion. It is also possible that the repeatability and reproducibility characteristics of the fluoroscopic referencing approach will be different than those obtainable through direct palpation or other methods. As a result, systematic differences in reported
component position may occur. Accuracy could possibly be increased if fluoroscopic referencing and direct point matching were combined in the same setting. Lastly, in addition to random error, subtle differences in the definition and calculation of the APP may alter the reported position of an individual cup. Based on the current study, the fluoroscopic referencing system would appear to be a satisfactory system for common usage.

References

Accuracy of the Medtronic Treon Plus CAOS System

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Background: Total Hip Arthroplasty is an effective surgical procedure in the treatment of patients with severe, end stage arthropathy. However, annual, cross sectional data from the United States demonstrate that 21.7% of hip arthroplasty surgeries are revision procedures¹. Although the exact frequency of acetabular component malposition and the quantitative linkage to hip reoperation is uncertain, it is clear that at least some reoperations could be avoided through more reliable acetabular component positioning at the time of surgery.

In one multicenter, European investigation, it has been identified that the use of a computer tomography based intraoperative system can reduce the incidence of acetabular component malposition². A focus group surveying US orthopaedic surgeons in 2004, concluded that surgeons did not trust existing commercial computer based intraoperative positioning systems³. They were concerned about the lack of information relating to system calibration, referencing, repeatability, reproducibility, reliability, usability and cost. We therefore elected to determine whether surgeons’ concerns about several of these characteristics in one commercial system were justified.

Methods: Calibration and Repeatability:

Using artifacts with traceability to the National Institute of Standards and Technology (NIST) the repeatability and linearity of the Medtronics Treon Plus system was evaluated. A Weber gage block with equally spaced reference platforms spaced 2.54 cm apart across a range of 25.4 cm was used as the primary artifact. The block was placed initially parallel and then perpendicular to the plane of the imaging bar. The perpendicular attitude was established by using a NIST traceable, triangular artifact. Each position of the Weber block was referenced using the point indicator six times in a random
order with varying probe attitudes. Ambient temperature was constant during the short period of data acquisition.

Reproducibility: An idealized foam block was constructed using numerically controlled milling machine. Faces for the acetabular socket were modeled at 45 degrees of abduction and 20 degrees of anteversion and referenced from the anterior pelvic plane. The pelvic frontal plane’s three reference points (the two anterior superior iliac spines and the pubic symphysis) were defined by placing fiducials into the foam block. An acetabular component (Modular Trabecular Metal Cup, Zimmer Inc.) was securely fixed into the foam block with screws and cement. An instrumented insertion device was attached to the cup using the threads in the cup apex. The position of the insertion device was recorded and then removed by three randomly assigned surgeons. Each surgeon performed eight repetitions to determine the reproducibility of the measurement of the component position.

Statistics: MS Excel 2003, SP1 and Minitab, version 14.13 were used for statistical analysis. Basic descriptive, ANOVA, and Regression Analytic routines were used.

Results: Accuracy: The Medtronic Treon Plus system was found to have small, but statistically systematic biases for the known fiducial platforms of the Weber Gage block in both parallel and perpendicular attitudes to the imaging bar.

The mean bias for the parallel condition was 0.26 mm. Regression analysis demonstrated a fixed bias of 0.52 mm. (P=0.00) The mean bias varied inversely according to the distance from the center of the imaging bar. The further the point of measure away from the center of the imaging bar the lesser the deviation from the known artifact. The slope of the deviation was small at -0.00232 mm but was statistically different (P=0.01)(Fig 1).ö

The mean bias for the perpendicular condition was 0.69mm. Regression analysis demonstrated a fixed bias of 0.79 mm. (P=0.00) The mean bias varied inversely according to the distance from the imaging bar. The further the point of measure away from the imaging bar the lesser the deviation from the known distance. The slope of the deviation was small at -0.00085 mm and was not statistically significant (P=0.33).

Pelvic Foam Artifact: Repeatability of the acetabular component position was performed. For the pelvic foam block, abduction was calculated with a mean of 46 (SD=0.0) degrees. Individual measures were all 46 degrees. Measured anteversion averaged 19 (SD=0.82) degrees. Individual measures ranged
from 15 to 19 degrees. All repeatability measures were within a predefined acceptability range of +/- 5 degrees.

Reproducibility of three independent observers in the determination of cup abduction and anteversion was performed. The mean measured abduction was 48.6 (SD=0.917) degrees. Individual measures ranged from 46 to 50 degrees. None of the twenty-four (0 %) abduction measures was outside of the predefined acceptability range of +/- 5 degrees. The anteversion, across all three observers, was 17.9 (SD=2.48) degrees. Individual measures ranged from 13.5 to 23.5 degrees. Only one of twenty-four (4 %) reproducibility anteversion measures was outside of the predefined acceptability range of +/- 5 degrees.

**Figure 1** Parallel to light bar

**Discussion:** Variability in the process of measurement potentially can be a function of multiple random or systematic errors. Systematic errors include variation in ambient temperature and physical limitations of the measurement system. Physical limitations of an optical measuring system may include the number and density of pixels available active field of view, the distance from the measurement plane, the attitude of the zone being measured in relationship to the measurement plane, the variability in target positioning,
the processing software and any non-linear characteristics of the measurement probe. Experimentally, errors may be associated with the measurement system itself or may also be due to the limitations of either referencing or device position measurement. These investigations did not address the establishment of the initial reference frame.

In summary, accuracy, repeatability and reproducibility of two degrees of positional freedom while using the Medronics, Treon Plus system are characterized in an ex-vivo system. In the assessment of accuracy, systematic measurement errors were identified and characterized. In the repeatability measurements of abduction and adduction the magnitude of these errors were within the predefined error believed to be of clinical significance. In the assessment of reproducibility, only one of the anteversion measurements was outside of the range believed to be of clinical significance.

References

Consequences of the femoro-tibial replacement on the femoro-patellar kinematics. An intra-operative in vivo study

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Introduction: Despite the major role played by the patella on 3D kinematics of the knee, in 2005 Total Knee Replacement (TKR) remains a femoro-tibial issue. Ligament balancing and implants alignment are implemented in any software and clinical results have shown a true efficiency of such tools. However, there is no clinical available package dedicated to patella tracking and patella navigation during TKR. In 2001, Praxim® implemented an add-on to the LCS® navigation software (Depuy®) to track the patella intraoperatively. We used it during a prospective randomized clinical trial under control of an ethical committee. Studying the patella was considered as a minor criterion during this study and was therefore not performed on each included cases of this clinical trial. In this paper we are reporting the 10 first cases of in vivo pre- and post-operative analysis of the patella trajectory. A complete analysis of the literature showed that this type of data has never been reported.

Methods: We are interested in studying the patella displacement as a consequence of the femoral implant location. This displacement will be evaluated with respect to the angle of flexion of the knee in a well-suited frame. Three problems then occur. First, data are displacements for pre- and post-operative relative to the camera frame. Second, several flexion-extension are done, so for a given flexion angle it is possible to have several
different displacements. Third, because of discreteness of the data, a given flexion angle may not exist both for pre- and post-operative data. To solve these problems, Bezier curves are used: They will smooth the data and allow accessing to any given flexion angle data both for pre- and post-operative data.

Displacement data consist in 3x4 transformation matrices. The rotation part is considered as a quaternion and a Bezier curve is then computed [1]. The translation part uses a 3D Bezier curve [2]. It is then possible for each given flexion angle to compute the pre-post transformation. This transformation is computed relatively to the camera frame which doesn’t have any surgical frame but it is possible to project results in any convenient frame. Here are used the following axes: the Y axis is the line passing through the medial posterior condyle point and the lateral posterior condyle point; the Z axis is the normal to the plan passing through these two points and through the hip center; the frame is then completed by the X axis. The results are then described in this anatomical reference system, which is the same reference system used intra-operatively to express the location of the implant and the computation of their alignments. Our results are based on 10 patients. Figure 1 shows the differences between pre- and post-operative data for patient 1. If the TKR had no consequence on the patello-femoral joint we should observe three lines centered on zero. The patella was never resurfaced and therefore the changes observed in the patello-femoral kinematics are only the consequences of the femoro-tibial replacement.
**Results:** Two different types of results will be reported at the conference. A) The global amount of rotation of the patella. B) The amount of translation along the $(Ox,Oy,Oz)$ axes as defined above. The global rotation ranges from $10^\circ$ to $40^\circ$. These differences decrease after $80^\circ$ of flexion but stay always above $10^\circ$. Translation values along $(Ox,Oy,Oz)$ axes show displacements as important as 15 mm. Several tables will be reported at the conference to express the variability and describe the specificity of each case.

**Discussion:** A tremendous work has been done in the past to study the kinematics of the patella. These studies can be classified as follows: a) in vitro or in vivo analysis b) On normal knee or on prosthetic knee c) based on image analysis (MRI or fluoroscopic images) or based on 3D localizers (optic as well as magnetic). If some recent papers published by Stiehl reports in vivo analysis of post-operative patellar tracking [3], none of them is able to report pre- and post-operative data and none of them is able to compare the consequences of the femoral implant location on the kinematics of the patello-femoral joint. Therefore the work presented in this paper is original.

In this first study we focused on the consequences of TKR on the femoro-patellar 3D kinematics. Despite the fact that these procedures have been done with the help of navigation system, one can observe major disturbances in patello-femoral joint kinematics after surgery. These changes are mainly observed along the medio-lateral axis, but all axes are concerned. This means that by replacing the femoro-tibial component one modifies deeply the 3D features of the kinematics of the patella. The differences are not reproducible from one patient to the other since numerous parameters can interfere with the patella. This suggests that the next generation of navigation software should absolutely integrate the control of the medio-lateral location of the femoro-tibial implant. Moreover this suggests that the femoro-patellar joint should be taken into account in the next generation of planning software since, as demonstrated in this study, controlling the femoral implant location is not sufficient to restore a good patella kinematics.

Based on the same data sets we will also describe the preoperative kinematics of the patella during flexion extension motion. The description of these features will be the base of a complete planning system.

**References**


The Hiploc: An innovative device to transfer the Lewinneck reference system into the surgical field

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Introduction: Hip dislocation, impingement, pelvic osteolysis and acetabular loosening are usually the results of an improper positioning of the acetabular cup with respect to the specific anatomy of the patient. Even with experienced surgeons, using conventional techniques, it is difficult to reach the “safe zone” described by Lewinneck in [1] since no mechanical device is accurate enough as demonstrated by DiGioia III in [2]. Today the main issue remains in the intraoperative definition of an absolute reference system and in a consensual framework in which the quantitative values of anteversion and inclination could be measured. In fact as Murray stated in [3] there is at least 3 ways of measuring these two parameters depending on the method of assessment. These three definitions results from different rotations around the transverse, coronal and sagittal axis. Depending on these rotations, one can observe very significant differences in terms of the quantitative assessment of the anteversion and inclination. Then, one must face the second issue: The definition of one absolute reference system. This means a reference system independent of the position of the patient on the operative table. Therefore, the anterior pelvic plane is now well accepted as an absolute reference system. This plan is defined by the two points located on bilateral anterior superior iliac spine and one point located at the midpoint of the bilateral pubic tubercles. Digitizing these three points when the patient is lying on his back is quite easy and can offer an accurate localization of the reference plane for anterior approach. In case of postero-lateral approach the patient stands in lateral decubitus position and anterior and posterior blocks are used
to stabilize the pelvis during the surgery. When these blocks are placed, it becomes almost impossible to accurately digitize the pubic and the contralateral iliac spine. In case of anterior approach in supine decubitus, it is also quite difficult to acquire these three points through draping. Therefore we developed an innovative device called HIPLOC© that is used to: a) Make an accurate acquisition of the three reference points, b) transfer these references into the surgical field after the draping. This paper will describe the device, how we use it in a clinical pilot study and why it is so important to have an accurate definition of the anterior pelvic plane to measure acetabular anteversion.

**Methods:** The Hiploc® is a device made of two separated parts (Fig. 1). The inferior part will be named as the base of the Hiploc®, the upper part as the satellite of the Hiploc® because of its shape. The satellite of Hiploc® holds a rigid body that will be used as a reference system for the pelvic bone. Two Hiploc® systems are used for each surgery which is performed in two consecutive steps.

![Figure 1](image.png)

*Figure 1*
*Intraoperative view of the Hiploc after the draping. The clamp is locked on its base which is under the draping*

a) First step: The patient is lying on his back. Then the base of the first Hiploc® is fixed to the bones thanks to two pins inserted manually in the anterior iliac crest. The satellite is then firmly locked to his base thanks to a specific design of the two parts that allow a perfect fitting between them. The Hiploc® is then calibrated and the surgeon can digitize the three reference points described above with the help of a specific passive tracker in a sterile or non sterile environment.

b) Second step: The satellite is removed from its base. For postero-lateral approach, the patient is set in lateral decubitus position. The draping is performed exactly as for a non assisted surgical procedure. The base of the
Hiploc® is therefore now located under the draping. Then a second sterile satellite is fixed to the first based over the draping. During this entire second step we assume that the base is strictly fixed to the pins and that it does not move with respect to the pelvic bone. Because of the specific shape of the base and its satellite we are able to find again the perfect fitting between the two pieces. The design asserts a perfect reproducibility of the satellite, whatever the draping thickness is. A second registration of the Hiploc® is then performed and we are now able to express the location of the three reference points in the new reference system.

This approach has been validated on cadavers and is now in use in our clinical daily routine.

**Discussion:** The Hiploc® system allows an accurate localization of the anterior pelvic plane in supine position without the interference of stabilization blocks, and the transfer of these points in the sterile surgical reference system. Its major drawback relies on the necessary two steps procedure and the associated risks such as pain or infection on the iliac side. At this point of the discussion one must underline that the consequences of a bad determination of the anterior pubic point in the sagittal plan can lead to a one to one error in the quantification of the anteversion of the acetabular cups. Since, an error of ten millimeters in the antero-posterior localization of the pubic point gives a 10° of error on the anteversion values. This is totally impossible to perform such accurate digitization in lateral decubitus with stabilization blocks in place, and very difficult in the supine position after draping. Concerning the controlateral iliac point, the issues are the same, but the consequences of an error on its localization are lower.

Because of the major role played by the anterior pubic point in the definition of the anterior pelvic plan we do believe that this two step procedure is acceptable with a reasonable balance between benefit (on the accuracy) and the increasing risks.

This approach has now been in use in our department for one year and more than 60 procedures have successfully performed.

**References**


Factors affecting the accuracy of minimally invasive total knee arthroplasty

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Introduction: Minimally invasive TKA techniques are currently being developed and evaluated to improve functional outcomes, especially in the early post-operative period, reduce peri-operative morbidity, and accelerate post-operative recovery. The reduced exposure necessitated by MIS-TKA could be associated with the performance of less precise surgical procedures which might compromise the functional outcome and longevity of the arthroplasty. A number of characteristics of MIS-TKA may adversely affect the accuracy with which the TKA is performed, including: 1) less visualization of important anatomy; 2) the use of smaller, potentially less stable, cutting blocks and instruments; and 3) alignment of instrumentation from the medial or lateral side of the knee. Computer assisted surgical techniques have been developed to increase the accuracy and reproducibility of TKA. CAS can also be used to measure the accuracy with which each step of the TKA procedure is performed. The purpose of this study was to use CAS to: 1) measure the accuracy with which each step of a TKA is performed using MIS instrumentation; and 2) determine the impact of rotating the cutting blocks on the accuracy of bone resection.

Methods: 49 consecutive TKA’s were performed using a standard surgical exposure. 25 were performed using conventional instrumentation and 24 were performed using MIS instrumentation. An image-free navigation TKA navigation system was used to measure the error introduced during each step of these procedures. The purpose of this portion of the study was to determine the extent of movement of the cutting blocks before and after resection, and to determine the accuracy of the cut surface in relationship to the position of the cutting block. The results using conventional blocks were
compared to the results using MIS blocks. In order to determine the impact of accuracy on altering the position of the alignment instruments, the tibial cutting block was rotated 45° medial to the frontal planed and the frontal and sagittal alignment of the tibial cutting block was measured using the navigation system with the block sloped 0°, 5°, and 10° posteriorly.

**Results:** The conventional distal femoral cutting block moved an average of 0.04° (range: 0 – 1, SD ±0.21) in the frontal plane (varus/valgus) and 0.3° (range 0 – 1, SD ±0.47) in the sagittal (anterior/posterior slope) plane following the distal femoral cut. The minimally invasive distal femoral cutting block moved an average of 0.19° (range: 0 – 1; SD ±0.40) in the frontal plane (varus/valgus) and 0.19° (range: 0 – 1, SD ± 0.40) in the sagittal (anterior/posterior slope) plane. Neither the conventional nor minimally invasive cutting blocks moved significantly as the result of the saw moving in the slot.

The conventional tibial cutting block moved an average of 0.48° (range 0 – 1, ±0.51) in the frontal plane and 0.52° (range: 0 – 2, SD ±0.54) in the sagittal plane following the proximal tibial cut. The minimally invasive tibial cutting block moved an average of 0.35° (range: 0 – 1, SD ± .49) in the frontal plane and 0.35° (range: 0 – 1, SD ± .49) in the sagittal plane following the proximal tibial cut.

The average difference between the position of the conventional distal femoral cutting block after the cut and the surface of the bone after the cut was 0.43° (range: 0 – 2, SD ±0.59) in the frontal plane and 1.83° (range: 0 – 3, SD ±1.03) in the sagittal plane. The average difference between the position of the minimally invasive distal femoral cutting block after the cut and the surface of the bone after the cut was 0.08° (range: 0 – 1, SD 0.27) in the frontal plane and 0.62° (range: 0 – 1, SD ± 0.50) in the sagittal plane.

The average difference between the position of the conventional tibial cutting block after the cut and the surface of the bone after the cut was 0.45° (range: 0 – 1, SD ±0.51) in the frontal plane and 0.75° (range: 0 – 2, SD ±0.55) in the sagittal plane. The average difference between the position of the minimally invasive tibial cutting block after the cut and the surface of the bone after the cut was 0.31° (range: 0 – 1, SD±0.47) in the frontal.

The tibial alignment jig was initially placed in the frontal plane so that the alignment rod was parallel to the long axis of the tibia. The tibial cutting block was then placed in three different positions in the sagittal plane, zero degrees, 5 degrees posteriorly sloped and 10 degrees posteriorly sloped. The alignment jig was then rotated 45 and then 90 degrees medially with the cutting block in each of these positions and the resulting posterior slope and
varus-valgus alignment of the block measured using the navigation system. The results are given in the Table below:

<table>
<thead>
<tr>
<th>Alignment rod in frontal plane</th>
<th>Cutting block: zero degrees</th>
<th>Cutting block: 5 degrees posterior</th>
<th>Cutting block: 10 degrees posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment rod rotated 45 deg</td>
<td>0 degrees post. 6 degrees post.</td>
<td>3 degrees val. 12 degrees post.</td>
<td>7 degrees val.</td>
</tr>
<tr>
<td>Alignment rod rotated 90 deg</td>
<td>0 degrees post. 0 degrees post.</td>
<td>5 degrees val. 0 degrees post.</td>
<td>10 degrees val.</td>
</tr>
</tbody>
</table>

**Summary:** The results of this study indicate that it is as possible to fix the smaller minimally invasive cutting blocks as securely to bone with pins as it is the larger conventional blocks. However, we found that these blocks are more likely to move as they are fixed if: 1) The bone is osteoporotic; 2) the bone surface is uneven; 3) the pins are inserted manually; 4) the pins are inserted obliquely and 5) pins with heads are used to place these blocks on uneven bony surfaces (e.g. the quadrant sparing approach’s placement of the cutting block on the medial femoral condyle).

The results of this study also indicate that the smaller minimally invasive cutting blocks do not necessarily move more than conventional blocks when a precisely fitting saw blade is used to resect the distal femur or proximal tibia. However, we again observed that block movement during resection is more likely with these blocks if the bone is osteoporotic or the surfaces to which the blocks are attached are uneven.

This study confirmed an observation of one of our earlier studies regarding the accuracy with which saw blades – even blades which fit precisely into the slots of cutting blocks – resect the femur and tibia. There is a consistent tendency for saw blades to be deflected from 1 to 3 degrees.

We are particularly concerned that surgeons may not appreciate the potential impact on the accuracy of implant placement of rotating the cutting blocks from the frontal plane. This study indicates that the errors introduced by moving the cutting blocks can be substantial. These inaccuracies are very difficult to see in a conventional exposure and would be even more difficult to appreciate through minimally invasive exposures.
Imageless navigation in minimally invasive total hip replacement with a posterior approach: Excellent clinical results and radiographic alignment

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Introduction: Minimally invasive total hip replacement has variable results with several authors demonstrating equivalent clinical results but others revealing increased component mal-position and increased operative complication rates. Decreased incision size certainly decreases the surgeon’s ability to use internal landmarks for component position. Navigation potentially can improve component position even with limited soft tissue dissection.

Imageless navigation of the hip has largely been performed from a supine position and the calculation of the pelvic plane is done in the same position as the surgery. Registration with imageless navigation from a lateral position is difficult so a method has been developed to register the patient supine and then place in a lateral position for the surgery. The purpose of this study was to determine whether the clinical and radiographic outcomes could be reliably achieved with this technique while incorporating a minimally invasive posterior approach.

Methods: One hundred and fifty three consecutive primary total hip replacements were performed by a single surgeon using supine registration with an imageless system (BrainLAB Vector Vision) and a minimally invasive posterior approach. The control group was comprised of 140 consecutive primary total hip replacements performed by the same surgeon in the same time period with traditional instrumentation. Important clinical markers such as transfusion rate, length of stay in the hospital, discharge to
home or to a skilled nursing facility, and incision length were also captured in this study.

**Results:** The average incision size in the cases performed with imageless system was 8 cm. The average length of stay was 2.8 days. In the control group, the length of stay was 3.1 days. 3% of the imageless navigation hip patients were transfused; 14% of the patients who had the traditional procedure were transfused. In the test group, 75% were discharged directly to home; in the control group only 69% were discharged to home.

No dislocations have occurred in the imageless group. The average component inclination on the postoperative radiograph was 45 degrees with an average anteverision of 15%. Comparison of the intraoperative measurements from the computer were consistent in regards to inclination but were variable in regards to anteverision with the computer consistently overestimating the anteverision compared to the postoperative supine radiograph.

**Discussion:** In spite of a minimally invasive posterior approach, imageless navigation resulted in reliable component position and excellent clinical results. The decrease in transfusion rate from 14% with traditional instrumentation to 3% with imageless navigation was a key finding in this study. Further outcome studies regarding function, walking ability, post operative pain scores and medication usages are ongoing to follow the progress of these cases with a goal of determining if the early benefits of the imageless navigation are maintained over time.

Through imageless navigation more information is available to surgeons thus enabling a better operative plan and a better description of anatomy. With imageless navigation, the surgeon receives immediate feedback so that better intra-operative decisions and, ultimately, better clinical outcomes will result.

**References**


CAS enabled minimally invasive TKA: Better clinical results and better alignment than mechanical instruments

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Introduction: Minimally invasive total knee surgery removes visual cues and can result in component mal-position. Computer assisted surgery (CAS) enabled knee surgery has been shown to improve component alignment compared to conventional instruments. CAS enabled minimally invasive surgery has the potential benefit of requiring less soft tissue dissection, decreased transfusion requirements, and decreased pain for the patient.

Minimally invasive total knee surgery with CAS facilitates earlier patient recovery while maintaining excellent component and limb alignment. The use of CAS in minimally invasive total knee surgery may also benefit hospitals and insurance payers, as CAS patients go home earlier, require fewer transfusions, and suffer lower complication rates.

Methods: The study examines a single surgeon series performed concurrently at two hospitals.

The concurrent series of thirty CAS enabled cases were performed using the DePuy Ci System along with the minimally invasive rotating platform knees. These were compared to a series of 20 minimally invasive rotating platform knees performed with minimally invasive mechanical instruments. All surgeries were performed by the same surgeon. The only selection criteria was whether the hospital had CAS enabled surgery available.

Results: The clinical results revealed a smaller incision size (15 cm vs. 12 cm) in the CAS enabled group. The CAS enabled group also yielded a lower transfusion rate with 0% of patients requiring any blood supplementation intra-operatively or in the post op period. The group performed with
mechanical instruments had a 15% transfusion rate. The CAS group also had a larger percentage of patients discharged to home, with 90% of the CAS patients going directly home, rather than to a skilled nursing facility (SNF) or to a hospital based rehabilitation program. In the mechanical instrument group, 50% required skilled nursing after care either in a SNF or in a hospital based program. An analysis of the intra-operative data revealed that the CAS group had an increased tourniquet time of eleven minutes over the mechanical instrument group. The tourniquet times for the CAS enabled group averaged 74 minutes, while the tourniquet time for the mechanical instrument group was an average of 63 minutes. All patients in the CAS enabled group had radiographic component position within +/- 3 degrees of desired plan as determined at the three month follow up visit. The mechanical instrument group had multiple outliers in radiographic component position. Post operative complications of all types were recorded for both the CAS enabled group and the mechanical instrument group. The CAS enabled group reported only 10% complications compared to the 15% complication rate reported by the mechanical instrument group. The length of stay for the CAS enabled group was 2.8 days, while the mechanical instrument group were hospitalized for 3 days.

**Discussion:** Reliable clinical results with early home discharge and lower overall complication rate can be achieved with CAS enabled minimally invasive total knee arthroplasty compared with mechanical instruments. Using computer assisted surgery, excellent component radiographic alignment can be achieved in spite of smaller incision size. The other key benefits to patients undergoing CAS enabled minimally invasive total knee replacement are a decreased rate of transfusion, and smaller incision size. Further studies are ongoing detailing functional outcomes, range of motion, pain and medication usage in CAS enabled total knee replacement surgery.

**References**

Feasibility of ultrasound-initialized bone morphing: Early experiences and evaluation of a computer-assisted surgical technique

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Introduction: The advantage of having an accurate, intraoperative ultrasound-based segmentation for minimally invasive orthopaedic surgery is a subject that has been broached by several scientists. Chan [1] and Lavallée [2] have explored methods using ultrasound to instantiate 3D bone morphing algorithms without the need of preoperative CT or MRI scans. Following in their spirit, we present here our first experiences using 2D B-mode ultrasound concurrently with our 3D bone morphing method [3] to provide for a rapid, automatic intraoperative segmentation technique for navigation and visualization in minimally invasive orthopaedic surgery.

Methods: For this experiment, we used our novel statistical shape model bone morphing technique, which is further detailed in [3]. The model was developed from a training database of patient proximal femur CT scans. The database constituted surface models generated from a training population of 14 scans. The bone morphing algorithm requires initialization via three landmark points that we chose during model-building (lesser trochanter, femoral notch, and greater trochanter), and the predicted shape is consequently refined from subsequent surface points.

Two different cast proximal femurs were chosen for this study. High-resolution CT scans of the two bones were segmented and fine 3D surface
models of these bones were generated. The cast bones were fitted with fiducial markers to register the CT surface models into the tracked bones’ coordinate space.

During the experimental trials, the CT surface models were registered into the anatomy’s coordinate space by using paired-point registration and surface matching from an in-house optical-tracking navigation system, yielding a registration error of 0.2 mm for this experiment. The registered surface models were considered as “golden” references that were used for error measurements (computed using Mesh [6]) and validation of the predicted bone morph models.

To initialize as well as provide surface points for our bone morphing method, we used bone surface contours extracted from the image planes of a tracked 2D B-mode probe of a Kontron Sigma 330 © diagnostic ultrasound system. The ultrasound calibration and automatic image segmentation correspond to those developed by Kowal [4, 5], and have reported errors of 0.151 mm and 0.42 mm respectively. Furthermore, this segmentation approach is currently being employed in a commercial system [2], showing good accuracy and repeatability results in the latter.

Three anatomical landmarks were first obtained from ultrasound bone surface contours, and subsequent bone contours provided surface points for bone morphing. The result was a predicted model in the anatomy’s coordinate space. To have a comparison of performance, a tracked pointer was used in parallel to digitize points for the bone morphing method.

Two different research scientists, to obtain stable estimates of the errors and to have an initial impression of the repeatability of our proposed method, each performed a series of 5 – 7 trials per bone.

**Results:** For the presentation of this experiment’s results, we will consider each user’s trials, for each bone, as a separate set of results, providing four series of results.

The tracked pointer-generated bone model yielded an average mean error of 2.46 mm and an average median error of 2.16 mm for the first bone. These measurements had been averaged over a series of 14 trials, using 30 surface points per trial. Considering the first cast bone, the first user obtained the worst results of the entire experiment. Through the user’s ultrasound trials, the predicted model’s mean error ranged from 3.88 to 13.65 mm. The average mean error of this series was 8.47 mm and the average median error was 7.78 mm, for 42 surface points per trial. These predicted models were quite
erroneous with respect to the pointer-based reference and we found that this was largely due to inadequate localization of the initial three landmark points.

The second user fared better for the ultrasound trials using the first bone, with a mean error ranging from 2.27 to 4.73 mm. This user attained an average mean error of 3.49 mm and an average median error of 3.10 mm, for 38 surface points per trial. The second cast bone had for the pointer-based approach a 2.57 mm average mean error and an average median error of 2.35 mm. These latter figures were taken from a series of 10 trials, using 27 points each. For this series, there was not a large discrepancy in the results of the users’ ultrasound trials. The first user had a mean error that ranged from 2.60 mm to 5.99 mm for 32 surface points. Their average mean error was found to be 3.89 mm and the average median error was 3.64 mm.

The second user’s results were slightly, though not significantly better, with a mean error ranging from 2.74 mm to 4.52 mm. The average mean error was found to be 3.54 mm and the average median error was 3.16 mm for 30 surface points. For the second bone, both users’ series of trials are comparable to their pointer-based counterpart in terms of error measurements.

Discussion: We have seen above that for most cases, ultrasound-based morphing in our experimental conditions can provide a stable and repeatable prediction for bone visualization, though the accuracy is still not to the level needed for clinical applications.
Let us first consider the ultrasound-based morphing. When investigating potential sources of error for our experiment, we identified that there were two causes for erroneous surface points. The first, and more severe cause was the inaccurate localization of the initial 3 landmarks. With 2D ultrasound as a visual guide, it is quite an arduous task to accurately identify a defined landmark. Unless the model’s dependency on the initial landmarks is relaxed, 3D ultrasound approaches would be more appropriate in this scenario. The second cause of error was due to image-warping occurring within the ultrasound plane. The latter would not have been a major source of error due to the bone morph method’s outlier resistance. Nonetheless, it is an aspect that needs to be rectified by using a newer system with a properly maintained probe.

Concerning the bone morphing technique there remain some steps to improve its potential for accurate prediction of patient anatomy. Reducing the method’s dependency on the initial landmarks by implementing a recursive registration algorithm, such as ICP, would improve prediction and has been shown to yield good results in similar work [1]. From our experience, it is feasible to obtain landmark points within 2 – 3 mm of their actual location with ultrasound-based techniques, which would then provide a reasonable initialization of the ICP registration. Finally, increasing the size of the model’s training population would also improve the shape prediction accuracy. We determined from our early experience, once the issues we have outlined are addressed, that the approach we have taken could be suitable for intraoperative navigation and visualization.

References

Accuracy and potential pitfalls of fluoroscopy guided acetabular cup placement

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Introduction: Recently, computer-assisted methods have been introduced for intraoperative navigation to improve the precision of acetabular cup placement in THA that can be categorized in three modalities. CT based modules require a time-consuming preoperative planning and complex intraoperative matching procedures that are subject to a considerable learning curve. Moreover, they usually go along with increased costs and radiation. Completely image-free techniques refer their angular feedback to percutaneously digitized anatomical landmarks, which can be difficult to obtain, in particular in obese patients and in lateral decubitus position [1]. Virtual fluoroscopy could provide both visual and angular feedback without preoperative planning as proven for other applications [2]. Therefore, the accuracy of a fluoroscopy based navigation system for acetabular cup positioning was evaluated in a cadaver setup and potential pitfalls of this method were analyzed. It was hypothesized that such a hip navigation system improves the probability of implanting the cup within the safe range and reduces the variability of cup orientation in comparison to the surgeon’s freehand positioning.

Material and Methods: 14 cadaver hips (7 specimens, 4 male, 3 female) were included in the first part of the study. With the help of a fluoroscopy based navigation system, the accuracy of cup placement was carried out both for the surgeon’s free-hand positioning and for the fluoroscopy based computer navigation. Using a tracked fluoroscope (Siremobil Iso-C, Siemens
Medical Solutions, Erlangen, Germany) two images were acquired of each of the osseous landmarks of the anterior pelvic plane. This is constructed by both anterior superior iliac spines and the midpoint between the pubic tubercles. Each landmark to be reconstructed was then marked in the two corresponding fluoroscopic images and its three-dimensional location was calculated by a back-projection algorithm [3]. The free-hand positioning was recorded with the surgeon blinded to the computer screen and the cup was finally placed under interactive real-time guidance aiming at 40° of cup abduction and 15° of cup version. The real cup orientation was determined with the help of a CT-based computer navigation system (SurgiGATE®; Praxim-Medivision AG, Bern, Switzerland) and a highly accurate fiducial based paired point matching.

The influence of malregistration of the pelvic reference coordinate system is shown. The white spots represent the real bony landmarks (the anterior superior iliac spines and the pubic tubercles) of the anterior pelvic plane. The resulting mean angle of a maldefined point is shown in the scatter diagrams, e.g., defining the pubis point to posteriorly (Point 9) would lead to a more anteverted cup.
The second part of the study analyzed the influence of inaccurate landmark definition on the calculation of cup abduction and version. 16 dry cadaver hips (8 specimens; 4 male, 4 female) were investigated. The midpubic point was marked with a metal sphere. According to the procedure of the first cadaver series, two standardized fluoroscopic projections were used to define the pubic reference: 1. An outlet view with the tip of the coccyx pointing to the superior symphyseal border, 2. an inlet view with overlapping inferior and superior pubic rami. The anterior superior iliac spines were digitized directly with a tracked pointer. Then, a tracked cup impactor was orientated in 40° of cup abduction and 15° of cup version and fixed rigidly to the operation table. Defined variations of the ideal landmark definitions were investigated and their effect on the calculated angulation of the impactor was displayed by the navigation system. For the superior iliac spines these variations included points along the four edges forming the trapezoid shape of the ipsilateral and contralateral spine (points 1 to 8). For the pubic symphysis three points at the cranial-caudal and anteroposterior extension of the symphyseal gap as well as their mid point were chosen (points 9 to 14) as variations.

**Results:** The surgeon placed significant smaller number of cups (2 of 13, 15.3%) within the safe zone in comparison to the navigation system (10 of 13 cups, 76.9%, \( p = 0.019 \), McNemar-Test). The mean cup abduction achieved by the surgeon was 41.4° ± 7.7° (range, 29° - 56°). The variability of cup placement could be reduced significantly for cup abduction (\( p = 0.001 \)) but not for cup version (\( p = 0.79 \), F-Test).

The spinae could be reconstructed with the image-intensifier with a higher accuracy in comparison to the pubis point (\( p = 0.003 \), Mann-Whitney-U-Test).

All of the three navigated cups placed outside of the safe range failed for cup version. A significantly higher reconstruction error was found for the corresponding pubis points in comparison to the group within the safe range (\( p = 0.04 \), Mann-Whitney-U-Test).

The influence of inaccurate definition of the iliac spines on the cup angles is negligible. None of the points of inaccurate landmark reconstruction led to a mean abduction of the cup outside of the safe range. Inaccurate definition of the pubis point affects particularly cup version. Cup version decreases when the pubis point is defined anteriocranial from the real intertubercle point (Points 11 and 12). Cup version increases with the pubis point defined posteriocaudally (Points 9 and 14). For two of the points, the mean version was outside the safe zone (points 9 and 14). A maximal deviation of 4° for
cup abduction was found for all the defined points (Point 14). The maximal deviation for cup version was 17° for the same two sets of points (9 and 14).

**Discussion:** The presented study demonstrates that fluoroscopy based computer assisted THA can improve the accuracy and reduce the variability of cup placement in THA with carefully defined reference points. The registration of the midpubic point is crucial for accurate determination of cup version. Misinterpretation of this point on a pelvic inlet view by an overlying inferior pubis ramus can compromise the accuracy of the results, especially in heavy patients with a limited range of motion of the fluoroscope. Besides the surgeon’s experience, this explains the fact that in our series only the variability of cup abduction could be reduced. Definition of the iliac spines can easily be achieved in an accurate manner and can potentially be used in lateral decubitus position with hybrid registration methods where a direct digitization with a pointer cannot be performed.

**References**

Prediction of individual hip joint motion and impingement: A validation study using surgical navigation

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Introduction: Femoroacetabular impingement (FAI) is the major cause of osteoarthrosis of the hip [1-3]. It is characterized by a repetitive abnormal contact between bony prominences of the antero-superior femoral head-neck junction and the acetabular rim during the end range of motion (ROM). Depending on the location of the bony abnormality, two types of FAI are distinguished: The “cam” for the femoral and the “pincer” for the acetabular pathomorphology. Typical findings during physical examination are restricted internal rotation and reproducible pain with forced internal rotation in 90 degrees of flexion (“impingement sign”). Although together with the radiological examinations, this allows diagnosis of FAI, an accurate method for anatomically based quantitative definition of the femoro-acetabular range of motion (ROM) and accurate planning of the amount of required corrective surgery is absent. A non-invasive method of assessing hip joints for the presence, location, and severity of FAI is essential for improved
understanding, accurate diagnosis, and appropriate treatment recommendations.

To address this problem, a computer-assisted method for kinematical analysis of any individual hip joint and accurate assessment for FAI was developed. The purpose of this study was to validate the accuracy of the system with a surgical navigation system and to determine the bony anatomical based ROM in normal and impingement hips. It was hypothesized that patients with FAI have a decreased ROM in terms of flexion, and internal rotation in 90 degrees of flexion.

Methods: Based on a CT-scan of the pelvis and the femoral condyles, the developed software reconstructs a 3D model of the pelvis and the femur and calculates the native preoperative ROM, the identification of the exact acetabular and femoral location of impingement, and the simulation of the postoperative hip motion after virtual quantified surgical acetabular and femoral reshaping. The anterior pelvic plane and the femoral axis were used as anatomical reference coordinate system [4]. The center of the femoral head was considered to be the center of rotation.

In a first part of the study, software validation was performed by comparing the virtually predicted with the actual measured ROM by means of an image-free computer navigation system for total hip arthroplasty (Image-free hip version 1.0, BrainLAB, Munich, Germany). Thirteen plastic hips and 14 fresh cadaver hips were included for validation. The four anatomical landmarks of the APP were dissected and digitized with a tracked pointer. The hip center was determined kinematically. By direct manipulation of the hip the real ROM was determined and compared to the predicted values. Flexion/extension, abduction/adduction, internal/external rotation in 90 degrees of flexion were assessed for the plastic bones, flexion and internal rotation in 90 degrees of flexion were assessed for the cadaver hips.

In the second part of the study, the ROM of normal (control group) and impingement patients (study group) were analyzed and compared with the help of the developed software. For the control group, the contralateral hip of 144 patients undergoing CT-based navigated total hip replacement was investigated retrospectively. All the painful hips, the hips with osteoarthritic changes and hips with radiographical signs of FAI were excluded from the control group, leaving 36 patients for determination of the normal femoroacetabular ROM. For the study group, 24 consecutive hips (16 patients) with FAI were recruited prospectively from the outpatient clinic of one of the authors. The impingement group consisted of 11 cam, 6 pincer and 7 combined pathologies.
Results: Validation of the software with the sawbones revealed accuracy for the developed software of \(-0.7^\circ \pm 3.1^\circ\) (range, \(-9^\circ - 6^\circ\)) for all the 78 measured angles. Validation of the software with the cadaver hips revealed an accuracy of \(-5.0^\circ \pm 5.6^\circ\) (range, \(-19^\circ - 7^\circ\)). The accuracy of angle detection did not differ among the different motions neither for plastic bones (\(p = 0.10\), Kruskal-Wallis-test) nor for cadaveric hips (\(p = 0.28\), Mann-Whitney-U-test).

There was no difference of ROM for any motion between men and women. Patients with FAI had a limited flexion, internal rotation in 90 degrees of flexion and abduction in comparison to the control group (\(p < 0.001\)). No difference could be found for extension, adduction and external rotation in 90 degrees of flexion. Among the study group, patients with cam impingement had a significantly increased internal rotation whereas patients with pincer impingement typically revealed a limited flexion.

Discussion: We describe a non-invasive tool for preoperative assessment of three-dimensional FAI-simulation and anatomically based calculation of the native hip ROM. This method of planning proposed surgery is essential both for appropriate preoperative assessment and treatment of this condition and for the minimization of risk and morbidity associated with such treatment. In a plastic bone setup, the system could be shown to be accurate; the cadaver measurements revealed that the system generally overestimates the actual range of motion. The system is limited to concentric joints and is not applicable to hips with a shallow acetabulum. In addition, it does not take into consideration the soft tissue tension.

However, since the restricted motions (flexion and internal rotation) in FAI are due to bone-to-bone impingement, this does not jeopardize results of this study. This kinematical hip simulation and surgical planning module represents the basis for future minimally-invasive surgical approaches for treatment of FAI.

References
Introduction: Malposition of the acetabular component during total hip arthroplasty is the most common cause for post-operative hip dislocation and revision surgery for recurrent hip dislocation [1,2]. Mechanical jigs used at the time of surgery assume that the pelvis is positioned properly. The current study uses intra-operative and post-operative radiographs to calculate with the help of previously developed computer software the variation in three-dimensional position of the pelvis during total hip arthroplasty performed in the lateral position.

Methods: 30 consecutive total hip arthroplasties were studied. There were 11 women and 19 men with a mean age of 52 years (standard deviation 11, range 30 – 74). The patients were secured in the lateral position using a peg board (White Surgical, Inc., Germantown, TN). During each procedure, a cross-table intraoperative AP radiograph of the affected hip was taken after the cup was inserted. The radiographic plate was positioned squarely to the operating table. Post-operatively, an AP pelvis radiograph was taken. Since the intraoperative radiograph was centered over the hip and the postoperative radiograph was centered over the symphysis, a correction factor of 5 degrees of cup version was implemented in the calculations [3].

The study method is based on the assumption that the acetabular component did not move significantly within the pelvis between the time that the cup was inserted and the time that the post-operative AP pelvis radiograph was taken post-operatively. With the help of a modified previously developed
computer assisted technique [4], the contour of a projected cup ellipse was reconstructed on the intraoperative radiograph and then repositioned to match the post-operative radiograph. Based on a cone projection model, the computer software is able to correct the projected ellipse of the acetabular cup for different pelvic orientations. The difference between the post-operative and the intra-operative position allowed for calculation of the position of the pelvis during surgery at the time that the intra-operative radiograph was taken. The position of the pelvis during surgery was correlated to sex, height, weight and body mass index to determine any patterns.

Results: Considerable deviations between the intra- and the postoperative pelvic position were detected. Pelvic rotation around the longitudinal axis varied over a range of 65.2° (mean 0.9° ± 12.7°, range -24.9° – 40.3°). Pelvic tilt varied over a range of 34.5° (mean -2.6° ± 6.4°, range -23.8° – 10.7°). Pelvic obliquity around the AP axis varied over a range of 23° degrees (mean -2.9° ± 6.8°, range -16.9° – 6.1°).

There was a statistically higher variation of pelvic rotation in comparison to pelvic tilt (p < 0.01) and pelvic obliqueness (p < 0.01, F-Test). No correlation between sex, height, weight, or body mass index with any of the three commutative rotations could be found.

Discussion: The current study demonstrates that the pelvis is frequently malpositioned during total hip arthroplasty. Further, the study demonstrates that the assessment of acetabular component position based on intra-operative radiographs is frequently difficult due to the significant variation in the position of the intra-operative radiographs relative to the pelvic plane. Improved assessment of acetabular component placement during surgery may be achieved by improved methods of correcting for malpositioned intra-operative radiographs or by surgical navigation.

References
Stereoscopic visualization and six degrees of freedom interaction in preoperative planning of total hip replacement

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Introduction: Due to the improvements of computer science, specialized Virtual Reality (VR) approaches have been proposed in medicine. VR techniques are more and more common in neuro [1], craniofacial [2] and orthopaedic surgery [3], since they help to perform a precise pre-operative planning and to accurately achieve that planning with minimally invasive surgical procedures.

Preoperative planning is a fundamental phase in total hip replacement (THR) surgery and the advantage of using a three-dimensional (3D) environment to plan the operation has been demonstrated [4]. Many systems for 3D preoperative planning of THR have been developed which allow surgeons to position prosthetic models within a 3D navigation environment, combining 2D and 3D graphical representation of the patient anatomical data.

The navigation through the 3D environment is obtained using a mouse with two degrees of freedom and a flat screen for pseudo-3D interaction even if it has been demonstrated that the accuracy in positioning the implant is strongly effected by the graphical user interface [5] and, in authors’ knowledge, there are no published studies that investigate the accuracy of such 3D monomodal interface in preoperative planning of THR surgery.

The present work is aimed to compare the positioning accuracy achieved with conventional mouse-monitor interfaces to that obtained with a stereoscopic display and two different six degrees of freedom (6DOF) tracking technologies.
**Methods:** An unambiguous and relevant task was used to assess the accuracy achievable with the interface in a specific planning task [5]. The accuracy achievable in stem and cup component positioning was independently investigated. The test was performed using a standard mouse-monitor interface (HipOp® pre-operative planning software, B3C, Italy) and an immersive system. In particular, the projection table used for the displaying was a Baron workbench (BARCO Projection Systems Inc., USA), which is a motorized table, that can be oriented at any angle between 0° to 90° and supports StereoGraphics CrystalEyes 3D shutter glasses. For the tracking a first series of positioning was carried out with Intersense tracking system IS-900 VWT which also includes a lightweight 6DOF stylus with two buttons. A second run of testing was realized with optical tracking (VICON Motion Systems, UK). Five users were enrolled in the study and the positioning was repeated for 10 times by each user for all three systems. The Root Mean Square Error calculated with respect to the known component position was assumed as indicator of the achievable accuracy and repeatability. The time necessary to perform the task was also recorded in each session.

**Results:** Both the immersive interaction modalities (Intersense and VICON) provided a better accuracy than the standard 2D mouse-monitor interface. In particular, this difference with respect to standard interaction is statistically significant for the cup positioning. The VR environment allowed also reaching the positioning in a shorter time, confirming the high usability of the new interface and the steep learning curve also for users unfamiliar with the new environment.

**Discussion:** This study has demonstrated that the application of VR environment for pre-operative planning of total hip replacement allows to shorten the duration of the positioning and to have consistent results even with first-time users.

The accuracy achievable with the immersive interface was lower or comparable with that achievable with standard mouse-monitor interfaces. Moreover, the user is much quicker using the immersive interface. That fact is a further proof of the usability of the new interface and also of the easiness with which users accept the new immersive environment, since for most of the participants it was the first experience with VR and 6DOF interactors.

One of the main limits of this study is that in case of a short time between the test sessions the user reports fatigue, eye-strain and cybersickness.

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References


An innovative multisensorial environment for pre-operative planning of total hip replacement

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Introduction: Due to the improvements of computer science, in last years specialized Virtual Reality (VR) environments have been proposed in medicine.

Preoperative planning is an important phase in total hip replacement (THR) and the advantage of using a three-dimensional (3D) environment in the planning has been demonstrated [2]. Many systems for 3D preoperative planning of THR have been developed which allow surgeons to position prosthetic models within a 3D navigation environment, combining 2D and 3D graphical representation of the patient anatomical data [1, 3].

The present work is aimed to describe an innovative pre-operative planning environment for total hip replacement, which includes advanced software modules for the planning and up to date technologies for immersive interface (stereoscopic display, six degrees of freedom (6DOF) tracking, speech recognition, and haptic devices).

The pre-operative planning environment: The implemented pre-operative planner requires a complete anatomical model of the muscle-skeletal apparatus. In the optimal condition CT, and MRI of the patient hip joints are available where CT data provide the skeletal anatomy and the outer body shape and MRI the muscle and ligaments anatomy. However in the standard clinical practice only a CT scan is taken to the patient before total hip
replacement surgery. In order to have the complete muscle-skeletal model of
the patient, a pre-processing unit has been implemented where a technician
can scale a generic muscle anatomy atlas (obtained from the Visible Human
Man dataset) to fit the patient skeletal anatomy.

Once the data of the patient have been prepared and imported in the planning
environment, the user can perform different actions and move within
different software states. The user can move from one state to the other using
voice commands that are representative of the action that the user will
perform in the next state.

First of all, the user can estimate the surgical access. The surgeon visualizes
the patient outer skin and marks on the external surface the line of incision.
The system shows the opens the skin incision letting the user inspect the
muscles behind. For each muscle the surgeon can decide to cut or to retract it.
During the muscle retraction a force feedback is given to the user in order to
understand if there is muscle damage and if it is possible to retract the muscle
enough to achieve the acetabular capsule.

Once a prosthetic component is loaded the user can move to the prosthesis
positioning section. During the positioning, a two-hands interaction is
available: Oe hand controls he camera and one hand the six degrees of
freedom positioning of the components. At any time during the positioning
the surgeon can check a series of functional indicators: feasibility of the
planned position, extension of bone-implant contact in cementless
components, primary stability of cementless components, range of motion of
the operated joint, thickness of the cement mantle in cemented components,
extension of bone-cement contact in cemented components, and limb
lengthening/shortening after joint reduction, balancing of soft tissues, and
alteration of articular muscles moment arms. A force feedback is available in
the evaluation of some of the above-mentioned indicators, such as the range
of motion, the feasibility of the planned position, and the primary stability
evaluation.

Once the pose of the prosthetic components is defined, the surgeon can ask
the system to compute the neck resection plane as well as the insertion path
of the reamer. Once the surgical planning is accepted, the system generates a
model of the post-operative anatomy on which the surgeon can perform last
verifications and inspections.

**Results and Validation:** Each specific user requirement is going to be
assessed with specific validation studies, using the following quantitative
metrics: capabilities not provided by existing systems, inherent accuracy,
time required to perform the task, global accuracy in performing the given
task, intra-operator and inter-operators repeatability, and learning curve. The different technologies integrated in the system have been independently validated with relevant but unambiguous tasks. The software modules providing quantitative indicators on the realized planning were also tested to assess the achievable accuracy and repeatability.

**Conclusion:** Pre-operative planning is a fundamental phase in total hip replacement. However, the interface to the user is mostly implemented by using a mouse and a flat (2D) screen. In this work the application of multimodal/multisensorial interface technology in the pre-operative planning was presented. In this approach to the user, the interface was realized with the integration of different interface units including 3D stereo displays, haptic and speech. It is believed that true benefits can be gained with the use of this multimodal/multisensorial interface in all aspects of medical planning and training including the time required to perform a task, accuracy and repeatability in performing the task, and the learning curve.

**Acknowledgement:** This work was supported by the MULTISENSE (IST-2001-34121) European project.

**References**


Accuracy of CT based navigation of tumors in the pelvis

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Introduction: CT based navigation systems were introduced into orthopedic surgery in 1994. Nowadays CT based navigation is used in all areas, like joint replacement, reconstructive surgery and tumor surgery. Pelvic tumor surgery still is a very complex and demanding challenge even for experienced surgeons. Even though the high standard of CT scans makes it possible to exactly localize tumors, reaching them intraoperatively still is a problem. In this study we investigated the accuracy of an image based navigation system. As reference a pin mounted reference plane was used.

Methods: A cadaver pelvis was prepared and 16 screws (Cranial Marker System, STRYKER, Leibinger, Freiburg, Germany) were randomly placed in one half of the pelvis. In both ASIS a navigation pin was inserted. A reference plane, which consisted of a plexiglas plane and 4 pins, was plugged on the navigation pin. CT markers were inserted on the pelvic screws and on the reference plane pins. Previous to the measurements two CT scans (1.2 cm thick slices) of the pelvis were performed. One with the reference plane ipsilateral to the target screws and one with the reference plane contralateral to them. The position of the CT markers (4 reference points and 16 target points) were digitized with the Neurosurgery Navigation System Version 1.1-9 (STRYKER, Leibinger, Freiburg, Germany). In order to find out the variations from the digitized target points related to the reference points from the real time position of the markers, 2 observer manually approached the markers with the image guided Navigation System Version 1.05 (STRYKER, Leibinger, Freiburg, Germany). Therefore the CT markers had to be replaced by navigation markers. The centers of both, the navigation markers, and the CT markers were the same. First the reference plane was mounted to the left ASIS of the pelvis, ipsilateral to the navigation markers. Then each observer
digitized the 4 reference points and the 16 target points in a defined order. After 10 measurements of each observer the reference plane was changed to the right ASIS, contralateral to the location of the navigation marker.

**Table 1** Comparison of deviations from tumor navigation to CT measurements of reference and target points regarding ipsilateral and kontralateral measurements

<table>
<thead>
<tr>
<th></th>
<th>ipsilateral</th>
<th></th>
<th></th>
<th>contralateral</th>
<th></th>
<th></th>
<th>total</th>
<th>N</th>
<th>SD</th>
<th>N</th>
<th>SD</th>
<th>N</th>
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<tbody>
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<td>20</td>
<td>0.1</td>
<td>0.3</td>
<td>20</td>
<td>0.1</td>
<td>0.6</td>
<td>40</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
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<td>0.1</td>
<td>0.6</td>
<td>20</td>
<td>0.1</td>
<td>0.6</td>
<td>40</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.547</td>
<td></td>
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</tr>
<tr>
<td>reference point R3</td>
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<td>0.5</td>
<td>20</td>
<td>0.1</td>
<td>0.4</td>
<td>40</td>
<td>0.1</td>
<td>0.1</td>
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<td>0.030</td>
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<tr>
<td>reference point R4</td>
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<td>0.1</td>
<td>0.5</td>
<td>20</td>
<td>0.1</td>
<td>0.5</td>
<td>40</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.327</td>
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<td>mean deviation of reference points R1 to R4</td>
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<td>0.1</td>
<td>0.5</td>
<td>20</td>
<td>0.1</td>
<td>0.5</td>
<td>40</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.758</td>
<td></td>
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</tr>
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<td>target point T1</td>
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<td>0.2</td>
<td>0.9</td>
<td>20</td>
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1) Mann-Whitney-U-Test
Again 10 trials per observer were made. The deviation in millimeters (mm) of each digitized reference point and each digitized target point was registered. Nonparametric tests were used for statistical analysis because most of the variables were not normally distributed and showed unequal variances regarding ipsilateral versus contralateral measurements. The differences between the groups were analyzed using the Mann-Whitney rank sum test. The results are expressed as mean and standard deviation. The alpha level of each individual test was adjusted downwards to ensure that the overall risk for a number of tests remained 0.050. This correction was done using the Bonferroni method. For the reference points (R1 to R4) a p value < 0.0125 was considered significant, and for the target points (T1 to T16) the critical alpha level was set to p < 0.0031.

**Results:** There was no significant difference between the ipsilateral and contralateral measurements of the reference points and the mean deviation of the 4 reference points. 13 of 16 target points showed a significantly smaller deviation ipsilateral than it was found on the contralateral side. Testing of homogeneity of variance (Levene test) revealed in 15 of 16 target points significant differences in variance between ipsi- and contralateral measurements, whereas the ipsilateral measurements showed better values. The intraobserver reliability demonstrated no significant difference.

**Discussion:** By comparing the navigated target points with the digitized CT target points the study demonstrated smaller variance ipsilateral (mean deviation: 1.3 mm) compared to contralateral (mean deviation: 2.6 mm). The lowest mean deviation ipsilateral was 0.7 mm, the highest 1.8 mm. Ipsilateral measurements revealed also better values in variance. This cadaver study shows that it is possible to approach a pelvic tumor with the tested navigation system within a range of approximately 5 mm.
Endoscope based hybrid-navigation system for minimally invasive ventral-spine surgeries

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Introduction: Surgical procedures on lumbar and thoracic vertebrae are common following trauma or for degenerative herniation. To treat these disorders, it is argued, endoscope based minimally invasive surgeries are better, compared to their invasive counterparts, due to decreased access morbidity and cost-effectiveness [1]. On the contrary, 2D visualization of operative site, minimal accessibility and reduced dexterity in minimally invasive surgeries, increase the possibility of injuring vasculature, spinal cord with its emanating nerves and inaccurate positioning of the prosthetic devices [2]. Opting for image guided navigation during these surgeries will counter the inadequacies and improve safety and accuracy to a significant degree. Computer assisted navigation, during posterior spine and anterior cervical spine surgeries, has proven to increase safety and helps in accurate positioning of prosthetic devices.

Computer assisted navigation has been tried during minimally invasive surgeries on anterior parts of thoracic/lumbar vertebrae [3]. The main difficulty is in rigidly fixing the dynamic reference base (DRB) to these vertebrae, which has to be done with a long stylus allowing it to protrude from the opposite abdominal wall or it is fixed to the iliac crest and stringent immobilization of the patient is ensured. These methods are susceptible to instability and hence inaccuracy. Therefore, there is a requirement for a new kind of tracking system to provide effective navigation during these surgeries. Availability of high resolution, magnified and relatively noise-free endoscopic images in a small work space, 4 – 10 cm from the endoscope tip, opens up the possibility of using endoscope as a tracking tool. We are developing a hybrid navigation system where image analysis based 2D-3D tracking is combined with the optoelectronic tracking (Optotrack®) for
computer assisted navigation in laparoscopic ventral-spine surgeries. Initial results are encouraging and are confirmative of the ability of the endoscope as a tracking tool in surgical navigation where submillimeter accuracy is mandatory.

**Methods:**

1. **Calibration of Endoscope**

To obtain 3D geometrical information from endoscope images it has to be accurately calibrated. Images of a black and white checker-board pattern, with squares of size 2.5 mm, are used for calibration with Matlab based calibration toolbox [4]. The reprojection error was 0.5 – 1 pixel, which is considered fairly adequate for the purpose. Projection matrix, radial and tangential distortion factors are obtained simultaneously.

2. **Tracking an artificial fiducial marker in the endoscope image**

Freely available augmented reality application toolkit (ARToolKit) is used, after some modification, for calculating the position and orientation of an artificial fiducial marker which is of pre-determined size and pattern [5]. Calibration procedure bundled with this toolkit is highly inaccurate. Therefore, video stream from endoscope is first undistorted and then fed into the algorithm, for image analysis, which gives out a transformation matrix from camera co-ordinate system to the marker co-ordinate system.

![Distance error](image)

*Figure 1*
3. Accuracy evaluation

Optoelectronically trackable marker shield is attached to the marker and its four corners and the center are registered for tracking by Optotrack. Similarly the endoscope is also tracked. Position and orientation of the marker is ascertained by both image analysis and Optotrack based tracking at various distances and orientations. Error is estimated relative to the Optotrack based method which is considered as gold-standard.

Results: The algorithm is quite robust and capable of tracking the marker with significant accuracy. Continuous tracking of the marker, of 2 cm size, was possible at distances of more than 3 cm (up to 13 cm). At closer distances, especially when the marker is directly facing the endoscope, reflection ovoid formed due to the high intensity illumination resulted in defective segmentation.

The mean positional error, of the center of the marker, was 0.60 mm (Fig. 1) and mean rotational error was 1.65° for a 2 cm sized marker. Accuracy was found to increase with increasing size of the marker. Evaluation was done on static images. The Effect of the orientation of the marker to the endoscope optical axis is shown (Fig. 1).

Discussion: Results confirm the ability of the endoscope as a tracking device. Proposed hybrid-system can be successfully integrated with minimal modification in the currently available navigation systems. The color-coded marker can be easily sterilized, occupies minimal space and no major modification in the surgical procedure is required.

There are some issues which need to be addressed before its integration into the navigation systems. Most of the currently available endoscope systems have either NTSC or PAL video output. The image grabbed from such an output will be an interlace between odd and even fields, which are acquired at a different time period. This will result in a highly distorted image even on slight movement of the endoscope. The latest endoscope models have a progressive camera with digital video output which can be effectively used to avoid this problem. The rapidly changing illumination intensity in the endoscope field of vision has a significant effect on the intensity-threshold based segmentation. There is a need to have an adaptive-threshold based algorithm. Automatic illumination adjustment feature in the latest endoscope models may also help in resolving this problem. Partial occlusion of the marker, by surrounding viscera, is an expected scenario during the surgical procedures. The algorithm has to be modified to address this problem. Our further studies will be focused on solving these shortfalls after choosing an
appropriate endoscope system. The possibility of using this system in other endoscope based minimally invasive surgeries will also be explored.

References

2. Thomas A. Zdeblick, and Stephen M. David, A Prospective Comparison of Surgical Approach for Anterior L4–L5 Fusion, Laparoscopic Versus Mini Anterior Lumbar Interbody Fusion, SPINE Volume 25, Number 20: 2682–2687
Image-free navigation system for total knee arthroplasty: Determination of accuracy by using, preoperative and postoperative, CT measurement

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Introduction: Accurate alignment of the tibial and femoral component and correct ligament balance are essential for good results in total knee arthroplasty (TKA). In fact incorrect positioning or orientation of the implant and misalignment of the limb can be correlated to early polyethylene wear and components loosening. Although mechanical alignment systems are continually being refined, errors in implant and limb alignment continue to occur. Jefferi et al. analyzed the results of 115 total knee arthroplasty and found a 24% rate of loosening when the mechanical axis exceeded ± 3° varus/valgus, while it was only 3% in the other cases. An “Image-free” navigation system, that can be associated with a robotic cutting guide, was used to implant a meniscal bearing knee arthroplasty at the Rizzoli Orthopaedic Institute of Bologna and in Casa di Cura Villa Salus of Messina. This is an innovative system for its simple cutting guide and movement device both in their hardware and in their way of using and for a simpler software interface.

Methods: In a prospective controlled trial 35 patients had total knee arthroplasty, 15 Medacta-Cinetique knee prosthesis and 20 Medacta-Evolis knee prosthesis, using Medacta computer navigation system with or without the robotic cutting guide (GP System®) rigidly fastened to the femur via an anchoring pincer. All Cinetique prosthesis (15 knees) were implanted with the GP System, whereas the Evolis group (20 knees) were implanted with the same Navigation System but without motorized cutting guide.
All cases underwent a CT evaluation preoperatively and postoperatively. The axial alignment and all the measured angles were evaluated on pre and postoperative CT image by two independent observers, three times on different days. On the sagittal plane the distal lateral femoral axis which is formed by intersecting the lateral femoral mechanical axis with the tangent to the femoral condyles, and the posterior proximal tibial angle formed by the intersection of the anatomical axis of the tibia with the tangent to the tibial plateau have been measured. On the frontal plane the mechanical axis has been evaluated as well as the á angle that is formed intersecting the femoral mechanical axis with the tangent of the femoral condyles and the ã angle formed by intersecting the mechanical tibial axis with the tangent to the tibial plateau. Femoral component rotation has been evaluated radiologically,
preoperatively and then after implantation of the prosthesis, using the epicondylar axis according to the method proposed by Berger et al. All these measurements were compared with the preoperative and postoperative limb alignment determined with use of the Medacta Navigation System.

**Results:** There were no complications related to the use of Medacta Navigation system. No patients were lost at follow-up or were excluded from our study. Regarding to coronal alignment almost all patients showed a mechanical alignment between 0° and 2°. In all cases we didn’t find a mechanical axis deviation of more than 3°. On the sagittal plane the mean femoral alignment was 91.2° (SD±2°). The tibial component was implanted with 7° of posterior slope for the Cinetique group and 3° of posterior slope for the Evolis group as recommended by the manufacturer. Only small variations have been observed in both groups. The assessment of rotational positioning of the femoral and tibia components showed that no patient of our study had a range of measurement outside of Berger’s value. The mean Knee Society scores improved in all patients.

**Discussion:** The purpose of this study was to determine the accuracy of an image-free Navigation System and to know if this new technology can improve the early outcome in total knee replacement procedure and if it is safe to use. This study was focused on the assessment of pre-operative and post-operative CT evaluation and then all these measurements were compared with the pre-operative and post-operative limb alignment determined with use of Medacta Navigation System. We chose to use computed tomography because it offers three planar alignment measurements, adding the possibility to asses the rotational alignment of the implant. In fact, previous studies demonstrated that radiographs are unreliable for accurate determination of pre-operative and post-operative limb and implant alignment. With the limitation due to the small series of patients observed in the our study we can conclude that Medacta-Navigation System allowed a significant accuracy of the surgery in relation to the mechanical axis of the lower limb.

**References**


4. Bathis H, Perlick L, Tingart M, Luring C, Perlick C., Grifka J: Radiological results of image-based and non image based computer-assisted total knee arthroplasty Internationl Orthopaedics (SICOT) 28: 87-90, 2004

Objectives and Background: Knee function after total knee arthroplasty is directly related to the position and the size of the prosthesis. Recently, several studies have shown improved alignment of knee prostheses when using computer navigation. The aim of this study was to assess if computer navigation also results in improved choice of prosthesis size. Therefore, conventional two-dimensional (2D) templating and intra-operative planning using a CT-free navigation system, and the actual implanted prosthesis size were compared.

Material and Methods: Fifteen NexGen total knee prostheses (Zimmer, Warsaw, Indiana, USA) were placed using Brainlab’s VectorVision computer navigation system (Brainlab, Munich, Germany). The results of these fifteen knees were compared to a control group of fifteen patients that were operated with conventional instruments and had the same degree of pre-operative radiological destruction. Pre- and postoperatively two independent observers templated and judged sizing of the components with respect to the bone (too big, correct, too small).

Results: In five (30%) knee prostheses, the pre-operatively planned size using conventional 2D templating differed from the size the navigation system suggested. Postoperatively, in the navigated group, the six femoral components and three tibial components were considered too large. In three of these navigated knees, postoperative manipulation was necessary because of insufficient flexion. None of these problems was seen in the control group.

Conclusion: In about half of the cases, the navigated prostheses were bigger than one would expect based on the size of the bones. In three cases (20%) this resulted in complications.
The accuracy of (registration of) the trans-epicondylar axis in computer assisted surgery

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Objectives and background: Knee function after total knee arthroplasty is directly related to the position and the size of the prosthesis. Cadaver and CT studies have demonstrated accurate identification of the epicondylar axis. The epicondylar axis is one of the axes used in CAS to determine the optimal position/rotation of the femoral component. The shape of the epicondyles and the soft tissue coverage make it difficult to determine the precise axis during surgery. However these points are used in the planning of femoral position by navigation and influence the patellar tracking after total knee arthroplasty.

The aim of this study was to demonstrate the accuracy of determining the epicondylar axis intra-operatively.

Design and Methods: 10 patients had a total knee replacement performed by a single surgeon, using Brainlab’s VectorVision computer navigation system (Brainlab, Munich, Germany).

The lateral and medial epicondyle points were pointed out during surgery and immediately marked with a 1 mm tantalum marker. Postoperatively a CT scan was used to analyze the difference between the intra-operatively pointed epicondylar axis and the CT based epicondylar axis. The difference was measured using the posterior condylar angle (PCA). This is the angle between the epicondylar axis and the posterior condylar axis.

Results: Using the postoperative CT scans the tantalum markers were identified and showed the intra-operative “epicondylar axis”. The posterior femoral cut was used as base-line for measuring the posterior condylar angle.
Taking the extreme values of the acquired points, there was a variation in rotation of 0 to 10 degrees exorotation.

The mean posterior condylar angle was 6 (SD 4 degrees) using the intra-operatively pointed axis. The mean posterior condylar angle was 3 (SD 5 degrees) using the CT based axis.

**Conclusions**: It has been demonstrated that it is difficult to point out the epicondylar axis inter-operatively, compared to the CT based axis. This has implications for the positioning of the femoral component and could cause patellofemoral tracking problems in total knee arthroplasty, especially with CAS and minimally invasive surgery potentially reducing the exposure. It may be more accurate to acquire a cloud of points on the epicondyles to obtain a best-fit axis.

**References**


Clinical use of virtual fluoroscopy in trauma surgery. Osteoid osteoma of the spine treated by combined computer-assisted and gamma probe-guided high-speed intralesional drill excision

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Introduction: Osteoid osteoma (OO) is a benign bone tumor characterized by a 1 to 15 mm nidus of highly vascularized mesenchymal tissue producing osteoid, which becomes calcified in the central part, surrounded by a dense sclerotic bone margin. In spinal localization, the posterior structures of the spine are affected in the majority of the cases. The classical pain, most noticeable at night, responds to aspirin and other nonsteroidal antiinflammatory medication. Plain radiography, triphasic bone scintigraphy and computed axial tomography (CT) are usually conclusive for the diagnosis of OO. Histology demonstrates a typical circumscribed focus of vascularized fibroconnective tissue containing immature ossification.

Complete surgical intralesional excision of the nidus is prerequisite for curative treatment of spinal OO. However, intraoperative localization of the small nidus is difficult. Incomplete resection of the nidus leads to local recurrence most often with persistent pain, requiring reoperation. Wide surgical resection of the surrounding bony structure including the nidus to
ensure complete removal of the nidus, however, may result in loss of stability of the posterior spine. Thus, precise intraoperative localization and resection of the nidus is mandatory for successful treatment of spinal OO.

Several intraoperative imaging modalities, including intraoperative CT guided procedures and intraoperative radionuclide localization, have been used to localize the nidus precisely. A combination of both techniques may improve the accuracy of complete removal of the nidus without removing excessive bone. In addition, computer-assisted surgery (CAS), using a CT-based electro-optical navigation system, in combination with radionuclide-guided surgery enables an even more precisely performed procedure and perioperative control for complete intrallesional excision of the nidus in spinal OO.

The aim of this study is to describe the surgical technique and the usefulness of the combination of both computer-assisted and gamma probe-guided high-speed drill excision for OO of the spine.

**Materials and Methods:** From September 2001 to July 2003, we encountered five patients, aged 14 to 33 years, with spinal OO (Table 1). Two patients had been treated before with CT-guided percutaneous radio-frequency thermal ablation in another hospital without response.

One day before operation, the patients had an intravenous injection of 700 MBq 99mTc-HDP (oxidronate) directly followed by dynamic imaging of the spine. Static bone scintigraphy was performed shortly before the operation and the skin of the patient was marked at the focus with increased uptake. During surgery, radionuclide activity measurements with a hand held gamma probe were used for accurate localization of the OO.

An instrument adaptor clamp with attached passive markers was mounted on a high-speed drill and calibrated using the instrument calibration matrix. Using the navigation system (Vectorvison Spine; BrainLAB, Munich, Germany), the positional association between the tip of the high-speed drill and the virtual images of the OO on the CT imaging was demonstrated clearly. After opening the sclerotic margin of the cortex of the affected vertebral arch with a 4.0 mm diamond ball of the high-speed drill, the nidus was excised with a curette. The excised nidus was histologically analyzed. To confirm complete removal of the nidus, radionuclide activity measurements were repeated at the end of the procedure. The measurement of a significant intraoperative decline in radionuclide activity was defined as complete removal of the nidus.
**Results:** The average operation time was 84 minutes (range 70 to 95 minutes). The navigation system enabled in all cases a reliable three-dimensional reconstruction of the CT-data. Intraoperative gamma probe control allowed accurate identification of the affected vertebral arch by measuring the highest radionuclide activity with the hand held probe. Subsequently, accurate CT matching between the CT data and the surgical field could be performed using surface registration of the posterior structures of the affected vertebral body with the navigation system. As a result, precise localization of the nidus allowed a pinpoint intralesional excision of the nidus using the CT image-guided high-speed drill.

During the surgery, the average radionuclide activity declined with 38% (range 20-56%) after excision of the OO. Postoperatively, all patients mentioned immediately characteristic pain relief. Histological analysis of the biopsy specimens confirmed excision of the OO in all cases. No recurrence or late complications were observed. At 6 to 33 months (mean 24.2 months) follow-up, all patients were without recurrence of symptoms related to the OO.

**Discussion:** CAS with a CT-based electro-optical navigation system has been proven to facilitate spinal surgery. However, especially in the thoracic spine, we experienced difficulties in identification and matching of the affected vertebral body with the preoperatively acquired CT scan during surgery. This is, however, not the case with simultaneous intraoperative gamma probe-guidance: The site of maximum radionuclide activity relates to the affected vertebral body. Thus, intraoperative localization of the affected vertebral body with a hand held gamma probe facilitates matching patient’s spinal anatomy with the preoperative acquired three-dimensional reconstruction CT scan of the spine during surgery.

The current study shows that the combination of both computer-assisted surgery and gamma probe-guided high-speed drill excision of spinal osteoid osteoma enables accurate localization and intralesional excision of the nidus. Matching of these two imaging modalities during surgery has a reciprocal increasing beneficial effect on each of the imaging modalities assuring complete excision of the nidus in all cases. In addition, significant decreasing radionuclide activity measurements during the surgical procedure demonstrate complete removal of the nidus. Differences in absolute count rates during surgery can be explained by the time between injection and surgery and the thickness of the explored bone. In addition, histological confirmation of the diagnosis is possible with the described technique.
Computer assisted high tibial osteotomy in clinical routine, a prospective study

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Introduction: The high tibial osteotomy (HTO) became a standard procedure for varus deformities of the proximal tibia in younger patients. To achieve good results the new axis must be planned and executed accurately. Retrospective clinical studies have shown, that the biggest problem is the postoperative axial malalignment, which can be either under- or overcorrection. The intraoperative control of axis and osteotomy is controlled usually using a cable method. The accuracy of this method has not been evaluated and irregular measurements might occur. In experimental studies the use of an image guided ct-free navigation system has lead to an increase in accuracy. The purpose of this study was to evaluate the precision of computer assisted HTO in clinical routine.

Methods: Within the scope of a prospective study a total of 25 patients were operated on with a prototype of a ct-free image guided navigation system which was introduced by G. Wang et al. on the 4th annual meeting of CAOS-international proceedings 2004 in Chicago using the SurgiGATE® navigation System (PRAXIM/Medivision, La Tronche, France). Dynamical reference bases (DRB) are attached to the femur and tibia. The anatomical landmarks are registered intraoperatively using registered biplanar fluoroscopic images. Alternatively kinematic pivoting movement and percutaneous digitization with a registered pointer can be used.

The surgeon then checks the soft tissue balance and measures the deformity and compares it with the preoperative plan. Correction can be planned on medial or lateral side, opening or closing wedge or focal dome. Changes of
leg rotation, slope and axes in the frontal plain can be tested by modifying the cutting plane interactively.

After planning with the aid of virtual fluoroscopy a third DRB is fixed at the proximal fragment of the tibia under visualization by the navigation system to avoid interference of the Schanz screw with the osteotomy.

Bone cut, correction of the axial alignment and fixation is done under permanent visualization by virtual fluoroscopy.

**Results:** Between January 2004 and December 2004 a total of 25 patients were operated on with the proposed system. Navigation was successful in 22 cases. In three times navigation could not be performed completely due to problems with the workflow and image transfer from the c-arm to the navigation system. All patients had a varus malalignment. Three times we performed a focal dome osteotomy, 19 times an open wedge osteotomy. Goal was an alignment of the mechanical axis to pass through 70% of the tibial plateau (70% Fujisawa line). The average correction angle was 10.1° with a range of 8 to 14°. The average radiation time was 1.5 minutes (1.1 – 2.3 min).

The additional time for placing the DRB’s, taking the fluoroscopic shots, registration of landmarks and calculating the plan was 21 minutes. In each of the 22 cases correction of the preoperative deformity was accurate after the operation. The evaluation of the postoperative full-leg X-ray images 6-10 months after correction showed consolidation of the osteotomy in all cases. There was no loss of the correction. The mean error was 0.8° (0 – 2°) with a standard deviation of 0.74.

**Discussion:** The software we used is a prototype, which still has some problems with the workflow. This leads to a significant prolongation of the operating time. The intraoperative realization of the preoperative plan was successful in 88%. Problems inherent to the system occurred in 12%. With a mean error of 0.8° we could show that it was possible to approve the high precision of this system in clinical routine. There was no need for additional radiation during navigation and visualization in multiple fluoroscopic images by the means of virtual fluoroscopy was excellent.
Process optimization for shorter operation times in navigated TKA. A comparison between navigated and manual procedures.

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Introduction: The presumption that a navigated procedure for the implantation of a total knee prosthesis needs more time than the manual procedure is widespread. Various studies report that the additional time input for a navigated procedure is about 10 to 30 minutes [1;4]. On the other hand, several clinical studies have shown that navigated knee implants are significantly better aligned [1;2;3]. The purpose of the presented process optimization implemented in October 2004 was to ideally avoid additional time consumption by navigation while optimizing the alignment.

Methods: The operation times of 50 manual knee implantations before October 2004 were retrospectively compared to 50 navigated COLUMBUS knee (Aesculap, DE) implantations between October 2004 and April 2005. The OrthoPilot navigation system (Aesculap, DE) was used for the COLUMBUS implantations. On submission of this abstract (Feb 11, 2005), 37 of the 50 COLUMBUS implantations have been completed. Two equally experienced surgeons who both had no experience with the navigated technique before October 2004 performed all operations. In order to perform a navigated implantation of a cementless COLUMBUS knee prosthesis, several pre- and intraoperative procedures in the operation room have been optimized. We have trained the OR staff and worked out a guidance that shows all relevant steps for a well timed instrument and implant handling. The navigated operation times are evaluated with the dampened logistic growth method in order to discover a trend with an approximated value. Simultaneously we monitored the accuracy of the navigated implantation by
measuring the mechanical whole leg axis and the angles of the femoral and tibial components towards the mechanical axis both in frontal view. Furthermore the mean operation times of the Columbus knee implants were compared to the previously used system.

**Results:** An evaluation of the first 37 navigated operations until Feb 11, 2005 showed an average operation time of the navigated TKA procedures of 52 minutes with a minimum of 34 minutes. A mathematical analysis of the consecutive operation times showed that the learning curve still continues and that an even shorter average operation time of 42 minutes is feasible. With the previously used manual TKA system the average operation time of the last 50 consecutive implantations was 56 minutes.

The time-optimized operation did not result in less precise alignment. In all of the 37 cases the post-operative anatomical leg axis was within 3° varus/valgus compared to the pre-operative planning. This range of deviation from the ideal mechanical axis was also considered as excellent in earlier investigations [5].

**Discussion:** The first results of this ongoing investigation are proving that navigation not necessarily lengthens operation time. Together with a straightforward process optimization and an easy to use navigation system the operation times can even decrease to values which are challenging for manual TKA. Precision does not need to suffer from speed. The authors could show that in their special circumstances precision and speed of operation could be significantly raised.

**References**

Computer-assisted auto-frame navigation system for distal locking of tibial intramedullary nails: A preliminary report on clinical application

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Introduction: Distal nail locking is a challenge in operation of interlocking intramedullary nail internal fixation. It increases complicity of the surgery and time of X-ray exposure to medical staff and patient. Although there have been many studies on it, the available methods established for nail locking still have many potential problems. According to literatures, failure of distal nail locking is the main complication of interlocking intramedullary nail fixation. Some foreign researcher statisticied and got inclusion that failure rate of distal nail locking is about 3-30%. Thirty one to fifty one percent of the whole time of X-ray exposure during surgery is for distal and proximal locking1. Harmfulness and risk of radiation exposure to surgeon and patient during surgical procedures has been extensively acknowledged in the orthopaedic literature. Although some authors have reported that the radiation dose associated with distal locking of tibial nails is relatively low, the actual amount of fluoroscopic exposure strongly depends on many factors, including the skill of the surgeon and the C-arm technician and the amount of the nail deformation. On account of variance of assessment criteria the precise level of the radiation risk to the surgeon is difficult to be assessed. The ALARA principle is widely accepted. Therefore, every conceivable effort should be made to lower possible radiation exposure for the patients
and operating room personnel. CAOS is a focus studied in recent years. By high speed processing of computer for medical images and precise, real time navigation technique, CAOS makes orthopaedic surgery being carried out more precisely, safely and simply, and reduces radiation exposure during surgical procedure. CAOS solved the problem in distal nail locking. But CAOS is just introduced into our country, its price is high, and its position navigation device cannot be used fluently in available operative surroundings. Theses reasons limited its application in clinic. Using our new system, distal locking may be performed successfully and radiation exposure may be decreased, and some clinical application rules are summed up to improve development of CAOS.

**Methods:** The hardware components of the system include a PC computer with a monitor, auto mechanical stereotactical localization cubic frame, foot holder, localization operative apparatus; special navigation software can be used for registering and real-time tool navigation controlling. 21 patients of tibial and fibular fractures were treated with closed intramedullary nailing, of these 21 cases, all fractures were close, 6 in median third, 12 in median and lower third, 3 in lower third; C-arm alignment and registration time, fluoroscopic time, drilling time associated with the locking procedure was recorded. Unreamed or reamed tibial nail sizes ranged from 8/300 – 11/330.

**Results:** All distal holes except 1 hole were locked successfully, in 9 of 41 holes (21.95%), the drill bit touched the canal of the locking hole, albeit with no damage to the nail and no clinical consequences. The fluoroscopy time per pair of screws was 2.23±0.31seconds.

**Discussion:** We summed up the following regulars from the clinical application of the new system:

1. Because distal nail locking requires a high precision of surgical location, it was the method of choice for applying the new system. In our study, the problem of distal nail locking was solved and precision of the mechanical arm locating technique was proved. All distal nail locking were performed successfully in our case series. Locating by mechanical arm is proved as precise as that by current optical method.

2. The new system does not occupy so much more space that it interferes with monitoring for anaesthesia and obstructs the passage for infusion. Its devices may be assembled easily. All its advantages meet clinical requirement of current traumatology and orthopaedics that includes more multiple injuries and complex injuries, requires more cooperation of multiple specialists, concentrates various devices for surgery and anesthemia monitoring, and needs reduction of surgical time.
3. The system clarifies some characteristic procedures of guiding surgery by perfecting surgical plan of the new system.

4. Based on this system, more suitable located surgical tools and a more perfect guiding surgical plan may be developed later. The system would be applied in femoral and humeral interlocked nail fixation for determination of the nail entering point and precise location in distal nail locking. We will make our efforts to develop more useful CAOS. Guido and Joskowicz et al. applied a robot for distal nail locking in treatment of long bone fractures based on locating principles of mechanical arm. Their experiments on bone models and cadavers were performed successfully. And they have no clinical application [4,5]. At present, most CAOS devices are aimed at spinal surgery and artificial joint replacement. The special software for interlocking intramedullary nail prices high. Cost of our system is further lower than that of the same products, and will promote clinical application of CAOS in normal hospitals.

References

Image-guided percutaneous vertebroplasty using electromagnetic tracking

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Introduction: Vertebroplasty is a fluoroscopically image-guided, minimally invasive therapy used to strengthen a fractured vertebra that has been weakened by osteoporosis, long term steroid use, or cancer. Vertebroplasty can be used to stabilize vertebral compression fractures by the injection of bone cement into the vertebral body [1]. This injection typically leads to dramatic pain relief within hours of the procedure. Vertebroplasty has been demonstrated to provide long-term pain relief, has a low complication rate [2, 3], and prevents further collapse of the vertebra that can lead to height loss and poor posture.

The procedure begins with fluoroscopic image guidance to place a trocar (typically 16 gauge) through the pedicle until the tip of the trocar is within the fractured vertebra. The trocar consists of a solid stylette and hollow cannula. The stylette is then removed and bone cement is pumped through the cannula, also under fluoroscopic guidance. The cement hardens quickly (typically within 15 – 20 minutes) and therefore real-time imaging of the trocar placement is essential. A CT scan or rotational angiography may be performed at the end of the procedure to check the distribution of the cement.

Needle placement is technically challenging and time consuming. A large amount of procedure time is spent taking repeated fluoroscopic images during incremental advancement of the needle to ensure that the vertebroplasty trocar is being correctly targeted. Trocar misplacement has complications similar to those inherent in pedicle screw placement, i.e. damage to surrounding nerves and vessels and even the spinal cord itself.
Since vertebroplasty is a percutaneous procedure, it is not acceptable to expose the spinous process to attach a dynamic reference as required for traditional “Fluoronav” or CAOS navigation.

To assist in correct placement and avoid complications, we have developed a novel trackable vertebroplasty trocar along with narrow gauge needles for registration. These devices were integrated into an image-guided navigation system to assist in the placement of the trocar. The system was used to place a vertebroplasty trocar into a spine phantom using a pre-operative CT and image overlay, but entirely without fluoroscopy. Fluoroscopic imaging was used at the end, only to verify that the trocar was placed correctly. The contributions of this work include: 1) The design of an electromagnetically trackable vertebroplasty needle; 2) the incorporation of two or three thin electromagnetically tracked needles for registration; and 3) the implementation of a registration algorithm using these needles along with their translation and orientation information.

Methods: A prototype electromagnetically tracked vertebroplasty trocar was used in conjunction with embedded electromagnetically tracked fine gauge needles for registration. Targeting tests were conducted using a vertebroplasty phantom (“Kyphon Ken”, Kyphon Inc.) designed to train interventionalists in the technique of kyphoplasty (a form of vertebroplasty). This realistic surgical model contains a removable “Sawbones” spine covered with a dense plastic “tissue” layer, with radiographic properties similar to human bone. Three 22-gauge needles (Traxtal Technologies, Belaire, TX) similar in size to those used to administer local anesthetics were inserted posteriorly and lodged in the perispinal “musculature” in the vicinity of the transverse processes of the targeted vertebrae. These locations were chosen because they were easy to see, not in the trajectory for the transpedicular needle placement which was to follow, and felt to be a low risk location for needle placement. Following needle placement, a CT scan of the lumbar spine was performed using 1 mm spacing.

Images were transferred to an image-guided software system developed at Georgetown based on the open-source standards ITK, VTK and FLTK. Registration was performed using a method that was a modification of that of Liu et al. [4], in which the end points of the sensor coils as defined on the CT scans were used to calculate the orientation and location of the distal part of the needle containing the sensor. This method has been previously employed on objects such as tracked bone screws (Glossop et al. [5]). Target locations for the tip of the vertebroplasty needles were selected from 3D reconstructions. Following registration, a total of 14 pedicles in 7 vertebrae were targeted using the vertebroplasty needle during two separate studies.
Results: In all cases, the vertebral body was successfully navigated using the electromagnetic tracking system. The physician placed the trocar using the image overlay alone, and fluoroscopy was only used to confirm correct needle placement. Example results are shown in the attached Figure.

The image-guided system was able to provide a path planning capability and targeting information in axial, sagittal, and coronal planes, along with a three-dimensional rendering. Registration using the needle technique was fast and accurate enough to perform the vertebroplasty. The fiducial localization error was calculated during registration and was always less than 1 mm. We did notice some artifacts when the C-arms of the fluoroscopy unit were brought in close proximity of the operative field and energized for obtaining the AP and lateral confirmation images. One advantage of electromagnetic tracking
is that the sensor coil is placed at the tip of the needles and therefore if the registration needles bend the effect on accuracy is minimal.

**Discussion:** We have successfully used an electromagnetically tracked vertebroplasty needle to perform computer assisted vertebroplasty. The technique does not require large punctures for attaching a vertebral body tracking clamp, and appears to be qualitatively accurate. Advantages include substantially reduced fluoroscopy during the procedure and enhanced visibility available from navigated CT images during the needle placement. Further studies are planned, including studies in swine.

**References**

Accurate calibration method for intraoperative ultrasound

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Introduction: The accurate calibration of US probe is essential for the recording of US 2D-data in the CAS [1]. This paper describes the accurate calibration of the ultrasound probe which is required to determine the position of the 2D US structures in the 3D-datasets (see Figure 1). The calibration dataset should describe the position and rotation of the US plane in the coordinate system of the plugged probe.

Materials and Methods: To get the demanded calibration dataset a thread phantom with a given geometry (see Figure 2) is used. The positions of each thread in the coordinate system of the fixed adapter are known by precise measurements. They were established from AESCULAP AG & Co KG by measuring the cone apertures with a Zeiss (Oberkochen, Germany) UMM 850 coordinate measuring machine.

For image scan a conventional US imaging system (Aquila Esaote, The Netherlands) was used together with an infrared localizer system (Polaris Northern Digital Inc., Canada). To calibrate the US probe it will be placed on a holder of the thread phantom (see Figure 4). For localizing the phantom and the US probe two passive rigid bodies were used. The phantom is filled with water which was adjusted with the sound velocity of 1540 m/s (which is assumed by US Standard Tissue [2]). Our phantom uses 16 threads which could be seen on each US scan (see Figure 3).

A contour search algorithm calculates automatically the center of this thread contour to get the exact position of the thread points on the ultrasonic image. These positions are matched to those which are already given by the precision measuring. A best-fit algorithm is used to match the determined points (image processing) and the measured points. The result is the demanded calibration matrix (rotation and translation).
The next step reviews the calibration. Due to the validation of the calibration procedure the ultrasonic transducer is placed at the same position like before and then it is turned in opposition (180°). After the calibration the software delivers the mean value and the deviation of the two positions (see Results, Validation 1).

The recorded points (between points founded in image processing and in the measured procedure) are compared again using the “Itrq3d”-software (NDI, Canada) to get the “Root Mean Square Distance” between the values. This calculation confirms the trueness of the resolution in the ultrasonic image and shows if any distortion of the US influences the calibration, e.g. bad localiser coordinates (see Results, Validation 2).
**Results:** Validation 1: The comparison of the established values with UMM 850 coordinate measuring machine of the thread positions the measured values the calibration software we received the following X, Y, and Z values:

Mean: -0.4721, 0.6481, 0.2538  
Deviation: 0.1153, 0.1062, 0.0534

Validation 2: The results of the second validation predicts how exact a point can be determined in the ultrasound image. Therefore all 16 points of the thread phantom are matched by precision measurement and are fitted by a best fit algorithm. The root mean square distance is getting bigger if any distortions affect the calibration.

Inquisition with “Best Fit Algorithm” (precision measuring room and image processing coordinates) to screen the degree of accuracy.

Root Mean Square Distance: 0.070 mm

**Discussion:** The mean and deviation values are comparable to [3]. The residuary inaccuracy may be caused by the navigation.

**References**


Osteochondral lesions of the talus: Clinical experience in navigated Iso-C3D based drilling

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Introduction: Retrograde drilling and cancellous bone grafting is one established method of treating osteochondral lesion of the talus, especially when localized dorsomedially [1]. Localization of the lesion and exact positioning of the reamer or a guide wire can be difficult using only standard 2D imaging by C-arm. Healthy cartilage can be injured by a misguided drilling procedure. 3D imaging using the SIREMOBIL Iso-C3D can be helpful in localizing the osteochondral area. Navigation can provide a safe method of performing the drilling procedure.

The aim of this study was to evaluate Navigation with SIREMOBIL Iso C3D in clinical routine usage in patients with osteochondral lesions of the talus.

Methods: The mobile SIREMOBIL Iso-C3D (Siemens AG, Medical Solutions, Erlangen), is a mobile C-arm with true isocentricity and 190° orbital movement. It is the first device that allows the intraoperative three-dimensional representation of bone structures. This facilitates direct process and result control of surgery [2 to 5]. The workstation simultaneously calculates a high-resolution isotropic 3D data cube in the isocenter with an edge length of approximately 12 cm. The link established between the SIREMOBIL Iso-C3D and the navigation system with the integrated NaviLinkTM (Siemens AG, Medical Solutions, Erlangen) interface makes it possible to transfer the generated 3D data directly to the connected navigation system (Surgigate, Praxim- Medivision).

In the period from January 2002 to December 2004 a total of 9 patients with osteochondral lesion of the talus were registered in a prospective study. These patients required retrograde drilling of the lesion. All patients were treated by computer-assisted percutaneous drilling and cancellous bone
grafting. The dynamic reference base was fixed at the neck of the talus. Registration of landmarks is not necessary in this system. In this study we used the Surgigate navigation system and the SIREMOBIL Iso-C3D to place a guide wire. This guide wire was overreamed and the defect filled with cancellous bone grafts. Postoperatively the drilling procedure and the correct localization of the bone graft was controlled by a second Iso C3D scan.

**Results:** All 9 patients (6 men, 3 women, age 41 +/- 13 y.) who underwent successful navigation with intraoperative Iso-C3D images were included in the study. The 3D pictures acquired with the Iso-C3D were of sufficient quality in all cases to perform planning in the navigation system, the osteochondral lesion was clearly visible and easy to identify. No system failures either of the Iso C or the Surgigate system occurred in our group. The mean time of radiation exposure was 0.9 minutes. The mean time for the operation, including the bone grafting and the control scan was 61 minutes. The postoperative control by SIREMOBIL Iso-C3D scans showed the success of the operation in all cases. Complications due to the navigation procedure did not occur.

**Discussion:** This prospective study shows the clinical application of navigation with three-dimensional data sets from the SIREMOBIL Iso-C3D and automatic registration for retrograde drilling in osteochondral defects of the talus. The purpose of the navigation system is to improve the precision of the drilling process and thus reduce intraoperative false drillings and corrections with potential danger to the healthy cartilage of the talus. Similar procedures are described using CT-based or 2D C-arm-based navigation systems. Compared to these methods the Iso C3D navigation provides advantages: Registration of the CT data set first requires a data set that is suitable for navigation, and hence it has to be custom made. The preoperative processing is time-consuming. While the registration is done automatically in C-arm-based 2D navigation, there are significant limitations with respect to the image quality and the display of complex, three-dimensional structures in 2D. Navigation with the SIREMOBIL Iso-C3D does not suffer all these limitations and disadvantages. The most important advantage is certainly the precision of the navigated actions. We found no incorrect drilling process in the entire Iso-C3D group. In this respect, Iso-C3D navigation is superior to the conventional approach, as described in the literature.

We conclude from our first clinical experiences that using Iso C3D navigation is a safe, reproducible and reliable method in retrograde drilling of osteochondral lesions of the talus. It can be recommended for daily routine usage.
References

Does computer-assisted navigation increase the precision of the high tibial osteotomy?

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Introduction: The opening-wedge high tibial osteotomy is an established procedure for the treatment of the unicompartmental gonarthrosis in young patients. Adequate correction of osseous malalignment is crucial for sufficient reduction in stress in a diseased compartment. We examined reliability and precision of an intraoperatively used computer-assisted navigation system for high tibial osteotomy. The aim of the study is to show the equivalent safety and effectiveness of high tibial osteotomies carried out with the computer-assisted navigation system. It is assumed that a good correlation between radiographic and navigation system measured mechanical tibio-femoral axis can be achieved.

Methods: 23 medial opening-wedge osteotomies were performed in 23 patients between 01/2004 and 10/2004 by two surgeons. 19 of the 23 patients were men and 4 were women. The average age was 47 years (23 – 64 years) and the average weight was 83.27 kg ±18.23kg. All Patients had degenerative joint disease involving the medial compartment and varus malalignment (average 8.32° ±3.46°) due to previous trauma or genu varum deformity. Patients’ charts were reviewed to evaluate demographic characteristics, previous operative procedures, the preoperative diagnosis and preoperative knee score. 11 patients had had previous surgery including arthroscopy, meniscectomy, arthrotomy and reconstruction of the anterior cruciate ligament. 1 patient had had an osteonecrosis, 2 patients had osteochondrosis dissecans. 5 patients had a torn anterior cruciate ligament, 2 patients had had a previous trauma.

We did an arthroscopy prior to every osteotomy. Additional simultaneously acl reconstruction has been performed 3 times.
The computer navigation system is based on the spatial location of instruments through an infra-red 3-dimensional optic system. The optic captor is able to supply, in real time, the spatial position with a theoretical precision of the order of one millimeter. The surgical procedure is only slightly different from the manual technique. The operation started with the percutaneous insertion of the transmitter support into the distal femur and the proximal tibia. The fixation of the transmitter to the foot was carried out by means of an elastic strap and a metal plate. Once the transmitters are fixed the operation carries on to the determination of the centers of hip, knee and ankle joint. Additional anatomical reference points are recorded with a pointer. By means of these data the kinematical center of the joints were calculated. Once the centers are determined the mechanical femoral-tibial axis results and is depicted on a computer screen. The navigation system was used to determine mechanical leg axis before and after the osteotomy in order to control if the planned angle of correction is achieved. We performed a standard medial approach. Intraligamentous opening-wedge technique was used. Osteosynthesis was realized with a rigid internal fixation plate. Allogene bone grafts were fitted in the opened wedge in order to realize early bone reunion.

Patients were reevaluated and radiographic evaluation was done 2 days and 3 months postoperatively. Full length anteroposterior radiographs of the leg (with the patient standing) were done 3 months postoperatively to determine mechanical tibio-femoral axis.

**Results**: Good correlation between radiographic data and the data acquired with the navigation system showed up.

Tibio-femoral axis (preoperative data: $8.32^\circ \pm 3.46^\circ$ radiographic; $8.38^\circ \pm 2.75^\circ$ navigated, varus alignment).

(postoperative data $2.37^\circ \pm 1.98^\circ$ radiographic; $0.75^\circ \pm 0.86^\circ$ navigated

Severe complications were not seen: 1 patient had a hematoma, treated surgically. 1 patient had a fractured lateral cortex, treated conservatively. No patient had total knee arthroplasty. Nerve injuries were not seen. 2 of the 23 patients were not available for long term follow-up.

The time for operation with navigation took only a few minutes longer than a usual manual procedure. The navigation system did not fail any time, thus no operation had to be finished manually.

**Discussion**: High tibial osteotomy is an established therapy procedure of the unicompartmental gonarthrosis. It can be improved in its precision and reliability by computer-assisted navigation. Though it is necessary to do a
preoperative radiographic planning some advantages showed up. It is concluded that the hitherto rather subjective determined alignment of the cuts is not any longer a risk factor for a postoperative malalignment. The navigation system depicts the achieved angle of correction immediately. A lag of extension is observed as well and can be corrected prior to fixation. It is assumed that the utilization of navigation systems will spread over to other, even more complex osteotomy procedures in the future.

References


Rotational alignment after navigated TKA

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Introduction: Rotational malalignment of the components will lead to instability, restriction in range of motion and patellar maltracking. Computer navigation in TKA was introduced to restore anatomical proportions. The aim of this study was to determine the accuracy of the Stryker Knee Navigation System to restore anatomical rotation of the femoral and tibial components. One-year-results after implantation of navigated TKA are presented. The importance of rotational positioning of TKA components remains important in preventing patellar maltracking, instability and maintaining knee movement. The aim of this study was to assess the accuracy of computer navigation in aiding the surgeon to restore anatomical rotational alignment of the femoral and tibial components.

Methods: Twenty consecutive patients underwent computer navigated TKA (Stryker Knee Navigation System). The ratio of male to female patients was nine to eleven. Mean age of the patients was 67 years (range 37-81). Indications for TKA were osteoarthritis in fifteen cases, posttraumatic arthritis in four cases and post infectious arthritis in one case. Each patient underwent both a pre- and post-operative CT scan of his or her knees, together with standard orthoradiology. Following surgery the radiological data was compared to the data received intraoperatively from the knee navigation software. Pre-operative and 1 year postoperative clinical assessment was performed using the HSS knee arthroplasty rating system.

Results: Pre-operative femoral rotation radiologically showed the femoral trans epicondylar axis to be 2.37° externally rotated (stdv 1.34°) to the posterior femoral condyles preoperatively and 0.65° externally rotated (stdv 1.31°) postoperatively (Fig. 1). Tibiae radiologically were internally rotated by 16.26° (stdv 7.61°) preoperatively and 16.25° (stdv 4.68°) postoperatively. Intra-operative measurements by the navigation system were 0° (stdv 0.4°)
for femoral rotation and 0.18° of internal rotation (stdv 0.41°) for the tibiae (Fig 2). HSS knee score improved from a mean of 76 points (range 57 – 96) preoperatively to a mean of 92 points (range 64 – 100) one year after TKA.

Figure 1 Rotation of the femoral component measured by CT-scan preoperatively and postoperatively. For intraoperative measurements the data of the Stryker Knee Navigation System was recorded. Yellow big rhombi show mean values whereas small red rhombi indicate standard deviations

Figure 2 Rotation of the tibial component measured by CT-scan preoperatively and postoperatively. For intraoperative measurements the data of the Stryker Knee Navigation System was recorded. Yellow big rhombi show mean values whereas small red rhombi indicate standard deviations
Discussion: With the Stryker Knee Navigation System constant anatomical rotational alignment of the femoral and tibial components can be restored. There was no case of femoral component internal rotation. Pre- and postoperative tibial rotation was found to be consistent.

References

Fully automated computer algorithm for calculating articular contact points with application to knee biomechanics

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Introduction: A fully automated computer algorithm for calculating the articular contact points between two bone surface models is presented. The algorithm requires the bone surface models and their relative positions as inputs in order to resolve the articular contact path. In the case of surface model overlap due to measurement errors or as a solution of an optimization procedure, the result is a volumetric estimation of the space confined between the two surfaces. The algorithm is based on attaching a grid of lines to one bone surface model and calculating the intersecting points of each of the lines in the grid with both bone surface models. The contact points are then determined as the closest points between the surfaces along the lines in the grid. The same contact points are used to evaluate any volume that is confined between two overlapping surface models. The algorithm is ideal for use in biomechanical studies, simulations of joint motion, and optimizations that require an iterative process to determine contact path and relative bone position. The algorithm is applied to a Sawbones knee model that is moved from flexion to extension while being tracked by an optical tracking system. The contact path of the two bones is generated and an example of calculating bone impingement is provided.

Methods: The contact points between the tibia and femur under flexion are vital information for biomechanical studies and simulations of knee motion, as well as for implant design. However, definition of the contact points is not always obvious since the information usually provided is the surface model of the bones and their relative position. For this algorithm, we begin with surface models of both the femur and the tibia, which are given as meshes of
triangles. In a general simulation we set one bone as the reference system and describe motion of the other bone relative to the first. Next we fix a sampling grid, of m by n points to the tibia and attach a set of parallel lines to each point at the grid such that when the tibia moves through different flexion configurations both the sampling grid and the set of lines attached to it transform with it. For every line within the set of lines we then solve for its intersection with the tibia and femur surface models. The points of intersection on the tibia and on the femur formulate two different sets of points. We compute the distance along the line between the intersecting points on the tibia and on the femur. The contact points are then chosen to be the ones corresponding to the smallest distance. This process is repeated for every flexion configuration to formulate contact path for the two bones.

Figure 1 (from left to right): Sampling grid on tibia; intersecting point on femur; contact path on tibia

Bone surface model overlap can occur as a result of measurement error or unfeasible solution of joint configuration based on optimization of a kinematic model of a joint. In these cases the algorithm provides a volumetric estimation of the intersection between the two surface models. For that, the lines are modeled as a cuboid with a given cross-sectional area a, which is determined as a function of the spacing of the sampling grid. The volume associated with the penetration is given by the sum of the cuboids which are calculated as the summation of the length of penetration along each line times the cross-sectional area, over all the lines.

For the experiment we used Sawbone models of the femur and tibia. Prior to the experiment, both bone models were scanned by CT and surface models were generated. The two bone models were then connected by four rubber tubes to simulate the lateral collateral ligament, medial collateral ligament, posterior cruciate ligament, and the anterior cruciate ligament. Optical
Trackers were attached to both bones models, and the surface registration procedure between tracking system and bone models was performed. Both bone models were then tracked throughout the experiment. The femur was rigidly fixed and used as the reference system, while the tibia was moved from flexion to full extension by quasi-statically pulling it by a wire connected to its center of mass. The tracking system provided the relative positions of the tibia and femur, i.e., the transformation matrices. Next we utilized the algorithm to solve for the contact points between the two bones (Figure 1). We also simulated cases where bone overlap occurred and applied the algorithm to resolve the overlap volume between the two surface models.

**Results and Discussion:** This study describes a fully automated computer algorithm for detecting contact points between surface models of the tibia and femur while subjected to flexion/extension motion. The general idea behind the algorithm is to attach a predetermined grid of lines to the moving bone (tibia) and use basic tools from computational line geometry to represent the grid lines, and calculate the line-surface intersections.

We also described an extension to the algorithm that results in a volumetric estimation of bone overlap in the case of two surface models that overlap each other. This could be a result of measurement errors or a result from an optimization procedure that calculates relative bone positions based on biomechanical models of the knee. Overlap may also occur when trying to predict joint motion based on a computer model of the geometry, and hard tissue and soft tissue mechanical properties. These models usually solve the joint kinematics based on optimization of an objective function. In the case where bone overlap is not compensated for in the objective function, e.g., as a penalty, the optimization algorithm can result in unfeasible configurations where bones overlap.

In both cases, the algorithm is fully automated and does not require an interface or input from the user during the process. The suggested algorithm is general and can be applied to any joint or two surface models that move with respect to each other provided that the contact surfaces are sufficiently rigid. In the case of deformable contact, this approach can be used as a starting point.
Mini snake robot for orthopaedic interventions

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Introduction: Despite the advantages of current minimally invasive technology, they still have limited access to the internal organs of the body. This technology can only reach locations on organs that are within a straight line to access ports. In order to overcome the limitations of current minimally invasive approaches, we develop a new 12mm in diameter, 300mm long flexible robot device (snake robot), which is capable of achieving both deflections and good compliance, in a small volume. The new snake robot design is capable of accessing hard to reach anatomical targets by using its high redundancy and maneuverability to poke through and navigate in the confined anatomical environment while minimally interacting with the environment along its path. This snake design will serve as a cutting platform for MIS knee and hip reconstructions of the next generation.

Method: Hyper redundant robots, also known as snake robots, are the main subject of several robotic researchers. It has been shown that the maneuverability inherent in these types of biological structures and their compliance (i.e. their ability to conform to environmental constraints) allow them to overcome obstacles of significant complexity compared to conventional robots. Hence they became a challenge for imitation in robotics. Until recently, only the promise of non-conventional actuation technology, such as shape memory alloys (SMAs), super-elastic tubes, super-elastic NiTi, etc., provided any possibility of developing a highly articulated probe that is both small, strong enough, and maneuverable, i.e., however, the mechanical complexity embedded in these materials imposed mechanical/design limitations on the overall dimensions of the snake. The snake robot that was developed by our group possesses all of the promise of non-conventional actuation but uses conventional actuation technology, while demonstrating superior capabilities to the previous devices.
The mechanism described in this report is essentially two concentric mechanisms, an outer one and an inner one, which perform a similar function. We term the outer mechanism as the “sleeve” and the inner one as the “core” mechanism. Each mechanism can alternate between being rigid and limp. In rigid mode, the mechanism is just that – rigid. In limp mode, the mechanism is highly flexible and thus either assumes the shape of its surroundings or can be reshaped. With this device, one mechanism starts limp and the other starts rigid. For the sake of explanation, assume the core is rigid and the sleeve is limp and both ends are coplanar. Now, the sleeve is both pushed forward for a distance of one link, by a feeding mechanism, and its “head” is steered by control wires. Once pushed forward and oriented (steered) the sleeve is made rigid and the core is made limp. The core is then pushed forward until it catches up with the sleeve. Since the sleeve is now rigid and the core is limp, the later follows the shape of the sleeve. Now, the core is made rigid, the sleeve limp, and the procedure repeats. The shape propagation of the snake resembles that of a follow the leader control mode for snake robots, in which the rest of the body of a snake robot follows the head as the later is being steered and controlled. The fact that both the core and the sleeve mechanism can be made both rigid and limp enables our snake robot to drive anywhere in three-dimensions while keeping history (“remember”) of its shape. The snake robot is made out of materials which are CT and MR friendly and therefore allow online tracking of the device.

**Results and Discussion:** Our group has already built a first snake robot prototype based on the described concept. The robot is 12 mm in diameter, 300 mm long and is capable of about 8cm radius of curvature (dimensions and capabilities can be improved). The snake robot proves to be steerable and highly maneuverable. The overall dimensions of the devise including the feeder mechanism is 130 mm (W), 100 mm (h), 400 mm (L) which makes it very compact and OR friendly. Once the snake is steered to the operational scene, the sleeve is made rigid and the core can be pooled out creating a 6 mm working port throughout the snake. With this configuration the snake can serve as a cutting platform for MIS knee and hip reconstructions.
Mini bone-attached robot for joint arthroplasty

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Introduction: A mini bone attached robotic system (MBARS) was developed for shaping of the bone cavity in joint arthroplasty. While the system is designed for a general use in joint replacement procedures, the initial implementation was for Patellofemoral Arthroplasty (PFA) procedure. The current application is image-based, with the plans to develop an image-free approach in which all data collection and planning is performed intra-operatively in the robot coordinate system, eliminating the need for external tracking in the operating room.

Experiments conducted using the first MBARS prototype supported the feasibility of the approach. The applied methodology could be extended to other orthopaedic procedures to improve the accuracy and operational time. Moreover, it enables use of the next generation, more anatomically shaped implants and related minimally invasive surgical procedures.

Methods: The first MBARS prototype has been built and tested on synthetic bones (Sawbones, Pacific Research Laboratories, Inc.) model of a knee. The robot is composed of six linear actuators that are connected in parallel between two rigid platforms: The lower reference platform and the upper platform, which is the moving end-effector of the robot. Each of the linear actuators is connected to the lower platform by a universal joint (2 degrees of freedom), and to the upper platform by a spherical joint (3 degrees of freedom). This structure is known as the classical Stewart-Gough six degrees-of-freedom robot. The mechanical structure of the robot and robot dimensions were optimized to cover the workspace for knee arthroplasty. For the PFA procedure, the robot was attached to the femur by three pins: One pin was placed into the medial epicondyle, one into the lateral epicondyle, and one into the metadiaphyseal region of the femur. A rigid connection of the robot to the operated bone was obtained through these three pins. The
robot was equipped with a milling device (a conventional surgical burr), which actively mills the bone according to the surgical plan.

The robot is controlled over an I2C (by Koninklijke Philips Electronics N.V., the Netherlands) data bus which contains 6 wires for the entire robot. This way wiring becomes a minor issue and does not interfere with the OR surrounding area. In our current design, there is one custom circuit board which contains six independent microcontrollers (one per link). The board is located inside the base platform of the robot. The firmware running on the microcontroller includes support for the I2C protocol, both send and receive mode. Moreover, the code also perform PID control loop for the motor locally, connected to it. For this use, the microcontroller reads the joint angle, and drives the motor amplifier with a PWM signal according to the data received on the I2C bus. It also has the ability to communicate with the host computer over the bus and provides, upon request, the current joint angle. The I2C bus is running on a 120 KB/s which are used for a 50 Hz data update rate on the bus. The PID control loop on board the microcontroller runs at a 1 KHz rate. Both the software and the control parameters can be updated over the I2C Bus.

Figure 1 (from left to right): MBARS concept; first MBARS prototype; MBARS preparing bone for patellofemoral arthroscopy

In the current implementation, we use a conventional image-based CAOS approach, in which the surgical plan is developed using the CT scan and implant geometric model, and then intraoperatively registered to the bone. In the next phase we will develop an image-free approach in which the robot will intraoperatively scan the trochlear surface of the knee. The robot will palpate the bone by manipulating a point probe, and obtain the surface points in its end-effector coordinate system. This will eliminate any need for preoperative imaging or intraoperative registration and tracking of the bone. Next, the system will automatically optimize the planned position of the
implant to ensure that it is properly aligned and in line with the surrounding bone surface.

Following data collection and implant placement planning, our algorithm uses cellular decomposition and sweep lines to generate a set of way points for the burr to visit, and then navigate between these way points using potential functions\(^1\). Our algorithm then results in the path for the robot to follow in order to move the cutting tool and shape the bone. The algorithm allows a uniform removal of waste bone with maximum control over the key parameters, such as depth and roughness of the final surface, ensuring complete coverage (removal of waste bone).

**Results and Discussion:** Our initial experiments have demonstrated the potential of bone attached robots in joint arthroplasty. Without loss of generality we examined the capability of MBARS in improving the accuracy of the femoral component preparation in patellofemoral arthroplasty. This procedure was selected since it represents in many ways the future trend in joint arthroplasty and related implant design changes. It is expected that there will be a need to machine bone surface into more complex nonplanar shapes that minimize the bone loss and enable less invasive surgery. Therefore, the technology demonstrated in this study is not specific to the patellofemoral procedure, and could be adapted to many other arthroplasty procedures. Our experiments have shown that MBARS is capable of executing bone preparation of complex 3D shapes with high accuracy while reducing the operational time. This system will allow MIS arthroplasty procedures of the next generation where complex resurfacing of bones is required, and it also simplifies introduction of new implants into the market since there will be no need for new supporting instrumentation, and the system will only be updated with new surface models of the implants.

**References**

Fluoroscopy-based navigation system for ACL reconstruction using theoretical AP-view and lateral-view images

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Introduction: One of the key factors to succeed in ACL reconstruction is the determination of the entry point of the ligament in the femoral site. A commonly putative criterion is the “isometric point” that can minimize the length variation of the grafted ligament during regular knee motion. However, the isometric point can be determined only from the kinematic model of the knee. Therefore, it is very difficult to find the isometric point without a proper navigation system during operation. Though there are criteria for retrieving the isometric point based on anatomic landmarks, the selected points are quite different [1]. In recent years, several image-free (neither CT nor X-ray is used) surgical navigation system for ACL reconstruction have been introduced. These systems rely on the palpation and selection of skin landmarks, the detection of the articular surface and insertion area, and the bending-extension of the patient’s knee to calculate the kinematic parameters and theoretic isometric point of the knee. Such systems need the surgeon to palpate and measure a lot of points within the tiny knee joint area and the palpated landmarks may vary for different surgeons. It would be better if a navigation system not only provides the function to determine the entry point, but also simplifies the setup procedure to prevent operation errors.

This article proposes a navigation system for ACL reconstruction using intraoperative C-arm images, which refers to the theorems for the determination of knee joint coordinate system based on the flexion facet
centers (FFCs) of femur posterior condyles. Once the knee joint coordinate system is built, the navigation system can guide surgeons to take the AP-view and Lateral-view from the theoretical directions, and surgeons will be able to figure out the optimal entry points and orientations of the tunnels on the two C-arm images. The guidance of surgical tools is done by minimizing the mapping errors between the tools’ projection onto the two C-arm images and the planned tunnel. The setup procedure for effective guidance is simple and the operation error can be reduced.

![ACL reconstruction using the proposed navigation system.](image1.png)

**Fig. 1 (a) ACL reconstruction using the proposed navigation system. (b) The position and orientation of the drill are projected and overlapped onto the AP-view and lateral-view images**

**Keywords:** Fluoroscopy-based Navigation System, ACL Reconstruction

**Methods:** At first, two Dynamic Reference Frames (DRFs) for tracking the movement of the tibia and femur are fixed onto the patient’s tibia and femur separately. Then, straighten the knee joint and use a measuring probe to palpate and measure two tibia anterior crest points. The line passing through the two points is defined as the Internal-External Rotation Axis (hereafter, the IERA). After that, bend the patient’s knee and record the frame coordinates of the two DRFs to calculate the line which connects the flexion facet centers (FFCs) of femoral posterior condyles. This line is defined as the Flexion-Extension Axis (hereafter, the FEA). The line defined by the cross product of IREA and FEA is the Varus-Valgus Axis (hereafter the VVA). All the three axes form the knee joint coordinate system.

After the image calibrator attached with DRFs has been mounted onto the C-arm detector, the X-ray projection direction of the C-arm machine can be guided by the navigation system to any desired direction. The AP-view image can be taken by moving the detector plane of the C-arm machine to be perpendicular to the VVA. Similarly, the Lateral-view image is obtained by
moving the detector plane of the C-arm machine to be perpendicular to the FEA. The distortion of the AP-view and Lateral-view images can be calibrated by using cubic camera mode [5], and then the imaging geometry (the spatial geometry between the X-ray source and detector plane of the C-arm machine) can be restored by calculating the intersection of the projection lines of the fiducial markers on the image calibrator. Since the imaging principle of the C-arm is similar to Single-point Perspective Projection, the positions and orientations of surgical tools can be projected and overlapped onto the AP-view and Lateral-view images. Therefore, the surgeon can move surgical tools to the planned entry point and tunnel direction by watching the computer displayed images.

**Results:** Fig. 1 (a) illustrates a preliminary clinical trial of the proposed navigation system. The surgeon can directly plan the optimal location and orientation of the tunnel on the AP-view and Lateral-view images. The tip of the marking hook and the center line of the guide sleeve are projected and overlapped onto the two images in real time as shown in Fig. 1 (b). Through the real-time displayed images, the surgeon can easily adjust the tool to coincide with the planned direction of the tunnel.

**Discussion:** Though the positioning accuracy and clinical outcomes need further investigation, the practicability and feasibility of the proposed navigation system has been demonstrated from the preliminary clinical trial. The C-arm images provide surgeons real-time information of knee anatomy together with the locations and orientations of tools and tunnels, which enables surgeons to feel confidence during operation. It is expected that the advantages of the C-arm image guided navigation system will emerge in more complex operations, for instance: Two-bundle ACL reconstruction.

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**References**


A two-level method for building a statistical shape atlas

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Introduction: A statistical anatomic atlas has many applications, such as visualizing and analyzing the inner anatomic structures, 2D-3D and 3D-3D registration, registration-based segmentation, surgical planning and navigation. Due to genetic, sex and life-style factors, there are inherent non-pathological differences in the appearance and location of anatomic structures between individuals. Surface mapping, i.e., registration of one mesh topology to multiple shape variations, is fundamental to the building of an atlas.

One important challenge in the creation of statistical anatomic atlases is dealing with the size and geometrical complexity of anatomical shapes such as the femur and pelvis, and hence the associated computational requirements for speed and memory. We present a two-level method for the construction of a statistical atlas. The problem is broken into two parts: A low-resolution solution to the correspondence and mapping of surface models, followed by a high-resolution interpolation and alignment to return to a full-featured shape-space. The most difficult step is determining the correspondence and mapping. We use Chui and Rangarajan’s¹ non-rigid registration based on fuzzy correspondence and thin-plate splines (TPS-RPM) to parameterize the non-rigid transformation problem. This two-level method is utilized in the building of a statistical atlas of the femur.

Methods: The data for atlas creation are comprised of surface models of triangular meshes derived from volumetric CT scans. The starting femur surface models have roughly 60,000 vertices (100,000 triangles). We first generate low-resolution surface models for all our data using Garland’s mesh simplification technique². Next, we register each study surface model with respect to a reference surface model using Chui and Rangarajan’s¹ TPS-RPM
method. TPS-RPM warps the reference model to each study model to get a corresponding point set on the study surface by minimizing the residual sum of squares of the distances. The resulting surface model has the same dimension and topology as the reference model and the approximate shape of the study model. After that we refine the correspondence between study surface and the reference surface by locating more precisely the vertices on the warped reference surface with respect to the vertices of the study surface. Then we use radial basis functions \(^3\) (RBF) to migrate from low to high-resolution. RBF allows us to interpolate the low-resolution models to a higher resolution from the correspondence solution of the low-resolution model. Finally, we refine the correspondence for the high-resolution models as we did the low-resolution models. This sequence is repeated independently for each dataset in the atlas population.

Once we align the topology of all the high-resolution surface models, we define the atlas as a three-dimensional cloud of points and apply principal component analysis (PCA) to solve for the eigenvectors of the atlas.

**Results:** The atlas population consists of 87 femur surface models. The surfaces are from 53 males and 34 females; 43 are left femurs and 44 are right femurs. The original CT images do not include the whole femur but only the mid-to-proximal femur and the distal femur containing the condyles. In the pre-processing step, we distribute the triangles into the two parts based
on relative height of the femur and its parts. To improve the performance, we applied the registration to the femoral head and condylar surfaces separately. In our experiments, the low-resolution condylar surfaces have, on average, 120 vertices (230 triangles), and the femoral head surfaces have 320 vertices (640 triangles). The high-resolution condylar surfaces have 22,000 vertices (45,000 triangles); the femoral heads have 40,000 vertices (78,000) triangles. Thus we can handle more than 60,000 vertices and 100,000 triangles for each femur model.

The TPS-RPM step takes about 2 minutes and the RBF step takes 8 seconds running in Microsoft Visual Studio 6.0 on an Intel Pentium 4 CPU, 2.40 GHz, with 1.00 GB of RAM.

**Discussion:** Our work focuses on a new methodology for building a statistical atlas from the huge dimension data using a hierarchic approach. Our two-level approach decreases the computational complexity and improves the speed while using less memory.

**References**


How can Ceravision system guide to achieve the ligament balance in total knee arthroplasty?

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Introduction: Many reports on computer-assisted systems for total knee implantation focused on accurate alignment. How to assess ligament balance and realize rotational position based on a CT-free system in total knee arthroplasty (TKA) was the aim of this study.

Methods: From November 2002 to June 2003, 21 patients with osteoarthritis received primary TKAs (Hermes*, France), performed by one senior surgeon (DG) experienced in conventional primary and revision TKA, using a image-free module (CT-free Knee 1.0, based on “Bone morphing”) of Ceravision System (Ceraver, France), implanted posterior stabilized total knee prosthesis, with fixed polyethylene component and resurfaced patella, all components were cemented. This cohort of 21 patients included 5 men and 16 women with an average age of 72.4 (range: 64 – 79) years. The pre-operative deviation of leg axis was 20° varus to 21° valgus. The data of patients real time recorded in CD Rom were analyzed. All patients were followed up for clinical, radiography and CT evaluation at a mean of 13.3 prospective months (12 – 16 months).

Results: Intra-operatively, the variability in rotational alignment of femoral components from internal rotation (IR) 1° to external rotation (ER) 5°, tibial components from 0° to ER 5°, in group of knees in varus, femoral components from ER 1° to ER 5°, tibial components from ER 2° to ER 5°, in group of knees in valgus, femoral components from IR 1° to ER 4°, tibial components from 0° to ER 4°, postoperative goniometric data variation from varus 2° to valgus 3°, mean valgus 0.175° were recorded. No complications influencing the clinical outcome were observed. Clinical check-up (3rd post-
operative month) for the initial result, this was not abnormal laxity, mean flexion angle measured as range of motion (ROM) was 115°.

**Discussion:** Using Ceravision allowed intra-operative visualization of leg axis, ligament balancing and knee kinematics. The Bone Morphing technique could provide more information for the individual morphologic and geometric data for intra-operative planning, especially in knee deformation in great varus/valgus even after the peri-articular osteotomies of knees. The rotational position of femur and tibia was noted for achievement the ligament balance, not always to implant all the components in 3° to 5° external rotational position, but to assess a rectangular flexion and extension gap as well, the operator should consider the individual situation to decide the amount of rotational position and to achieve the ligament balance after the medial or lateral release. The frontal laxity should also be paid attention to restore a stable prosthetic knee, within 3° deviation of axes is acceptable when examination performed in the position of full extension and 15° to 20° flexion intra-operatively. In this series, there was not patellofemoral complication and abnormal laxity observed postoperatively.

**References**


Measurement of traction load and torque transferred to the lower extremity during simulated fracture reduction

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\textbf{Introduction}: Femoral neck fracture is one of the common fractures in elderly people because of their osteoporosis. In spite of the recent improvement of surgical techniques and devices, femoral neck fracture has still affected mortality, especially in high risk patients with cardiac and/or respiratory diseases, and non-ambulatory condition due to poor reduction and inadequate fixation of fracture. Fracture reduction still depends on surgical skill. The reduction maneuver consisted of traction and rotation of patient’s limb is based on “surgeon’s experience”, and judgment of fracture reduction is relied on “surgeon’s eye” using two-dimensional fluoroscopic pictures, which can often result in inappropriate reduction and fixation of the femur. To aim to resolve these problems, we have developed robotic surgical assistants to provide safe and accurate fracture reduction and an adequate reduction process calculated by computer. In order to develop such surgical assistants, it is necessary to define medical safe range of motion and loading in human subjects. Our objectives in this study are to establish these parameters.

\textbf{Methods}: We measured forces and torques applied to the lower limb during simulated fracture reduction for healthy volunteers without any history of lower limb injury. In this study, healthy and young volunteers were included. There were 30 males and 32 females, with an average age of 22.7 years (range 18 to 34 years). The average height was 165.4 cm (range 148 to
183.0 cm), and the average weight was 57.5 kg (range, 43.0 to 92.0 kg). The average of girth of thigh was 44.3 cm (range, 37 to 61 cm) and the average of girth of calf was 35.4 cm (range, 30.5 to 46 cm). Range of motion in volunteers’ hip joint was as follows: The mean flexion was 127.0 degrees. The mean external rotation was 46.3 degrees, and the mean internal rotation 28.5 degrees.

According to the conventional reduction process, the volunteers’ limbs were tracted and then rotated. Force of traction and torque of rotation were measured using force sensor (Nitta Corporation, Osaka, Japan). Volunteers were positioned on a fracture table and their lower limbs were fixed in the position of 0 degrees of flexion and 30 degrees of abduction in the measured limb and 40 degrees of abduction in another limb. The force sensor was put where their measured lower limb was fixed. We defined the coordinate axis. We defined $F_y$ as the direction of traction and $M_y$ as the rotation around $F_y$. Volunteers’ limbs were tracted slowly in increments of 5 millimeters, and then rotated slowly externally in increments of the 5 degrees, and finally rotated internally. We measured the forces and torques until each volunteer felt pain or abnormality in their lower limbs. Maximum force and torque to the lower limbs was defined as force ($F_y$) and torque ($M_y$) when volunteers felt pain or abnormality to their limbs. We graphed the force versus traction distance and torques versus degree of rotation.

Figure 1  Graph of a torque-degree of rotation graph externally
**Results:** The maximum traction force applied to the lower limbs was averaged 232.9 N (range, 114.0 to 311.0 N), and the maximum torques were averaged 7.69 Nm (range, 2.28 to 14.23 Nm) in internal rotation and 6.31 Nm (range, 1.32 to 15.56 Nm) in external rotation. These values in male were larger than those in female. The maximum traction force applied to the lower limbs was averaged 268.23 N in male and 201.58 N in female. The maximum torques was 9.10 Nm in external rotation and 8.19 Nm in internal rotation in male, and 6.33 Nm and 4.69 Nm respectively in female.

In this study, there is no correlation between the maximum traction force and volunteers’ height, weight, girth of thigh, girth of calf and range of hip motion. There is also no correlation between the maximum torques of rotation and these parameters.

We could represent each graph of traction force pattern and torque pattern for every volunteer. During the reduction process, the traction force was proportionate to distance, whereas the torque of rotation was sharply increasing past maximum range of hip rotation. We showed a torque-degree of rotation graph externally (Figure 1).

**Discussion:** We could analyse the force and torque to lower limbs quantitatively when they were tracted and rotated. These parameters can be used as one of safe range of motion and loading to the lower limbs using robotic surgical assistants.

However, we measured the parameters only for conscious volunteers. We cannot forget volunteers’ resistance by their muscles of lower limbs and soft tissue around them. In the future, we need to measure the traction force and torque of rotation for patients with femoral neck fracture under anesthesia.

We measured forces and torques applied to the lower limb during simulated fracture reduction for healthy volunteers. We could analyse the force and torque to lower limbs quantitatively.
Kinematic analysis of two different tunnel orientations in double-bundle ACL reconstruction

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Introduction: The kinematic effect of tunnel orientation and position, during ACL reconstruction, has been only recently related to the control of rotational instability[5].

This paper presents a detailed computer-assisted in vitro evaluation of two different femoral tunnel orientations with the same tunnel position, at 10.30 o’ clock, during the intervention of ACL reconstruction with double bundle technique[1]. Results highlighted better kinematic performances of the horizontal tunnel, with respect to the vertical one, in controlling antero-posterior (AP) laxities at 30º, and internal-external (IE) laxities.

Materials and Methods: Four cadaver knees were operated of DB ACL reconstruction with original technique[1]. An optical navigation system was used to record relative motion of the tibia and the femur and to digitize anatomies[2].

Reference arrays were fixed to the bones in order to have a minimally invasive system; tibial array was fixed in the access for hamstring harvesting, while femoral array was inserted on lateral condyle near the femoral tunnel entrance. On each knee both reconstructions were performed, tunnels were differently oriented but had the same position at femoral footprint.

The acquisition protocol of our study consisted in the following steps:
1. Kinematic test on knees with ACL intact, ACL deficient, horizontal tunnel and vertical tunnel reconstruction.
2. Acquisition of anatomical data.
Figure 1. Results of the AP and IE test in all specimens with ACL intact, after ACL cut and with ACL reconstruction with horizontal and vertical tunnels

Kinematic acquisitions included the passive range of motion from full extension to full flexion, the internal/external rotation at 90° and 30° of flexion and at maximum force, the drawer test at 90° of flexion and the Lachman test at maximum force. All of them were recorded twice by two surgeons and all the 6 degrees of freedom of the knee joint were recorded during tests in different conditions.

The following anatomical regions were digitized: Distal condyles and tibial plateaux, femoral and tibial ACL insertions, femoral and tibial tunnel holes, malleoli, most medial and lateral points of tibial plateaux, epicondyles and center of the femoral head by pivoting the femur[4].

**Results:** Femoral and tibial internal tunnel holes were within ACL insertion.

The femoral horizontal and vertical tunnels were oriented respectively 28±2° and 41±2°, with respect to the joint line in the frontal view, on coronal view horizontal and vertical tunnel were oriented, with respect to posterior condyles line, respectively 40±4° and 43±3°.

The tibial tunnel was almost vertical and directed posteriorly on the sagittal plane.

The mean orientation of the bundles, with respect to the femoral notch, was 29±6° and the variation during PROM was small (less than 20°) similar to
ACL; Elongations of anterior and posterior bundles of reconstructed ACL, for both reconstructions, decreased during PROM respectively by 20% and 40%.

Total length of the graft varied during PROM, mainly due to graft elongation during tests, graft length on horizontal tunnel varied from 237 to 213 mm while graft length on vertical tunnel varied from 257 to 233 mm.

Kinematic tests showed a better performance of horizontal tunnel in the control of IE rotations at 30° and 90° and of the Lachman test with respect to the vertical one. Stability was restored with both reconstructions. See Figure 1 for details.

**Discussion:** In this paper we evaluated, by computer assisted procedure, two different femoral tunnel orientations during the intervention of double-bundle ACL reconstruction. The reconstructed bundles were compared with the normal ACL; in all cases the reconstruction was able to restore normal knee kinematics[3,5].

The two ACL reconstructions that provide an over the top bundle, demonstrated, with respect to normal ACL, a slightly different elongation and orientation pattern but the same behavior during PROM especially in the orientation and elongation of the anterior bundle. The main result of this study is that, despite both reconstructions had the same insertion hole on femur and present the same behavior during PROM, grafts positioned in horizontal tunnel give a better control of internal and external laxities at 30° and 90° degrees of flexion and a better control of the anterior displacement during Lachmann test with respect to vertical tunnel.

**References**


Navigated intraoperative clinical test for kinematic assessment of ACL graft behavior

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Introduction: This paper describes a new protocol for an accurate and extensive computer-assisted evaluation of joint laxities during reconstructions of anterior cruciate ligament (ACL) [1]. The paper reports in details the proposed acquisition procedure to be performed by the surgeon and the evaluation protocol which will permit to estimate quantitatively and qualitatively the performance of the intervention. First three in vivo cases are also reported, with kinematic evaluation of joint laxities before and after ACL DB reconstruction. Results showed the high repeatability and sensitivity of the tests and the possibility to evaluate in a precise way the increased stability after the reconstruction.

Methods: Before the intervention evaluation of soft tissue structures of the knee and IKSS score are recorded by the operating surgeon.

The intraoperative setup has been designed to be minimally invasive and minimize possible interactions with surgical actions. To evaluate the joint behavior an optical localizer [2] has been used with tibial reference array fixed medially in the access for hamstring harvesting, while femoral array was inserted on lateral condyle near the femoral tunnel entrance, distally oriented.

The acquisition protocol consists of the following steps:

- Initial set-up of the femoral and tibial frame for the navigation system
- anatomical acquisitions on the leg
- kinematic tests on the ACL-deficient knee
- surgical intervention according to the technique
- kinematic tests on the reconstructed knee.

Kinematic acquisitions include the valgus/varus (VV) rotation at $0^\circ$ and $30^\circ$ of flexion at maximum force, the internal/external (IE) rotation at $30^\circ$ and $90^\circ$ of flexion and at maximum force, the drawer test (AP) at $90^\circ$ of flexion and the Lachman test maximum force. All tests are repeated four times by the operating surgeon and all the 6 degrees of freedom of the knee joint are recorded during tests in different conditions.

The following anatomical regions are digitized, with a navigated pointer: Most distal points on distal condyles and most distal points on distal tibial plateaux, femoral and tibial ACL insertions, femoral and tibial tunnel holes, malleoli, most medial and lateral points of tibial plateaux, epicondyles and center of the femoral head by pivoting the femur [4].

Postoperative IKSS score is repeated after fifteen days.

Table 1 Results of the VV, AP and IE test in all specimens with ACL deficient knee and after ACL reconstruction

<table>
<thead>
<tr>
<th>PRE 0º</th>
<th>varus valgus rotation (avg±st.dev)</th>
<th>POST 0º</th>
<th>PRE 30 º</th>
<th>POST 30 º</th>
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<tr>
<td></td>
<td>val</td>
<td>var</td>
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<tr>
<td>case 1</td>
<td>1.2 ±1.1</td>
<td>1.3 ±1.1</td>
<td>1.0 ±0.0</td>
<td>1.0 ±0.7</td>
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<td>case 2</td>
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<td>0.9 ±0.4</td>
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<tr>
<td>case 3</td>
<td>2.9 ±0.5</td>
<td>2.6 ±0.3</td>
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<th>Internal external rotation (avg±st.dev)</th>
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<td>PRE 30º</td>
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<tr>
<td>ext</td>
</tr>
<tr>
<td>case 1</td>
</tr>
<tr>
<td>case 2</td>
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<tr>
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<table>
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<th>anterior posterior displacement (avg±st.dev)</th>
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<td>PRE 30º</td>
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<tr>
<td>ant</td>
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<tr>
<td>case 1</td>
</tr>
<tr>
<td>case 2</td>
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<tr>
<td>case 3</td>
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Results: Setup for the test, including array fixation and test repetition, was lower than 15 minutes.

All ACL reconstructions were performed according to the technique, tunnel holes were within ACL insertions and femoral tunnel orientations were oriented (45±7°) laterally with respect to tibial femoral mechanical axis on frontal plane and (61±4°) posteriorly with respect to femoral mechanical axis on sagittal plane. Intra-patient repeatability of the tests was very high; all repetitions remained within 2 mm/2°. The stability of the test was very high, secondary laxities during the tests remained within 3 mm/3°. Inter-patient repeatability of the test showed good results especially for IE rotations at 30° and AP translations, VV test and IE rotations at 90° highlighted some differences between the patients.

After ACL reconstruction varus laxities decreased at 0° by 65% and at 30° by 48%, internal rotations decreased at 30° by 43% at 90° by 39%, anterior laxities decreased at 30° by 63% and at 90° by 76%; the other laxities, also, decreased after the reconstruction. In all patients stability improved from preoperative value of an average of 66%. See Table 1 for results.

Discussion: The proposed protocol, designed to optimize surgical times and minimize invasiveness, gave excellent results. An extensive analysis of graft positioning, of tunnel orientations and of kinematic behavior of the reconstructed ACL is possible by increasing the surgical times by only 15 minutes, including reference array fixation, anatomical digitization and kinematic tests.

The protocol allows to quantify the effect of ACL reconstruction on overall stability of the knee joint by using classical clinical tests. The high repeatability and stability of the tests allow, also, to highlight the contribution not only of the ACL but also of other damaged structures; two of three cases, in fact, presented also associated lesions to the medial structures, this leads to an increased laxity, on ACL deficient knees, during VV test at 30° and to the IE test at 90°.

For all patients the reconstruction gives a complete restore of AP stability at 30° and 90° degrees giving an increased stability up to 76% confirming the role of the ACL in the control of AP dislocation, the external laxities were also satisfactorily restored after the graft fixation, at 30°, in particular, the reconstruction gives a good control of the joint, reducing laxity up to 43% [3,5].
This protocol could be used to document and evaluate ACL reconstruction at time zero and could permit to better evaluate the control of ACL reconstruction and peripheral laxities.

References

Fluoroscopy-based rigid registration for image guided spine surgery

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Introduction: 2D-3D registration of volumetric data with a series of calibrated and undistorted projection images has shown great potential in CT-based navigation because it obviates the invasive procedure of the conventional registration methods, which match the actual location of implanted fiducial markers, anatomical landmarks, or a cloud of points on the surface of the anatomy to the corresponding points in the pre-operative model.

In this paper, we are interested in intensity-based 2D-3D image registration, particularly in a recently introduced spline-based multi-resolution 2D-3D registration algorithm, which has been assessed in our previous work [4]. In this paper, we focus on improving this spline-based multi-resolution 2D-3D registration algorithm for practical use in spine navigation systems.

Methods: Spline-based multi-resolution 2D-3D image registration was first introduced by Jonic et al. in [1]. It is based on cubic splines interpolation and is tuned to a multi-resolution strategy. It follows the same computation framework as other intensity-based 2D-3D registration. Accuracy of approximately 1.4 +/- 0.2 mm when starting from an initial mis-registration of approximately 9.02 mm has been previously reported in [2].

Least-square difference was selected as the similarity measure for its simplicity in [1] [2]. It has least-squares form that could be well adapted for Levenberg-Marquardt non-linear optimizer. But it might be less robust and accurate when soft tissues or interventional instruments are presented in the fluoroscopic images. To improve the robustness and the accuracy of spline-based multi-resolution 2D-3D image registration algorithm, a novel similarity measure "lease-squares normalized pattern intensity (LSNPI) was proposed in [4]. It has the advantages of both pattern intensity that is able to register
robustly and accurately when soft tissues or interventional instruments are presented in the fluoroscopic images [3] and least-square difference that is well adapted for Levenberg-Marquardt non-linear optimizer.

Table 1 Study results on 27 plastic vertebrae

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5.34±1.42 1.53±0.44

In [2], spline-based multi-resolution 2D-3D image registration, like most of intensity-based 2D/3D image registration, needs a good initial transformation to achieve the final accurate transformation. We propose to adopt the paired-point matching between pre-operatively defined anatomic landmarks on CT volume and intra-operatively reconstructed anatomic landmarks based on fluoroscopy-based navigation technology. This allows intra-operatively
defining the deep-seated anatomic landmarks without the risk of soft tissue damage. For registering a vertebra in practical use, four anatomic landmarks on vertebra body have been chosen.

For evaluating our improved spline-based multi-resolution 2D-3D image registration, 27 plastic vertebrae and a frozen cadaver spine specimen were prepared. All volume data were obtained using a GE Lightspeed Ultra CT scanner and all project images were taken from a SIEMENS Iso-C3D C-Arm. Three titanium fiducial markers were implanted onto each plastic vertebra to compute the ground truth transformation while five titanium fiducial markers were used for the frozen cadaveric spine. Note that we have also provided the cadaveric spine data set to Jonic et al. It was previously used in [2].

**Results**: We first evaluated the proposed paired-point matching based initial transformation methods with 27 plastic vertebrae data. For each plastic vertebra, four anatomic landmarks on the vertebra body are defined on CT volume and reconstructed from two C-arm images. The error of initial transformations is 5.3+/−1.4 mm. All of the initial transforms are in the range of (+10, -10) degrees around the ground truth for rotation parameters and in the range of (+10, -10) mm around the ground truth for translation parameters.

In each case, starting from the obtained initial transformation the overall robustness, accuracy, and efficiency of improved spline-based multi-resolution 2D-3D image registration were validated as following. For the cadaveric spine data set, we run the registration 20 times while for each plastic vertebra we run the registration once. Each time the algorithm could successfully converge. It was found that the overall registration error of 20 times running on cadaveric spine data set was 0.8+/−0.01 mm and the overall registration error for 27 plastic vertebrae testing was 1.53+/−0.44 mm (Table 1).

**Discussion**: We have improved spline-based multi-resolution 2D-3D image registration algorithm for practical use in spine surgery by combining a novel similarity measure – lease-squares normalized pattern intensity (LSNPI) with a paired-point matching based initialization. Our study results on a frozen cadaveric spine data set and on 27 plastic vertebrae confirmed our finding.

**Acknowledgement**: We are thankful to S. Jonic and M. Thevenaz for the spline-based multi-resolution 2D-3D image registration toolbox and insightful discussion. This research was partially funded by the Swiss National Centers of Competence in Research CO-ME.
References


Imageless navigation of unicompartimental knee arthroplasty: First impressions

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Introduction: Unicompartimental knee arthroplasty represents nowadays a well codified solution in literature, in cases in which there is a compromission of a single compartment, lateral or medial, like in unicompartimental arthrosis or osteonecrosis of a condyle.

One of the first complications was the short and medium term failures of these prostheses, mainly due to a bad positioning of one or both prosthetic components. The continuous development has brought to more and more precise and reliable instruments concurring to obtain good results also in the long term. However, correct positioning of the components is still a problem, especially in consideration of the mini-invasive technique that can limit the vision of the surgical field.

In the last years in order to improve the accuracy in the positioning of the prosthetic components, some authors have begun to apply computer assisted technology also in the unicompartimental arthroplasty (1). Such authors have been able to state that, analogous to total knee arthroplasty, also for unicompartimental prostheses, greater percentage of implants had better positioning during computer assisted navigation compared to traditional technique (2, 3). The technique can be considered reliable and reproducible (4). Navigation, moreover, concurs in ligament balance that turns out to be an important prognostic factor (5), above all in those cases of unicompartimental arthrosis with particular one side capsular retraction.

For years we have used various unicompartimental prosthesis models in our orthopaedic unit. Currently we prefer the Accuris (Smith-Nephew) model which guarantees the good positioning of the prosthetic components, thanks to its instruments. We have begun, among the first, to implant this type of
prosthesis using the computer assisted technology and bring back the first experiences.

**Method:** Between September 2004 and January 2005 10 Accuris-Genesis unicompartmental prostheses (Smith-Nephew), have been implanted in as many patients, from the same senior surgeon.

In 5 cases we have applied the traditional technique, while in the other 5 cases the BrainLab imageless system was used for navigation. Seven patients were females and 3 males, the average age was 65 years (58 – 73). Two patients had medial femoral condyle necrosis, 8 patients had a medial unipartimental arthrosis.

In all cases we made a mini-invasive incision (range 8 – 11 cm) and cemented a totally polyethylene tibial component and Oxinium femoral component. Patients begun passive motion on first day (day of the participation time zero); partial weight bearing on second day; complete weight bearing by a month.

At follow-up patients had weight bearing inferior limbs X-rays, in AP and lateral projection for comparison.

**Results:** No complications were recorded on both groups. Surgical time in computer assisted group increased, average 15 minutes. In the follow-up no complications like deep vein thrombosis or infections were noted. The femoral-tibial axis was 176° (range 173° – 182°) for traditional group, while for the computer assisted group was 178° (range 176° – 180°) measured from X-rays. All patients were satisfied.

**Discussion:** The unicompartmental prosthesis we used has already a long follow-up and has already proved its validity.

One of the main characteristics is its instrumentation that allows precise navigation of femoral and tibial component. We think that navigation can further help arthroplastic surgery, being able to better estimate the mechanical axis, but also the rotation of the components. Navigation, moreover, allows a precise ligament balance, not always easy to evaluate, avoiding excessive manual release or lasting of contractures with possible overloads. These first experiences of navigation arthroplasty are encouraging however, they demand further evaluation in time.

**References**

1) Jenny JY, Boeri C.: Unicompartmental knee prosthesis implantation with a non-image-based navigation system: rationale, technique, case-control comparative


In 1999 the Swiss federal government upon request of the Swiss National Science Foundation introduced the National Centers of Competence in Research (NCCR) to promote projects at the leading edge of scientific research. Emphasis is given to interdisciplinary approaches and innovative initiatives within various disciplines. In organisational terms, each NCCR compares to a medium-size business, enjoying corresponding autonomy and responsibility for its own research. The program will run for 12 years.

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- Intra-operative navigation
- Instrumentation for minimally invasive interventions
- Computer-aided clinical applications

Within 12 cross-linked, individual research projects, special emphasis is given to syndisciplinary collaboration of engineers and clinicians. Based on the expertise of the medical doctors and the support of industrial partners, the engineers produce powerful tools in a manner that patients, doctors, medical institutions, and health care providers will benefit from:

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- High-fidelity surgical training
- Improved degrees of freedom during interventions
- Enhanced safety
- Less invasiveness
- Higher efficiency
- Lower costs

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To carry out an event such as CAOS would not be possible without the support and contributions by the following companies and organizations. Their help is highly appreciated.

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<td>(Maurice E. Müller Award for Excellence in Computer Assisted Surgery)</td>
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### Exhibitors (in alphabetic order)

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