ASSESSING THE RELATIVE POSITIONING OF AN OSTEOSYNTHESIS PLATE TO THE PATIENT-SPECIFIC FEMORAL SHAPE FROM PLAIN 2D RADIOGRAPHS

Moritz Ehlke MSc[1,2], Mark Heyland Dipl.-Ing.[3], Sven Märdian MD[4], Georg N. Duda PhD[3], Stefan Zachow PhD[1]

[1]Zuse Institute Berlin, Berlin, 14195, Germany, ehlke@zib.de

[2]Berlin-Brandenburg School for Regenerative Therapies, Berlin, 13353, Germany

[3]Julius Wolff Institute for Biomechanics and Musculoskeletal Regeneration, Charité, Berlin, 13353, Germany, mark.heyland@charite.de

[4]Center for Musculoskeletal Surgery, Charité, Berlin, 13353, Germany

INTRODUCTION

The goal of this study is to derive the distance between an osteosynthesis plate and the patient-specific surface of the distal femur based on 2D radiographs. The offset between plate and bone directly influences the stability and stiffness of the osteosynthesis construct (Ahmad et al., 2007; Gautier et al., 2000; Krishnakanth, 2012). Its stiffness alongside muscle and joint forces in turn determines the amount and type of relative movements of bone fragments, and interfragmentary movement is crucial for the process of fracture healing. We therefore aim at studying the relationship between plate-to-bone distance and bone healing retrospectively using clinical data. Recommendations for load bearing and physiotherapy may, for example, be adapted based on precise knowledge about the plate position (location and orientation, clearance and inclination). If the distance between plate and bone differs significantly from an ideal offset in a larger cohort, navigation should be introduced into trauma surgery (Al-Ahaideb et al., 2009; Wilharm et al., 2011).

The relative positioning between implant and femur is, however, infrequently assessed (Al-Ahaideb et al., 2009; Wilharm et al., 2011), because it typically requires Computed Tomography (CT) scans to derive the patient-specific femoral shape. CTs impose a relatively high radiation dose on the patient, come at increased cost, and are difficult to process due to artifacts near metal components of the implant in the images. Instead, 2D-X-ray images in orthogonal planes are used in clinical routine to visually assess the alignment of bone fragments.

In recent years, computer-aided methods have been proposed to reconstruct the patient-specific 3D shape of an anatomy of interest from one or few 2D radiographs (Schumann et al., 2013; Ehlke et al, 2013; Karade et al., 2014; Zeng et al., 2014). At least two X-ray images from different angles (e.g. coronal and sagittal view) are required in order to derive the correct scale of the anatomy. In addition, the position of the individual X-ray sources and detector planes must be linked in a global coordinate system, assuming that the 3D position and pose of the anatomy of interest is not altered in between screenings. This can either be achieved by simultaneous screening in a bi-planar X-ray setup (Karade et al., 2014; Zeng et al., 2014) or by projecting a calibration phantom of known size together with the anatomy in consecutively generated X-rays (Schumann et al., 2013). The global X-ray setup is restored using point correspondences on the projected calibration object while keeping the relative positioning between phantom and anatomy fixed.

We present a method to reconstruct the 3D shape, scale and pose of the femur and the fracture implant position and orientation from 2D radiographs that are taken routinely for follow-up of osteosynthesis. Unlike previous reconstruction approaches, the method proposed in this work does not rely on simultaneous bi-planar imaging or custom designed calibration objects, but instead utilizes the known shape of the implant to derive the scale of the femur. A-priori statistical knowledge about the shape and bone-interior density distribution is applied to extrapolate the bone over fracture regions and in case the implant overlaps with the femur in the reference images. The relative positioning between bone and implant is then assessed in terms of surface distance between the reconstructed femur and the reconstructed plate.

MATERIALS AND METHODS

The method takes as an input a computer-aided design (CAD) model of the fracture implant, two X-ray images (e.g. in coronal and sagittal view), their corresponding pixel size and the distance between the X-ray source and scanner. CAD-models for the individual implant type can for example be created manually or segmented from CT-scans of the respective implant. The pixel size and the source-detector distance are typically standardized and recorded in the DICOM-header of digital scans. If not available, the source-detector distance can be tape-measured at the X-ray device for a given field-of-view.

The patient-specific shape and pose of the femur and the pose of the implant are estimated in three steps. First, the X-ray images are preprocessed in order to extract the outline of the implant/femur and to mask surrounding structures that are not reconstructed. In a second step, the known implant geometry is registered to each radiograph separately in 3D space. Based on the transformation of the implant in individual X-ray setups, a global setup is computed that relates the images spatially in a single coordinate system. The third step then consists of the computer-aided 3D-reconstruction of the patient-specific femoral shape in the global X-ray setup.

Preprocessing

In the preprocessing stage, one reconstruction mask and two segmentations are derived per X-ray image. The mask excludes pixels that are overlapped by the implant, show the fracture gap, surrounding tissue or X-ray artifacts. The segmented X-ray images depict only those structures that are within the outline of the femur or implant (implant-only/femur-only). The rationale behind masking and segmenting the images is to enhance the robustness of the reconstruction. Information is removed that is not contained explicitly in the 3D models applied in later stages. Although we currently preprocess the radiographs semi-automatically, we believe that in future these steps can be performed fully automatically using available image-processing techniques.

X-ray setup and implant pose

Since the source-to-detector distance and the pixel sizes of the X-ray images are known, two virtual X-ray setups can be derived by placing the X-ray sources arbitrarily in 3D space and assigning a virtual detector plane at the respective distance. The goal is to relate the two individual setups in a global coordinate system, such that the implant position is fixed and the implant viewed from two virtual cameras at the correct angle. For this purpose, the CAD model of the implant is converted into a volumetric model by assigning a constant X-ray absorption property to all cells (e.g. to mimic the X-ray absorption of titanium). It is then registered rigidly to each segmented X-ray image (implant-only) using an intensity-based registration method (Ehlke et al., 2013).

The process returns a transformation matrix of the implant in the respective X-ray setup. The global X-ray setup and implant pose are then derived based on the relative transformation of the implant between the individual setups (Figure 1).

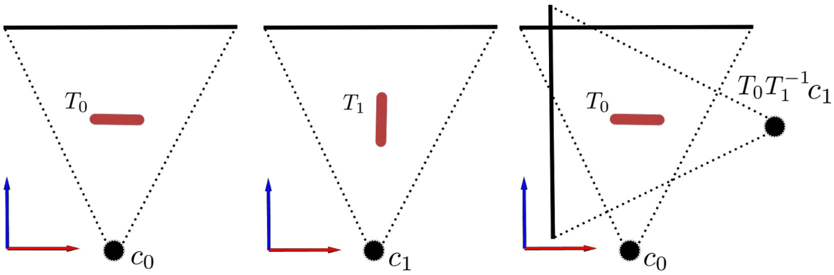

Figure 1: Two individual X-ray setups (left and center) are registered into a global setup (right) based on the transformation T_0 and T_1 of the implant (simplified by a red line). The camera translation and orientation in a setup is given by *c*, the black dot illustrates the position of the virtual X-ray source (e.g. the camera origin).

3D-reconstruction of the femur

The reconstruction is performed by means of an iterative process, in which a deformable shape and intensity model is fit to a pair of X-ray images until the model's 2D projection onto the X-ray planes matches the anatomy depicted in the 2D references. We make use of statistical shape and intensity models (SSIMs) of the femur that were generated a-priori from clinical CT-datasets using the method described by (Ehlke et al., 2013). In each iteration, the SSIM is transformed and deformed. In accordance with the global X-ray setup, virtual 2D X-ray images are generated from the deformed SSIM instances, utilizing the bone density information from the statistical model. A normalized mutual information similarity measure is then applied to quantify the similarity between pairs of virtual X-ray images and the segmented reference image pair (femur-only). Pixels are excluded from the similarity evaluation if they are labeled by the mask defined in the preprocessing stage. The SSIM thus extrapolates over regions in the reference images that show the implant or the bone fracture. Once a suitable match is established, the process returns a tetrahedral grid which represents the femoral 3D shape as depicted in the 2D radiographs.

Experiments

We performed a preliminary cadaver study based on 2 pairs of distal femoral bones and Digitally Reconstructed Radiographs (DRR) from CT. The surrounding tissue was removed, then a standard locking plate (9-hole 4.5/5.0 LISS DF, Depuy Synthes, Zuchwil, Switzerland) applied distally using 7 locking screws (all distal options). A 10mm fracture gap model of the distal femoral shaft was imposed and the plate was fixated using 3 screws proximally. Based on CT-scans of the fixated bone, DRRS were generated in coronal and medio-lateral view in order to mimic clinical X-ray images taken at a source-detector distance of 1m. The global X-ray setup was then derived as proposed using a CAD model of the implant. Afterwards, the 3D shape of the femur was reconstructed in the global X-ray setup using an SSIM from 18 CT training sets. The cadaveric bones were not contained in the training base of the statistical model.

A surface model of the intact bone was registered to the CT data, which then acted as ground truth for evaluation. To assess the distance at consistent point locations on the plate, an ideal plate geometry was registered to each reconstructed plate as well as the plate depicted in the CT. The surface distance between the reconstructed bone surface (from SSIM) and the reconstructed plate as well as surface distance between the intact bone and the ground truth plate were then compared to each other.

RESULTS

Figure 2 exemplary shows the osteosynthesis from CT compared to the reconstructed femur and implant for case 1-L. The error in surface distance between ground truth and reconstruction are given in Table 1. Figure 3 exemplary depicts the implant-bone offset for case 1-R. Root-mean-square-error (RMSE) remains ≤1.54mm for all tested cases with an absolute mean deviation of ≤0.77mm and absolute median deviation of ≤0.83mm. The span in deviation of individual nodes ranges from -4.34mm to +4.74mm. Excluding the distal plate section yields RMSE ≤1.31mm with mean RMSE for bone #1 of 1.23mm and for bone #2 of 0.43mm. Without the distal section, the span is reduced to -3.55mm to +2.09mm. Further restriction of nodes to only the mid-section of the plate results in RMSE ≤1.24mm with mean RMSE for bone #1 of 1.11mm and for bone #2 of 0.41mm. Span for only the mid-section ranges from -2.39mm to 2.09mm.

Region	ERROR	1-L	1-R	2-L	2-R
all plate nodes	**RMSE [mm]**	1.50	1.15	1.31	1.54
	Mean [mm]	0.04	-0.76	-0.34	-0.77
	Span [mm]	+4.74 -3.55	+1.71 -2.39	+1.59 -3.95	+1.16 -4.34
distal section of plate excluded	**RMSE [mm]**	1.15	1.31	0.48	0.38
	Span [mm]	+2.09 -3.55	+1.71 -2.39	+1.42 -0.83	+1.06 -1.42
only mid-section of plate	**RMSE [mm]**	0.97	1.24	0.47	0.34
	Span [mm]	+2.09 -2.39	+1.71 -2.39	+1.42 -0.83	+1.06 -1.42

Table 1: Error in plate-to-bone distance in mm between reconstructed plate and femur compared to ground truth. Listed are the Root-mean-square-error (RSME), mean and median error as well as the span (maximum and minimum) in different regions of the plate.

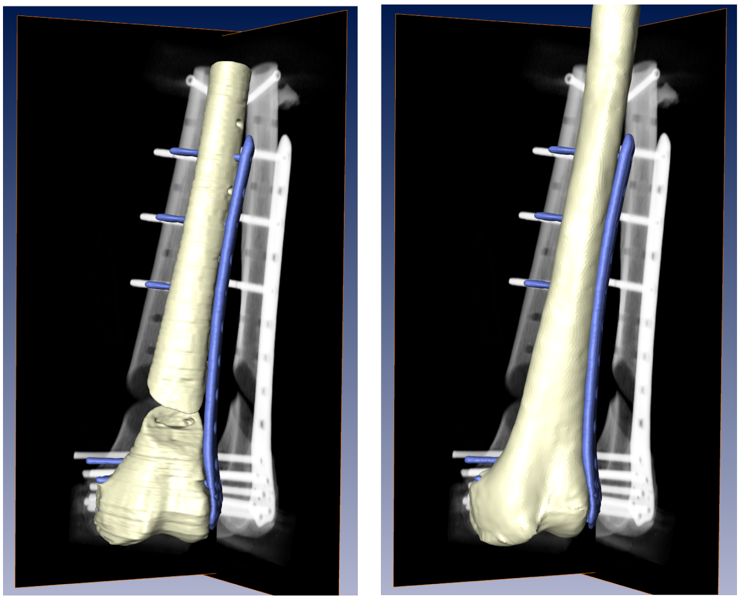

Figure 2: Ground truth shape of the femur and implant from CT (left) of case 1-L and the 3D-reconstructed femoral shape and implant pose based on reference DRRs (right).

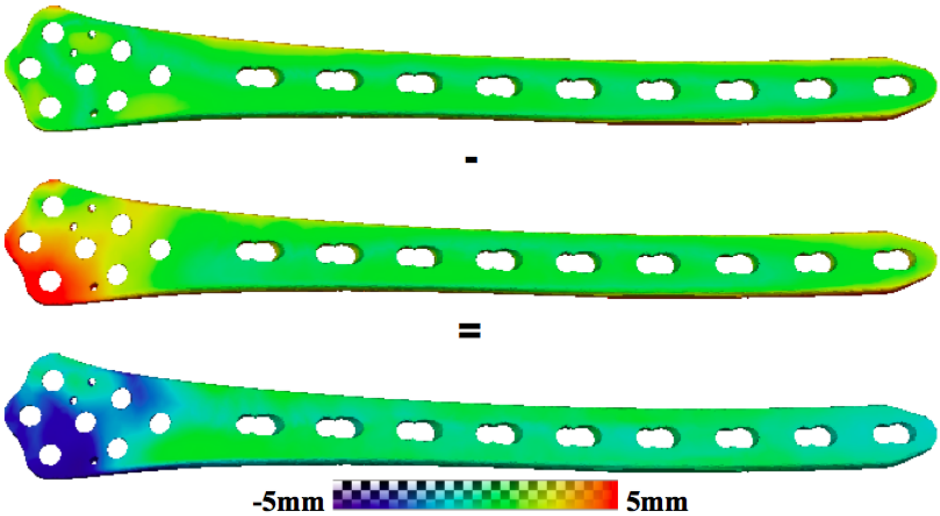

Figure 3: Surface distance in mm between the reconstructed implant and femur (top) and between the ground truth implant and femoral shape (center) of case 2-R. The distances deviate mostly in the distal region of the plate (bottom).

DISCUSSION

We developed a reconstruction method to assess the 3D-positioning of fracture fixation implants w.r.t. the patient-specific femoral shape based on plain 2D radiographs. The method utilizes the known geometry of the implant as a calibration phantom and relates both images and the implant in a global X-ray setup. A-priori statistical knowledge about the 3D bone density is then used to derive the scale-correct femoral shape simultaneously from both reference images.

A first evaluation based on DRRs shows that the surface distance between plate and femur is reconstructed with a sub-millimeter mean error and a RMSE of 1.5mm. The RMSE reduces to 1.2mm in the midsection of the plate. This region is of particular interest for retrospective studies because the free plate working length (gap bridging plate length) in relation to the plate-to-bone distance in the midsection (close to the fracture) mainly determine the interfragmentary movement and therefore biomechanical behaviour of the osteosynthesis (Stoffel et al., 2003; MacLeod and Pankaj, 2014).

In the distal section of the implant, the mean and maximum error were higher (Figure 3). We partly attribute this to the relatively small (18 datasets) and homogeneous training base of the statistical model that only allows for a coarse approximation of the condyles.

The DRRs projected 3D-artifacts from CT due to the metal implant that are depicted as a “white mist” and "streaks". Although real X-ray images are also prone to metal artifacts, we believe that the DRRS induced an additional error when reconstructing the femoral shape, since artifact regions had to be masked that are normally preserved in clinical radiographs. This is especially true for the distal region of the femur, where the fixation screws cover larger regions of the bone in the images.

We consider the implant geometry to be an adequate calibration object, since the predefined X-ray source and detector positions to generate the DRRs and the reconstructed global X-ray setup only deviated slightly (e.g. within few millimeter in position and few degrees in orientation). It will be future work to assess, how deviations in the global setup influence the overall reconstruction result from clinical images.

Our future goal is to further automate the preprocessing stage and thus provide means for a fully automated assessment of 3D implant positioning based on conventional 2D radiographs for retrospective studies and to predict the potential performance of the implant after surgery.

ACKNOWLEDGEMENTS

We thank Prof. Dr. Werner Schmölz (Department of Trauma Surgery, Medical University Innsbruck, Austria) for providing the cadaver bones and CT images for this study.

We would like to thank Depuy Synthes for the kind assistance.

REFERENCES

Ahmad M, Nanda R, Bajwa A, Candal-Couto J, Green S, Hui A, Biomechanical testing of the locking compression plate: when does the distance between bone and implant significantly reduce construct stability?, Injury, 38(3), pp. 358-64, 2007.

Al-Ahaideb A, Quinn A, Smith E, Yach J, Ellis R, Pichora D, Computer assisted LISS plate placement: an in vitro study. Computer aided surgery, 14(4-6), pp. 123-26, 2009.

Ehlke M, Ramm H, Lamecker H, Hege HC, Zachow S, Fast generation of virtual X-ray images for reconstruction of 3D anatomy. IEEE Trans Vis Comput Graph, 19(12), pp 2673–82, 2013.

Gautier E, Perren S, Cordey J, Effect of plate position relative to bending direction on the rigidity of a plate osteosynthesis. A theoretical analysis. Injury, 31, Suppl 3:C14-20, 2000.

Karade V, Ravi B, 3D femur model reconstruction from biplane X-ray images: a novel method based on Laplacian surface deformation, Int J Comput Assist Radiol Surg, 2014 [Epub ahead of print].

Krishnakanth P, Mechanical considerations in fracture fixation, PhD Thesis, Queensland University of Technology, 2012.

MacLeod AR, Pankaj P, A simple analytical tool to optimise locking plate configuration, In 7th World Congress of Biomechanics, Boston, 2014.

Schumann S, Liu L, Tannast M, Bergmann M, Nolte LP, Zheng G, An Integrated System for 3D Hip Joint Reconstruction from 2D X-rays: A Preliminary Validation Study. Ann Biomed Eng, 41(10), pp 2077-87, 2013.

Stoffel K, Dieter U, Stachowiak G, Gächter A, Kuster MS, Biomechanical testing of the LCP-how can stability in locked internal fixators be controlled?, Injury, 34, Suppl 2:B11-9, 2003.

Wilharm A, Gras F, Rausch S, Linder R, Marintschev I, Hofmann G, Mückley T, Navigation in femoral-shaft fractures - From lab tests to clinical routine, Injury, 42(11), pp. 1346-52, 2011.

Zeng X, Wang C, Zhou H, Wei S, Chen X, Low-dose three-dimensional reconstruction of the femur with unit free-form deformation, Medical Physics, 41(8), 2014.