VALIDATION OF THREE-DIMENSIONAL MODELS OF THE DISTAL FEMUR CREATED FROM SURGICAL NAVIGATION POINT CLOUD DATA

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INTRODUCTION

Longterm satisfaction of patients with total knee arthroplasty (TKA) has lagged behind that of total hip arthroplasty (Bourne et al. 2010). There is considerable variability in distal femoral shape (Mahfouz et al. 2012; Mahfouz et al. 2009) and one explanation for patient dissatisfaction is a mismatch between the shape of the native distal femur and its shape post-operatively. This mismatch could have detrimental functional implications to the joint and therefore an awkward 'feel' during use. The shape of the distal femur following surgery depends on two factors, the shape of the femoral component and its positioning when implanted (Akbari-Shandiz 2015). The impact of this mismatch is unknown as the three-dimensional (3D) morphology of the distal femur is not measured during surgery, nor is the exact position of the implant recorded in conventional knee arthroplasty surgery.

A technique that would allow for quick feedback on morphologic concordance between the native femur and implanted femur with no additional imaging requirement could potentially offer a pathway to optimize function and satisfaction, if first validated against clinical data.

Statistical shape models (SSMs) provide the ability to generate various plausible shapes of a certain anatomical structure by adjusting just a few parameters, the so-called shape modes. This technique has been used on femoral heads (Rajamani et al. 2007) and for navigated TKA (Stindel 2002, Fleute 1998), but the former was only on cadaveric bone, and only the accuracy of the digitized points was reported in the latter. Changes in articular shape were recently compared to postoperative quality of life (Akbari-Shandiz 2015), but only for a limited set of patients.

The objective of our overall study is to investigate relationships between changes in knee shape and clinical outcome for a large cohort of patients (data already collected), including those with good and poor outcomes. As a first step, the objective of the present study was to develop and validate a fitting procedure for a SSM of the distal femur using surgical navigation data. This procedure is applicable to any investigation of image-free knee navigation data.

MATERIALS AND METHODS

A total of 20 patients who underwent navigated TKA also had a magnetic resonance imaging (MRI) scan within 2 months preoperatively as part of a previous study protocol. The first 3 processed cases are presented here.

During surgery the standard surgical protocol was followed which included digitization of the anterior cortex of the femur, the distal and posterior femoral condyles, the medial and lateral epicondyles and the femoral center (a point roughly corresponding to the entry point for a intramedullary guide rod). Postoperatively these data were extracted from the navigation unit, imported into Matlab (Mathworks, Massachusetts, USA) and stored as point clouds. A SSM match was optimized iteratively to approximate the shape of the distal femur from the available point clouds. To overcome the challenge in fitting the SSM to a sparse point cloud, a Gaussian prior with adjustable distribution parameters was used in an alternating optimization scheme to constrain the generation of femoral shapes while still allowing the flexibility to adapt to individual features. To account for measurement errors, a robust correspondence estimator was used to optimize the rigid transformation and shape parameters. The final SSMs were exported into ZIBAmira (ZIB, Berlin, Germany) for further analysis.

MRI data from the same group of patients were segmented to develop 3D models using ZIBAmira, and used as the control against which the 3D SSM-generated femur model was compared. The quality of the generated model was evaluated visually and by calculation of the mean and RMS error of the models.

RESULTS

The difference between the statistical shape model-generated femur and the manual MRI segmentation averaged less than 2 mm (Fig. 1, Table 1), with maximum errors occurring in the intercondylar notch and the superomedial edge of the articular surface (Fig. 1).

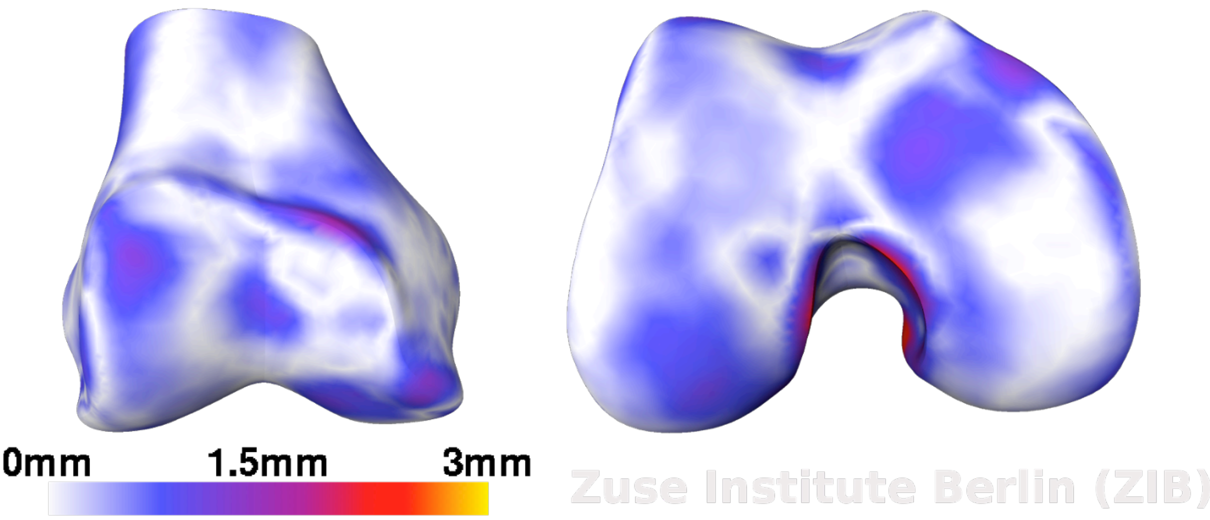

Figure 1: Average surface distance (in mm) between all three automatic fitting results and manual segmentations shown on the average distal femur.

	Mean (mm)	SD (mm)	RMS (mm)	Max (mm)
Case 1	1.21	1.02	1.58	7.59
Case 2	1.56	1.07	1.89	5.51
Case 3	1.45	1.15	1.85	6.01

Table 1: Surface distance between automatic fitting result and manual segmentation.

DISCUSSION

This study evaluated the accuracy of fitting a statistical shape model to digitized surgical navigation data. Maximum errors occurred in less clinically-relevant areas, and the mean errors appear acceptable, given that prosthesis-bone distances of up to 6 mm have been reported even in well-functioning patients (Akbari-Shandiz 2015), and the fact that the MRI segmentations also have a range of uncertainty. Although smaller errors have been reported previously (Stindel 2002), these were for a direct comparison between the bone surface and the bone model only in the region of the digitized points.

The preoperative models will subsequently be compared to the postoperative shape, and the variations in bone-prosthesis shape compared to clinical outcome and gait data. Uncertainty in the preoperative model, based on all 20 validation datasets, will be taken into consideration.

As TKA evolves, a patient-specific approach will be demanded by patients. Patient-specific implant positioning may be a strategy to improve function postoperatively, whereby surgical navigation allows the surgeon to place the components with high precision in any position (Kim et al. 2005). However, current navigation systems generally do not account for patient-specific morphology except with expensive preoperative CT imaging. Currently available patient-specific surgical cutting systems may improve mechanical alignment (Nunley et al. 2012), but have not been shown to improve the morphologic match between the native and implanted femur, joint function, or subsequent patient satisfaction.

The results of this study show that even with the relatively sparse dataset available from routine navigated TKA, the statistical shape model can provide an accurate approximation of the distal femur. These models can be used retrospectively to compare native anatomy with implant positioning, providing valuable insight into patient function and satisfaction. Once clinical significance is proven through the larger study, these models could be incorporated into a surgical navigation unit, providing a surgeon with accurate real-time feedback on the exact concordance of the proposed femoral component positioning with the native anatomy without any additional imaging. This could allow for optimization of implant selection and position for a given patient and potentially improve patient satisfaction and function.

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DISCLOSURES

Dr. Dunbar has performed paid consultancy services with Stryker Orthopaedics International.