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Technical note

# Three-dimensional measurement technique to assess implant position and orientation after total knee arthroplasty

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ABSTRACT

The performance of implant placement technologies are often evaluated based on their achieved post-operative implant alignment. Therefore accurate assessment techniques are necessary to compare pre-operatively planned implant positions with the corresponding post-operatively placed implant positions in total knee arthroplasty. This paper describes a CT based 3D measurement method for evaluation of implant positioning accuracy comparing post-operative implant position to the corresponding pre-operative planned implant position using 3D virtual models. TKAs were carried out on three phantoms and processed three times to investigate the accuracy of the method. The measurements were then assessed against measurements taken through an optical scan. The results indicate that an average measurement error less than 1° and 0.5 mm can be obtained except in the proximal–distal direction where the error was up to 1.34 mm. The accuracy of this 3D measurement technique is sufficiently reliable to enable reporting on implant position and orientation in the same coordinate system as pre-operatively defined independently of the planning system or the surgical implant placement technology (patient-specific guides, robotics, and navigation).



## 1. Introduction

Accurate three-dimensional (3D) placement of implants in total knee arthroplasty (TKA) is considered a crucial factor for good long-term clinical outcome [1–6]. Both conventional techniques as well as new implant placement technologies including navigation, robotic surgery and guided surgery using patient-specific instruments are often evaluated based on the post-operative implant alignment. Although numerous publications exist that evaluate the accuracy of implant placement, the accuracy of the measurement techniques used to evaluate the implant position is typically not recorded [7–13]. Even though the creation of 3D models derived from medical images such as Magnetic Resonance Imaging (MRI) and computed tomography (CT) is a well-known and accepted practice to allow pre-operative planning, it is rarely used to assess the post-operative implant placement accuracy. Often, the assessment is done on one or two, short-leg or long-leg post-operative radiographs. Although radiographs expose the patient to a smaller radiation dose than CT imaging, projection errors are an inherent problem of this assessment technique and the measuring methods are questionable [14]. Even with more advanced techniques, such as optical navigation systems or CT based measurement techniques, the validity of the measurement can be subject to debate, when for example planned and achieved implant alignment are measured on different systems using different frames of reference [15].

This paper describes a CT based 3D measurement method for evaluation of implant position using 3D virtual models and assesses its accuracy using synthetic bones and total knee replacement implants. Provided with a preoperative virtual surgical planning the same method can be used to assess the performance of implant positioning technologies by comparing post-operative implant positions to the corresponding pre-operative planned implant positions.

## 2. Materials and methods

### 2.1. Imaging

The experiments were conducted using synthetic bones made from solid foam with cortical shell (Sawbones Europe AB, Malmö, Sweden) prepared with tantalum markers. The bones consisted of

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left femur and tibia models. The tantalum markers were glued on the bones in specific locations to achieve a balanced distribution.

The 3D measurement method under investigation required a full leg pre- and post-operative CT scan according to a standardized scanning protocol (135 KVp; 100 mAs; pixel size $= 0.4 \times 0.4$ mm; slice thickness $= 1$ mm). It was calculated that one such CT scan has an effective dose of approximatively 14 mSv, equivalent to an abdomen CT scan. For all three phantoms, CT scans were acquired pre-operatively. Commercially available TKA implants were optically scanned using a calibrated, white-light optical scanner (ATOS II by GOM mbH, Braunschweig, Germany) with a resolution of 1.2 million pixels per measuring volume, yielding an accuracy of 0.02 mm. to create high-resolution implant reverse engineered models (REM). Subsequently, the TKA implants were implanted into the phantoms using conventional instrumentation. For each post-operative bone phantom, an optical scan and three CT scans were acquired post-operatively. 3D CT models of the femur, tibia, markers and metal implants were generated from the pre- and post-operative CT scans using Mimics® (v17, Materialise NV, Belgium) through a segmentation process. All segmentations were performed by experienced operators in two steps. First Hounsfield unit threshold filters were applied to generate masks delineating the regions of interest (bones or implants). Only the highest Hounsfield unit were kept for implant segmentation to mitigate the effects of metal scattering. Secondly the operators refined the masks manually to correct remaining errors. 3D CT models were reconstructed from these masks.

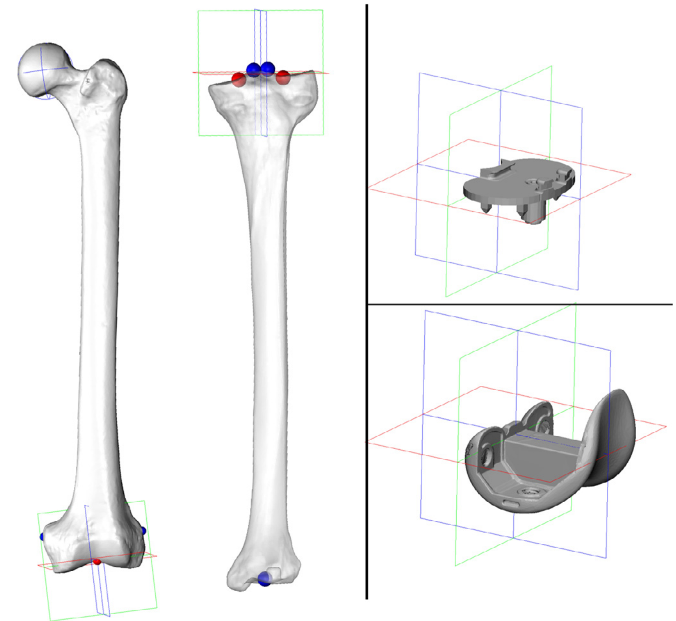

**Fig. 1.** Illustration of the coordinate systems used, represented in this figure as three planes outlined in red, blue and green planes. On the left anatomical coordinate systems of the femur and tibia with anatomical landmarks displayed as small spheres. On the right coordinate systems attached to the femoral and tibial implants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### *2.2. 3D measurement technique*

The pre-operative CT scan was used to prepare a pre-operative plan of the desired implant position by virtual placement of the implant REM on the CT derived virtual bone models. The data from the post-operative CT were compared to this pre-operative plan to quantify the accuracy of the surgery.

To accurately assess the deviation between the planned implant position and the post-operative implant position, a reference anatomical coordinate system was created to perform all measurements. In a first step, the implant REM were registered to a segmentation of the implants on the post-operative scan using 3-matic® (v9, Materialise NV, Belgium). All registrations were performed by experienced operators following the same protocol. First, overlapping surfaces were identified on the respective models to serve as a base for the following registration steps. Second an initial registration was performed to align the inertia axes of both surfaces. Third a global iterative closest point (ICP)-based registration was performed [16]. For surfaces of implants extracted from CT imaging, a manual quality check was subsequently performed by controlling and fine-tuning the model position to the source imaging using Mimics to mitigate the errors caused by metal artefacts. This step is performed to eliminate the effect of metal artefact from subsequent measurements.

In a second step, the post-operative bone models were registered onto the pre-operative bone models, moving along the implant REM. Consequently, the position and orientation of both the pre-operative planned implant as well as the post-operative placed implant were described in the same coordinate system.

Anatomical coordinate systems were defined for the femur and tibia from the pre-operative CT scans and orientation planes were set for each implant REM (Fig. 1). For the femur, the coronal plane was defined by the medial and lateral epicondyle and the center of the femoral head. The mechanical axis was defined by the center of the femoral head and the femoral middle notch. For the tibia, the mechanical axis was determined by the mid-point between the malleoli and intercondyloid eminence. The coronal plane includes the mechanical axis and was defined parallel to an axis connecting the centers of the tibial plateaus. The sagittal planes were defined as orthogonal to the coronal plane and including the mechanical axis. The axial planes were defined as orthogonal to both the coronal and sagittal planes. For the implants, the planes were linked to the resection and symmetry planes (Fig. 1).

The implants' positional deviations were expressed with a rotational and a translational component, projected into the anatomical planes (Table 1).

### *2.3. Quantification of measurement errors*

The 3D measurement technique can be described as a two step method where on the one hand accurate implant REM are registered on 3D CT models to eliminate the effect of metal artefacts and on the other hand 3D CT models of long bone are registered on one another. Segmentation and registration errors can occur for each step [17,18]. The implant registration error and the bone to bone registration errors were investigated separately. The total error introduced by the 3D measurement technique was determined as the sum of both errors projected in the pre-operative coordinate system. This can be seen as a worst case scenario as in practice these two errors may partially cancel each other out.

The implant registration error was quantified by first registering a copy of the optical scans of the implant REM on the post-operative 3D CT implant model (Fig. 2). Then the optical scans of the bone were registered on the post-operative 3D CT model of the bone, taking along the implant REM previously registered on the 3D CT implant model (Fig. 3). The implant registration errors were defined as the absolute differences measured in the anatomical coordinate system between orientation planes and position of the implant REM registered on the optical scan (ground truth) and the implant REM registered on the post-operative CT. Therefore, we assumed that the registration inaccuracy between optically scanned bone models and 3D CT bone models is negligible compared to the error in implant registration.