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Measuring Knee Laxity After Total Knee Arthroplasty using EOS Biplanar X-Ray: A First-step Phantom-based Repeatability Study

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Abstract

Knee joint laxity or instability post total knee arthroplasty (TKA) is a common reason for patient dissatisfaction, and in some cases, can even result in the need for revision TKA. With the ultimate goal of developing an EOS-based knee joint laxity technique, the objective of this study was therefore to determine how repeatably EOS biplanar X-rays can measure 3D knee joint transforms on a radiographically realistic knee phantom between the femur and tibia in the presence of a TKA implant.

To assess repeatability, we first scanned a femoral and a tibial anatomical model (Tactile KneeTM, Tactile Orthopaedics) using a clinical CT scanner and segmented the scans semi-automatically. The fully assembled TKA phantom was then placed within a jig that maintained a fixed and rigid connection between the femur and tibia. This model was then scanned 10 times with the EOS system, with approximately equally spaced perturbations ranging up to ±30º around the superior/inferior axis, applied manually between scans. We then implemented a 2D-3D registration technique to assign Euler coordinate systems to both the femoral and tibial phantoms using JointTrack Auto. This process was completed for both the femoral and tibial TKA phantoms, and coordinate system assignment repeatability was calculated.

The mean deviations from the mean for the medial-lateral, anterior-posterior, and superior-inferior translational axes were all submillimetric: 0.6 ± 0.7 mm, 0.4 ± 0.6 mm, and 0.7 ± 0.8 mm, respectively. The mean deviation from the mean around the medial-lateral, anterior-posterior, and superior-inferior rotational axes were all on the order of 1 degree or less: 1.0 ± 1.2º, 0.8 ± 1.1º, and 1.0 ± 1.2º, respectively.

1 Introduction

Knee joint laxity or instability post total knee arthroplasty (TKA) is a common reason for patient dissatisfaction [1], and in some cases, can even result in the need for revision TKA (as high as 7.5% of all revisions are due to knee instability [2]). Unfortunately, the low repeatability of current manual assessment techniques limits their clinical utility. In contrast, stress radiography techniques relying on a single-plane measurement of laxity report better repeatability, though out-of-plane motions may not be detected [3]. Additionally, radiation exposure from these techniques may result in health risks to patients and clinicians. To our knowledge, automatic stress radiography measurement techniques have not been presented with the objective of measuring knee laxity on the knee joint post-TKA [4].

The EOS biplanar X-ray device is a low-dose imaging system that simultaneously captures both anterior-posterior and medial-lateral scans of weight-bearing patients, reducing radiation exposure by up to 8 times compared to CT scans [5] and 2.5 times compared to X-ray [6]. By performing 2D-3D registration, biplanar imaging should be able to capture the full 3D motions across the knee joint.

With the ultimate goal of developing an EOS-based knee joint laxity technique, the objective of this study was therefore to determine how repeatably EOS biplanar X-rays can measure 3D knee joint transforms on a radiographically realistic knee phantom between the femur and tibia in the presence of a TKA implant.

2 Methods

To assess repeatability, we first scanned a femoral and a tibial anatomical model (Tactile Knee™, Tactile Orthopaedics) with a posterior stabilized knee implant installed using a clinical CT scanner. We segmented the scans semi-automatically using 3DSlicer. The fully assembled TKA phantom was then placed within a jig that maintained a fixed and rigid connection between the femur and tibia. This model was then scanned 10 times with the EOS system, with approximately equally spaced perturbations ranging up to ±30º around the superior/inferior axis, applied manually between scans.

EOS's slot-scanning technology avoids the vertical magnification inherent in X-rays. To use an X-ray based algorithm, we re-applied the magnification-correction algorithm using a technique previously developed in our lab that removes the normally beneficial unidirectional magnification inherent to EOS. The correction adjusted the resulting images to be compatible with standard 2D-3D registration techniques for CT and X-ray images [7]. We then implemented a 2D-3D registration technique to assign Euler coordinate systems to both the femoral and tibial phantoms using JointTrack Auto [8]. This technique works by projecting CT volumes of the TKA implants onto a 2D plane and performing edge-detection. The implant volume transformations were then optimized through translations and rotations to best match the edges of the implants in the EOS X-rays (Figure 2). This process was completed for both the femoral and tibial TKA phantoms, assigning coordinate systems to each using the registration process and calculating the femoral-tibial transform across each of the individual scans.

We assessed repeatability in determining joint transforms by comparing the generated transformations across the 10 scans and calculating the deviation from the mean for all components of all transforms.

3 Results

The mean deviations from the mean for the medial-lateral, anterior-posterior, and superior-inferior translational axes were all submillimetric: 0.6 ± 0.7 mm, 0.4 ± 0.6 mm, and 0.7 ± 0.8 mm, respectively. The mean deviation from the mean around the medial-lateral, anterior-posterior, and superior-inferior rotational axes were all on the order of 1 degree or less: 1.0 ± 1.2º, 0.8 ± 1.1º, and 1.0 ± 1.2º, respectively (Figure 2).

4 Discussion

To our knowledge, this is the first assessment of the repeatability in knee joint position achievable using EOS biplanar imaging in specimens with TKA implants. This technique demonstrated good repeatability with mean deviations on the order of <1 mm and ~1º. The high resolution, low-dose modality, and weight-bearing nature of the EOS system makes it an intriguing option for use in measuring knee joint laxity post-TKA [4], [5], [6].

This study has some limitations. First, only the repeatability of measurements was assessed in this study and not the overall accuracy of the approach. However, other studies using EOS imaging for 2D-3D registration of the knee joint (without TKA implants) has demonstrated mean accuracy as high as 0.1 mm (limit of agreement: -1.64 mm to 1.80 mm) and 0.1º (limit of agreement: -0.85º and 1.05º) when compared against optically tracked markers [4]. Another study assessing tibiofemoral pose using EOS (but creating 3D models using proprietary EOS statistical shape model algorithms) reported mean accuracy of 0.6 ± 1.0 mm and 0.3 ± 1.0º. The cross-measurement repeatability achieved in these studies was similar to that achieved in this study with the presence of metal implants [9].

Additionally, only a single phantom was used in the present study. Future work will aim to further develop this approach by implementing a knee laxity measurement pipeline through the addition of an arthrometer and quantifying knee laxity measurements across multiple phantoms or cadaveric samples compared to optically tracked measurements.

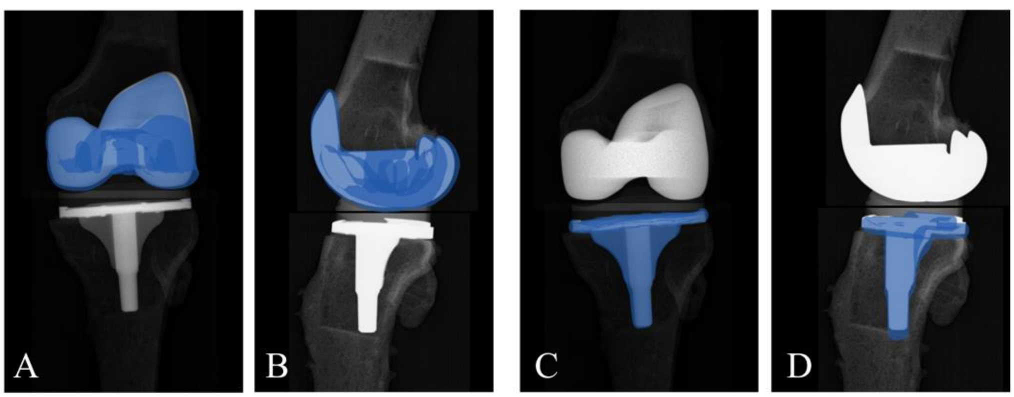

Figure 1: Visual results from the 2D-3D registration pipeline for the femoral component (A-B) and tibial component (C-D). A & C shows the registration on the anterior-posterior EOS images while B & D shows the medial-lateral images. The blue object shows the final registration placement of the implant CT volumes.

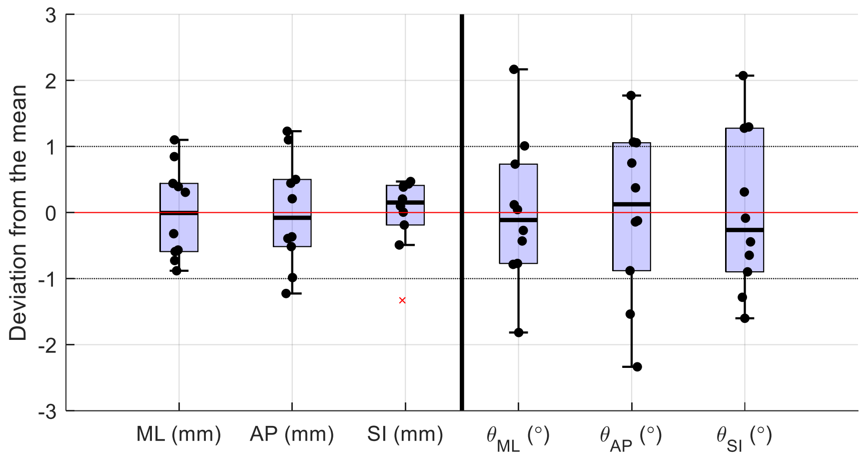

Figure 2: Deviation from the mean for medial-lateral, anterior-posterior, and superior-inferior translations and rotations for a single TKA phantom scanned 10 times with perturbations ranging up to ±30º around the superior/inferior axis.

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