Sequential-Biplane Radiography for Measuring Pre and Post Total Knee Arthroplasty Kinematics

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Introduction: Although total knee arthroplasty (TKA) is considered successful based on the revision rate, 15-20% of patients are not satisfied with the outcome [1]. The kinematic differences between patients with and without pain, particularly anterior knee pain (AKP), are unknown, as are differences in patellofemoral (PF) kinematics of patients with different implant designs. Preop to postop TKF kinematic changes, which can also affect satisfaction, are likewise unknown. No in vivo method currently exists to fully compare these patients. Single-plane and bi-plane fluoroscopy systems have been successfully used to measure six degree of freedom (DOF) kinematics of the tibiofemoral (TF) joint. However, the single-plane approach lacks accuracy for out-of-plane DOFs, especially for the PF joint [2]. Conventional bi-planar systems cannot image the patellar component in both planes since the patellar component is obscured by the large metal femoral component when viewed from more than ~20° off-sagittal [3]. A multi-planar method was recently developed that tracks the movement of a C-arm using optoelectronic markers, following pre-calibration [3]. As an alternative, we use an electronically-controlled source and detector with a permanent calibration frame, taking two sequential images in rapid succession.

The purpose of this study was to develop and validate a clinical sequential-biplane radiography imaging protocol to visualize the knee, in particular the patellar prosthesis, such that pre- and post-TKA 6 DOF TF and PF kinematics, as well as patella location within the femoral groove can be measured.

Materials and Methods: The radiography procedure is identical for preop and postop knees. The individual’s knee is first sagittally imaged using sequential-biplane radiography (Siemens Axiom dRf) at 0°, 15°, 30°, 45°, 60°, 75°, 90°, and maximum flexion (Fig. 1) by adjusting the step height using different numbers of 3/4” thick plexiglass sheets. At each knee flexion the individual holds the position for <5 see while two images are acquired. The first image is taken with the X-ray source 10° below the horizontal plane; for the second it is electronically moved to the horizontal plane to capture the traditional sagittal image (Fig. 1).

In addition, single-plane skyline radiographs (Fig. 2) are captured on X-ray cassettes at 45°, 60°, 75° and 90° knee flexion to locate the patellar prosthesis within the femoral groove. All images are weightbearing. IRB approval and informed consent were received.

As the X-ray source is constantly moved between various angular positions, every image requires calibration. For this purpose a custom-built calibration frame having three planes of known locations of tantalum beads is included in every image. Custom software was written to obtain the external and internal X-ray camera parameters.

Post-imaging analysis requires 3D models of the bones (preop) or implants (postop). Pre-TKA individuals undergo high-resolution volumetric computed tomography (CT) imaging. The CT images are automatically rendered using statistical shape models [5] (Zuse Institute Berlin), with minor manual corrections, to generate 3D femur,ibia and patella models. Coordinate systems are computed for each 3D bone model using anatomical features. For post-TKA individuals the femoral, tibial and patellar prostheses are reverse engineered, with coordinate systems assigned using prosthesis features.

These 3D bone and prosthesis models are registered to the sequential-biplane radiographs in 2D-3D registration software (JointTrack Bi-plane, Florida, USA). Due to slight movements between the two image acquisitions, matching was done first to one image, using the second image as a reference, then vice versa, and the results averaged. TF and PF kinematics are computed as position and orientation of the tibial and patellar bone or prosthesis relative to the femoral bone or prosthesis, respectively. Shift of the patellar bone or prosthesis apex is computed relative to the deepest point within the femoral groove.

For validation, femoral, tibial and patellar prostheses were implanted into an artificial bone model which was fixed in place at one flexion angle and then CT scanned. The prostheses were matched to the CT data using a rigid-body version of the statistical shape modeling process, based on image gradients and known geometry. TF and PF kinematics from CT were computed and compared to those obtained from sequential-biplane imaging. To examine the repeatability of the procedure, two observers each determined the TF & PF kinematics two times for two different subjects, with differing patellar component visibilities, at 8 different flexion angles.

Results: This procedure has been used to date on 38 subjects (41 knees), including 12 preop and 26 postop subjects, with different implant designs, with and without pain. Sample kinematic data are shown in Figs. 3-5. From the validation testing, the mean absolute differences between CT and sequential-biplane kinematics were < 0.84 mm, 0.51° for TF, and < 0.37 mm, 0.89° for PF. Mean inter-observer differences for the repeatability analysis were < 1 mm for TF and PF translation except for mediolateral translation (TF, 1.8 mm; PF, 1.2 mm). Mean TF rotational differences were < 1°; mean rotational differences were < 2° except for patellar mediolateral tilt (2.8°). Intra-observer differences were similar to inter-observer differences.

Discussion: A sequential-biplane radiography imaging protocol to measure 6 DOF knee kinematics was successfully developed, validated and has been used clinically. The sequential nature limits acquisitions to static poses, and disallows exact matching between the bi-planar images, but permits investigations that were not previously possible. To our knowledge, this is the first time that 6 DOF PF kinematics have been reported in vivo post-TKA through a full range of motion. The procedure is currently being used to compare subjects with different implant designs, with and without pain, and pre and post surgery with the goal of improving prosthetic design, surgical technique, and patient selection.

Significance: Over 500,000 TKA procedures are performed in North America each year [4]. Sequential-biplane radiography provides a tool to measure complete TF and PF kinematics accurately in pre- and post-TKA individuals. This method will help us identify why some individuals continue to experience problems after TKA.

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References: