Computer Modeling to Predict Effects of Implant Malpositioning During TKA

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abstract

Computer-assisted surgery has focused on alignment of implants and soft tissue balancing but the end results during surgery as they pertain to long-term function of the implants are not yet realized. One parameter that continues to be variable despite the use of computer navigation is the placement of the implants in the transverse plane. The objective of this study was to determine whether implant and anatomic registrations could be used in a computer model (LifeMOD/KneeSIM, LifeModeler, Inc., San Clemente, California) to show differences in the resulting contact patterns of the medial and lateral condyles of the polyethylene insert. The simulations included tibiofemoral and patellofemoral contact, passive soft tissue (medial and lateral collateral, and posterior cruciate ligaments, as well as the capsular tissues), and active muscle elements (quadriceps and hamstrings). Components of a fixed-bearing cruciate-retaining total knee (Columbus knee system; B. Braun Aesculap, Tuttlingen, Germany) were imported into the model. The systems were subjected to one 60-second cycle of a lunge. Both the femoral and the tibial components were positioned in 5° of internal or external rotation in varying combinations and the resulting kinematics analyzed. The resulting kinematics showed variations in anteroposterior translation of the lateral and medial femoral condyles that resembled several of those reported in the literature for individual patients with a cruciate-retaining knee implant system.

Nearly 600,000 total knee arthroplasties (TKAs) are performed in the United States each year and this number is predicted to exponentially increase over the next decade. Current health care expenditures, which continue to increase, make it necessary to critically evaluate surgical procedures and their outcomes in TKA. As the number of primary surgery cases increase, so will the number of revision surgeries. Because the cost of revision surgery is several times that of the primary procedure, it is necessary to critically evaluate how surgical technique impacts function and satisfaction after TKA, and to strive for a personalized approach to optimize longevity of the procedure.

Approximately 10% to 20% of primary TKAs lead to outcomes that do not meet patient satisfaction and these patients may undergo revision surgery. The leading causes for revision surgery are infection, as well as loosening, instability, and polyethylene wear, which are thought to be associated with altered biomechanical kinematics and kinetics.

Malalignment of the components may be a cause of unsatisfactory outcome leading to TKA revision. Rotational alignment of the femoral component is believed to be critical, and rotational malalignment has been observed to occur in 10% to 30% of patients. It is not known why some patients with femoral component rotational malalignment become symptomatic and require revision surgery and some do not.

Anatomic landmarks are often used for rotational positioning of the femoral component and have been studied extensively. Computer navigation has been shown to improve alignment,
but the poor identification of landmarks from soft tissue overlying bony landmarks of the epicondyles or a hypoplastic trochlear groove can make femoral implant alignment difficult. The tibial landmarks have not been as extensively studied and variations in patient anatomy such as internal tibial torsion can make use of this landmark difficult.\textsuperscript{15-17}

This study sought to investigate how rotational malalignment affects TKA function when the transverse plane of either the femoral or tibial components, or combinations of both, results in changes of kinematics of the TKA during closed-chain simulated loading during a lunge maneuver or during the gait cycle. The objective of this work was to determine the influence of these rotational malalignments on the kinematics of a cruciate-retaining TKA. Furthermore, this study begins investigation of whether intraoperative computer modeling is a feasible adjunct for optimizing rotational mating of the femoral and tibial components.

\textbf{Materials and Methods}

A virtual knee simulator (LifeMOD/KneeSIM, LifeModeler, Inc, San Clemente, California), based on multibody dynamics, was used to simulate a lunge in a manner similar to the in vivo lunge maneuver reported in fluoroscopic studies of TKA kinematics. The model included tibiofemoral and patellofemoral contact, passive soft tissue (medial collateral ligament, lateral collateral ligament, and posterior cruciate ligament, as well as the capsular tissues), and active muscle elements (quadriceps and hamstrings). All of the soft tissue attachments can be taken from the registration data collected during a computer-navigated TKA. Parasolid models of a fixed-bearing cruciate-retaining total knee (Columbus knee system; B. Braun Aesculap, Tuttingen, Germany) were imported into the model (Figure 1). The modeled systems were subjected to one 60-second cycle of a lunge (0°-105°-0° flexion). The anteroposterior (AP) positions of the lowest points on the femoral and tibial condyles closest to the tibial tray (the same measure used in fluoroscopic studies) were recorded relative to the dwell points for each of the inserts. Both the femoral and the tibial components were positioned in 5° of internal or external rotation in varying combinations and the resulting kinematics analyzed. The tibial component was placed with 0° of posterior slope. The neutral alignment was placed according to the epicondylar axis and the medial third of the tibia tubercle.

We simulated a lunge, similar to that carried out in kinematic studies using fluoroscopy and calculated kinematic apparent contact positions in a manner similar to the technique used in fluoroscopic studies. The model included tibiofemoral and patellofemoral contact, passive soft tissue including the elements of the knee capsule and retinaculum, and active muscle elements. In the model, a constant vertical force of 180 N was applied at the hip and a closed-loop controller monitored knee flexion and compared it with the prescribed input. The error was multiplied by a gain, and quadriceps and hamstrings loads are adjusted accordingly. The force applied to the hamstrings was proportional to the product of the error and quadriceps force. The ankle was free to move in AP translation and in abduction-adduction, and it was given internal-external rotational stiffness and damping properties as derived from literature.\textsuperscript{18}
Flexion-extension was prevented at the ankle. One cycle of flexion-extension was simulated over a total duration of 60 seconds to perform the lunge.

The resulting contact points on the mediolateral aspect of the TKA were then reported throughout a range of motion for the lunge as they would be in a fluoroscopic study. The changes in the AP distance on the mediolateral aspect of the tibial insert were then calculated for comparison with the neutrally aligned implants in the transverse plane. This was taken to represent the extent of the predicted potential AP wear scar that would result on the polyethylene insert and was used for comparison.

RESULTS

The resulting kinematics showed variations in AP translation of the femoral lateral and medial condyles that resembled those reported in the literature for individual patients with a similar type of cruciate-retaining knee implant.19-22

In comparing the different variations of component malpositioning, we found that the neutrally aligned femoral and tibial component with matching of the transverse plane rotation of the femoral and tibial component showed the least amount of translation and variation in the flexion-extension cycle. Figure 2 shows a 5.5-mm AP length wear scar on both the medial and lateral aspects of the polyethylene insert. In comparison, the largest variations occurred with the femoral and tibial components both internally rotated. Figure 3 shows a 9.0- and 7.5-mm length wear scar on the medial and lateral aspects of the polyethylene insert, respectively. Different extents of variations between those reported for the internally positioned components and the neutral scenario resulted for the other combinations as well (Figures 4-6).

The resulting medial and lateral contact profiles of the model can also give a prediction of the resulting kinematics for the various implanted positions of the components in the transverse plane. All component rotational pairing scenarios showed a slide-forward pattern in the medial and lateral aspects of the polyethylene insert (Figures 2-6). The least amount of slide-forward resulted in the scenario with both implants externally rotated (Figure 4), <5.0 mm of slide-forward on the medial aspect of the polyethylene insert. The most slide-forward occurred in the scenario with both components internally rotated (Figure 3), >8.5 mm of slide-forward on the medial aspect of the polyethylene insert.

DISCUSSION

This study reported the resulting contact pattern changes in the medial
and lateral aspects of the tibial insert in a cruciate-retaining TKA with different implant alignments in the transverse plane from the manufacturer-defined rotational landmarks of the implants. The largest resulting wear scars occurred when the components were both internally rotated, which also produced the most slide-forward pattern on the medial aspect of the polyethylene insert.

The resulting rotational orientations of the TKA components in published fluoroscopic studies have not been reported, so a direct comparison cannot be made. In addition, the lunge maneuver used in vivo involves resting the contralateral knee on the ground during deeper flexion, which probably reduces the extensor forces on the examined knee, an adjustment that was not modeled in the simulation. Nevertheless, the individual patterns of motion for the various combinations of internal and external alignment of the femoral and tibial components by just 5° resulted in patterns that resemble 5 of the 9 published patterns for a similar knee implant.19-22 This may imply that variations in rotational placement can play a role in determining the kinematic outcome of TKA in terms of femoral rollback patterns and internal-external rotation during a lunge maneuver.

Intersubject variation in kinematic outcome, as measured in a fluoroscopic surveillance of TKA patients performing a lunge maneuver, may be partly due to variations in rotational placement of the femoral and tibial components, both with respect to each other and with respect to each patient’s individual knee anatomy. In addition, the specific nature of the lunge maneuver, the patient’s need for arm support, and the potential ground contact with the contralateral knee in deep flexion could influence the kinematics. In the most recent of these fluorokinematic studies, the variations in the condylar contact points vary significantly from one patient to the next with the same geometry and design of implants in each patient.19-22 The amount of variation in these studies may equal the variation we modeled with varying degrees of femoral and tibial implant placement in the transverse plane.

The one aspect of proper implant placement during navigated TKA that remains subjective in nature is the placement of the tibial baseplate in the transverse plane. Currently, when using a fixed bearing, the methods to align the baseplate include using the medial third of the tibial tubercle, a free-floating trial baseplate during trial reduction of components and aligning the baseplate with the best contour of the femoral component. Whereas variations in the femoral component have
been documented to be on the order of 5°, tibial baseplate placement has not been as well documented. The results of this study may now be considered as a starting point for a functional component positioning algorithm.

**Conclusion**

The results of this study serve as a preliminary step toward the functional evaluation of the way implants are placed in a patient intraoperatively. This type of analysis will allow a personalized medicine approach to TKA and allow the best chance for the patient to have the longest functioning implant during his or her lifetime.

**References**


