As the number of total knee arthroplasties (TKAs) has increased, so have the number of revision procedures performed every year and the cost associated with the procedure.1,2 There has also been a trend of younger patients now undergoing TKA who generally place higher demands and have higher expectations for the procedure.3,4 As more outcome measures focus on patient satisfaction rates, more attention is given to implant design variables and surgical techniques to improve patient-reported outcomes. Some manufacturers have focused on design changes in TKA, while others have focused on technique advancements such as robotics to affect a change in patient-reported outcomes and some surgeons have focused on patient activation.5-8 Complex assessment techniques, such as fluoroscopic kinematic analyses, have now been reported for years to try and determine the kinematic profiles associated with successful TKAs to improve patient-reported outcomes.8-18 Using fluoroscopic analysis techniques, studies have been performed to compare the kinematics of different types of implants to determine how or if these kinematics may impact the long-term survivorship and/or patient satisfaction after TKA.9-14,17-19 This paper reviews the kinematics of posterior-stabilized implant designs and the design variations of the post and cam that may affect
kinematics after surgery. The clinical kinematic results are compared with the wear patterns shown in implants either obtained at time of necropsy or after wear simulations to attempt to exemplify the findings.

**Post and Cam Positioning in Posterior-Stabilized Implant Design**

Total knee arthroplasty implants have undergone a wave of design changes over the past 2 decades, and multiple biomechanical analyses have been report-ed.\(^{1,17-29}\) These changes have been driven by the desire to improve function and decrease recovery time. These posterior-stabilized TKA implants afford stability to the knee by blocking posterior translation of the tibia on the femur through a post (on the polyethylene insert) and a cam (on the posterior femoral condyles or bridging a box between the condyles of the femur) (Figure 1). The design changes that affect the guided or constrained motion of the femur on the tibia have been in the position and shape of the post and cam.

Starting with the Insall-Burstein design, the post and cam were symmetric in nature.\(^{30}\) The post was positioned centrally within the tibial polyethylene insert, and the cam spanned the posterior femoral condyles. This design engaged the cam on the post around 60° and then drove rollback of the posterior femoral condyles on the tibial polyethylene in a symmetric manner until edge loading occurred around 120° of flexion. This was the basis of design for all posterior-stabilized TKA implants from this point forward.

If one examines how the post and cam positioning will affect when and how the interaction of the post and cam occurs, then a basic understanding of design attributes can be inferred (Figure 1). If the post is positioned centrally in the base-plate, then surgeons can determine how moving the cam will affect the interaction of the 2 and drive the motion of the femur with respect to the tibia. If the cam is positioned more anteriorly across the sides of the box, then the post will interact with the cam sooner during the flexion arc. The cam will also move up the post with further degrees of flexion and, therefore, create a shorter jump height that the cam needs to jump the post past 90° of flexion. As the cam moves to the top of the posterior condyles, the cam will not interact with the post until later in the flexion arc, and the articulation will remain at the base of the post even with extremes of flexion thereby maximizing the jump height (Figure 2).\(^{20,23,26}\)

If the cam is fixed across the posterior aspect of the femoral condyles, then surgeons can see how repositioning the post will affect the femorotibial contact and kinematics as well as when contact is initiated. As the post is either angled posteriorly or moved posteriorly, the interaction with the cam will occur sooner in the flexion arc and will position the femoral condylar contact points more posteriorly as well.\(^{26}\)

Cam and post geometry in the transverse plane will also change the way the femur and tibia interact. If the post has a rectangular cross-section, then it will constrain rotation of the femur on the tibia in the transverse plane to an extent. This design feature will cause edge loading of the cam or even the condylar edges of the femoral component. This can be seen in a retrieved implant in Figure 3. This implant shows the square edges of the polyethylene post with a wear scar along the sides from overconstraint in the transverse plane. If the post has a rounded transverse plane geometry with less condylar constraint to internal and external rotation,
then less burnishing and edge wear may result (Figure 4). 20, 23, 26

Post height and position can also affect flexion and kinematics. If the post is too straight and anterior, then there is risk for impingement of the top of the post on the inferior aspect of the patellar button known as post patellar conflict (Figure 4). When this occurs the patient feels a block to further flexion and pain as the post collides with patella.

Asymmetric cam designs have now been introduced where one side of the cam has a larger diameter. The smaller diameter is placed on the medial side and the varying larger diameter on the lateral (Figure 5). This type of design feature is used to guide a medial pivot. This occurs due to the wider diameter of the cam on the lateral side with increasing flexion guiding the lateral femoral condyle to have more rollback, while the smaller diameter on the medial side tends to keep the medial femoral condyle centrally located with more glide motion.

**Kinematics Overview From In Vitro Studies**

One frequently studied topic compares the maximal forces exerted on the posterior cruciate ligament (PCL) in cruciate-retaining implants during deep knee bending against the maximal forces exerted on the post in posterior-stabilized implants. Wünschel et al 17 described their experiment and results related to this topic in 2013 in Knee. These tests were performed using a robotic system for measurement of knee kinematics by fixing the tibia to a ground stage and attaching the femur to the end-effector of the system. The tibia exhibited 0° of freedom while the femur could be moved in all 6° of freedom. This study found a maximal PCL force of 40 N at 80° of flexion. This study also found that the resultant forces for the posterior-stabilized implant were higher throughout flexion but not significantly different than those in the cruciate-retaining design. 17

Li et al 18 also studied the translation of both the lateral and medial femoral condyles in cruciate-retaining and posterior-stabilized implants, and compared the findings to what is seen in a typical knee. In the cruciate-retaining implant, the posterior translation of the lateral condyle was similar to that seen in the cruciate-retaining implant from extension to 60°, but increased to 5.1±5.9 mm at 90° and went up to 13.1±5.9 mm at 120° of flexion. The posterior translation of flexion. This study also found that the resultant forces for the posterior-stabilized implant were higher throughout flexion but not significantly different than those in the cruciate-retaining design. 17
the medial condyle at full extension in the typical knee was found to be 0.2 ± 0.6 mm. It increased steadily up to the maximum of 10.4 ± 11.7 mm at 120° of flexion. In the cruciate-retaining implant, the posterior translation of the medial femoral condyle was 0.9 ± 4.5 mm at full extension. It then translates anteriorly at 30° and 60° of flexion, then posteriorly at 90° and 120° of flexion at significantly lower magnitude than in a typical knee. The translation of the medial condyle of the posterior-stabilized implant was similar to what was seen in the cruciate-retaining implant. However, the translation for this type remained anterior at 90° of flexion and did not translate posteriorly until 120°. At 120°, the mean value of translation was 6.9 ± 7.0 mm, approximately 60% of a typical knee.18

**IN VIVO FLUOROKINEMATIC STUDIES**

Fluoroscopy is used to assess the kinematics of implants in vivo. In a study by Zingde et al.19 fluoroscopy was used to analyze the angle at which cam-post interaction initially occurs, the cam-post distance throughout flexion, the location of the tibial post when contact occurs, and the height of contact of the cam on the tibial post during deep knee bending for 3 types of implants: cruciate-stabilized, fixed-bearing posterior-stabilized, and rotating-platform posterior-stabilized. In this analysis, patients did deep knee bend cycles under fluoroscopic surveillance. Results showed that the cruciate-stabilized TKA had lower contact angles, lower cam-post distance throughout flexion, and a higher height of contact on the tibial post compared with both posterior-stabilized designs. The researchers also found that the location of contact on the tibial post remained centered in the rotating-platform posterior-stabilized implant, but in fixed-bearing posterior-stabilized designs moved from the medial aspect of the tibial post to the center of the tibial post during flexion.19

Another study by Meccia et al.11 looked at how 2 different groups, 1 with greater than 15° of normal rotation and 1 with greater than 3° of reverse rotation, affected the maximal flexion angle. The researchers found that the group with reverse axial rotation had lower maximum flexion angles than those with normal rotation; therefore, axial rotation was found to influence weight-bearing knee flexion. Knees with normal rotation obtained deeper flexion than those with reverse rotation; therefore, the reverse rotation pattern may limit flexion. Meccia et al suggested that more research be conducted to determine whether the axial rotation or the lateral condyle translation is a more important predictor of this flexion.11

A study by Victor et al.13 reviewed a TKA with a dual cam constraint design. If this were the case, there would be no intra-surgeon differences in in vivo kinematics. Three different groups created from 3 different surgeons were analyzed using a 3-dimensional (3D) model fitting approach by manipulating a computer-aided design model in 3D space. The overall motion patterns among the groups were similar, but intra-surgeon differences were found in in vivo kinematics. One group had a greater relative axial rotation than the other 2 groups.13 This difference shows that this type of implant does not function as a mechanically constraint system, and surgical technique and soft tissue handling play a role in the outcome of implant function.

**TKA COMPUTATIONAL KINEMATIC MODEL REVIEW**

Thompson et al.14 created a forward-dynamic simulation of the Oxford Rig that simulates knee flexion under quadriceps control. The goal of this study was to determine ranges of acceptable and unacceptable alignment to establish guidelines for orthopedic surgeons for more successful postoperative function. This model used 1 quadriceps muscle and 4 ligaments (patellar, lateral collateral ligament, medial collateral ligament, and PCL when present). The other muscles were included in the model but remained passive (the forces are less than 5 N). Both cruciate-retaining and posterior-stabilized implants were used in this study, which found that the variables of interest were affected differently by femoral rotation and tibial rotation. When femoral component rotation was varied with tibial component remaining fixed, the maximum medial collateral ligament (MCL) forces were 475 N at 90° for cruciate-retaining and 700 N at 120° for posterior-stabilized. Externally rotated femoral components introduced varus alignment, while internally rotated femoral components induced valgus alignment. Anteroposterior translation for both cruciate-retaining and posterior-stabilized implants were more sensitive to tibial alignment than femoral. The medial condyle of the cruciate-retaining implant exhibited anterior translation, while the lateral contact point exhibited posterior translation when the tibial component was internally rotated. In the posterior-stabilized implant, all combinations of component rotation exhibited posterior translations. This model found more posterior femoral rollback for the posterior-stabilized implant compared with the cruciate-retaining implant, which is consistent with in vivo studies.14

Williams and Mihalko31 used a 3D computational model validated off of the Oxford Rig to show how small rotational variations in transverse plane implant alignment can alter the femorotibial contact in TKA. These variations may be a contributing factor to reverse rotation of the femur with respect to the tibia that has been reported in some fluorokinematic studies.

**CONCLUSIONS**

Considering the post and cam geometry and placement affects on kinematics, as well as the reports in the literature for both, computational and in vivo fluorokinematics, it becomes evident that the resulting kinematics after surgery are multifactorial. Other variables such as surgical technique, implant alignment in all 3 planes, soft tissue balancing technique, and patient anatomical considerations all play roles in the resulting kinematics and motion obtained after TKA surgery. All
variables should be taken into considerations to assure that any one design characteristic does not impede the resulting motion that a TKA obtains after surgery. A review of these design variables will help surgeons in the decisions they make concerning the implant designs they use during surgery.

REFERENCES


