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Posterior Tilting of the Tibial Component Decreases Femoral Rollback in Posterior-Substituting Knee Replacement: A Computer Simulation Study

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Summary: Posterior tilting of the tibial component is thought to increase the range of motion in posterior cruciate-retaining total knee replacement, but its effect on implant motion in posterior cruciate-substituting total knee replacement is unknown. This issue has become of interest recently because manufacturers have introduced instrumentation that produces a posteriorly tilted tibial cut for both implant types. The purpose of this study was to investigate how motion of posterior cruciate-substituting total knee replacement is affected when the tibial component is installed with posterior tilt. Sagittal plane implant motions were predicted from prosthesis geometry with use of a computer simulation in which the femoral condyles were assumed to sit in the bottoms of the tibial condylar wells when the knee was in extension. Rollback of the femoral component was produced by a cam-spine mechanism at higher angles of flexion. The simulations revealed that even small degrees of posterior tilt reduced rollback by limiting the interaction between the cam and spine. Tilting the component posteriorly by 5° caused the cam to contact the spine at a knee flexion angle that was 18° higher than with the untilted component. The results suggest that posterior tilting of the tibial component in posterior cruciate-substituting knee replacement may not produce the same beneficial effects that have been reported for the tilting of tibial components in posterior cruciate-retaining knee replacement.

Posterior tilting of the tibial component by 6-10° in posterior cruciate ligament-retaining total knee replacement is a common practice that has been advocated for improving the range of motion (4,7,9, 10,14) and preventing loosening of the component (8). Posterior tilting is thought to increase the range of motion in posterior cruciate ligament-retaining knee replacement by facilitating rollback, which is posterior motion of the tibiofemoral contact point with flexion (10). Other purported benefits of posterior tilting include preservation of the anatomic slope of the normal tibia and relocation of the tibiofemoral contact point to the posterior portion of the tibial plateau, where the underlying trabecular bone is stronger (8). Various means have been used to demonstrate the value of posterior tilting. Studies of wear patterns (15), *in vitro* implant mechanics (8,16), and computer-simulated kinematics (7) have generally supported the idea that posterior tilting of the tibial component contributes to a favorable outcome when the posterior cruciate ligament is retained.

Posterior cruciate ligament-substituting knee replacement, in contrast, involves removal of the posterior cruciate ligament. Rollback in posterior cruciate ligament-substituting knee replacement is usually produced by interference of a femoral cam with a tibial spine (Fig. 1) rather than by tension in the posterior cruciate ligament. Because a different mechanism guides rollback of the femoral component in posterior cruciate ligament-substituting knee replacement, it is unclear whether posterior tilting of a posterior cruciate ligament-substituting tibial component has the same effect on knee motion that it is reported to have in posterior cruciate ligament-retaining knees.

The effects of posteriorly tilting a posterior cruciate ligament-substituting tibial component are of interest because several manufacturers have introduced knee replacement systems featuring instrumentation that produces a posteriorly tilted tibial cut for both posterior cruciate ligament-retaining and ligament-substituting implants. These modular systems have given surgeons greater flexibility in choosing between posterior cruciate ligament-retaining and ligament-substituting implants and have allowed operating room inventory to be reduced through the use of a single set

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of instruments (12). Often, the instruments in a modular system are designed to cut the tibia with a posterior tilt to capitalize on reported benefits for posterior cruciate ligament-retaining knee replacement, resulting in both posterior cruciate ligament-retaining and ligament-substituting knee replacements with tibial components that are tilted posteriorly. Some posterior cruciate ligament-substituting implants feature a posterior slope that has been built into the tibial component to mimic the anatomic sloping of the natural tibial plateau, and these implants may be tilted further posteriorly if instrumentation that produces a sloped tibial cut is used. Implanting such tibial components with a slight (2°) posterior tilt has been recommended to avoid the reduced range of motion that may accompany anterior tilt (4). Even when the tibial component is intended to be placed neutrally, posterior tilt may occur through surgical error. Colizza et al. (1) measured sagittal plane tilt of the tibial component from lateral radiographs of 101 posterior cruciate ligament-substituting knee replacements and found a mean of 2° posterior tilt (range: 8° posterior to 3° anterior).

Although posterior tilting of posterior cruciate ligament-substituting tibial components—whether intentional or unintentional—is likely to occur frequently, its influence on implant kinematics is unclear. The results of studies of tilt in posterior cruciate ligament-retaining implants cannot be expected to generalize to posterior cruciate ligament-substituting knee replacement, because the mechanisms that guide the rollback of the femoral component on the tibial component are fundamentally different for each type of knee replacement.

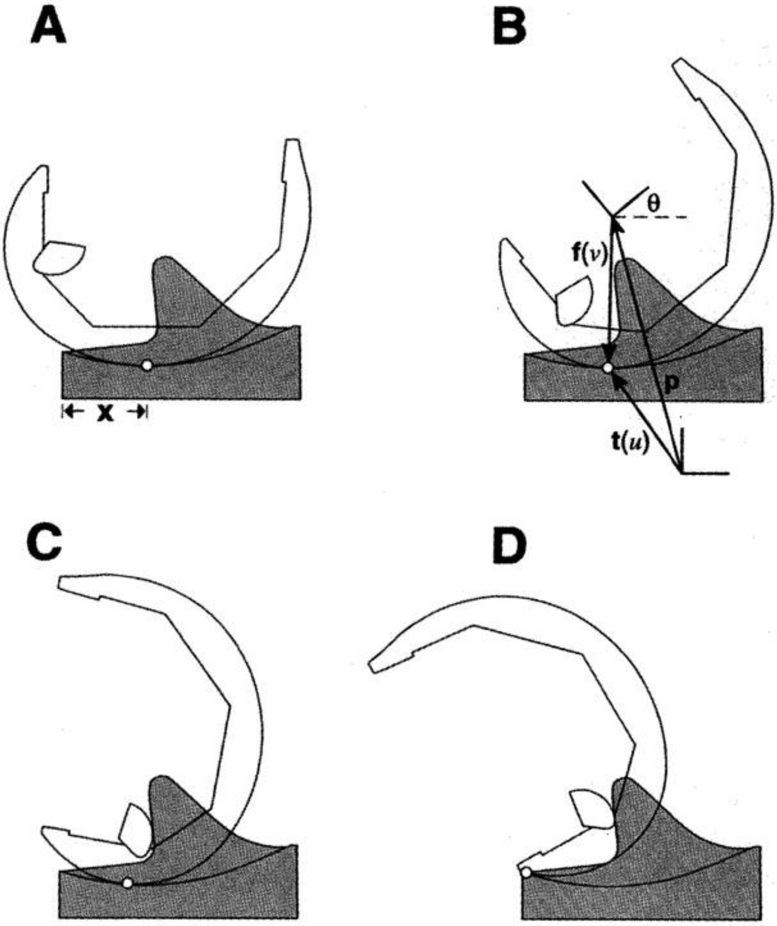

FIG. 1. Illustration of the function of the cam-spine mechanism in posterior cruciate ligament-substituting knee replacement. The components are shown in full extension (**A**) and in 40 (**B**), 80 (**C**), and 120° (**D**) of flexion. White circles denote the point of contact between the femoral condyle and tibial well; anteroposterior distance (x) from the posterior lip of the tibial well to the contact point is shown in **A**. Vectors **p**, **f**, and **t**, which were used in the formulation of the kinematic constraint equations (see text for details), are shown in **B**. Note that cam-spine contact and rollback (posterior motion of the condylar contact point) occur at higher angles of flexion (**C** and **D**). θ = angle of knee flexion, u = tibial spline parameter, and v = femoral spline parameter.

The purpose of the present study was to investigate how sagittal plane tilt of the tibial component in posterior cruciate ligament-substituting total knee replacement affects sagittal plane implant motion. A computer simulation created to study the effects of

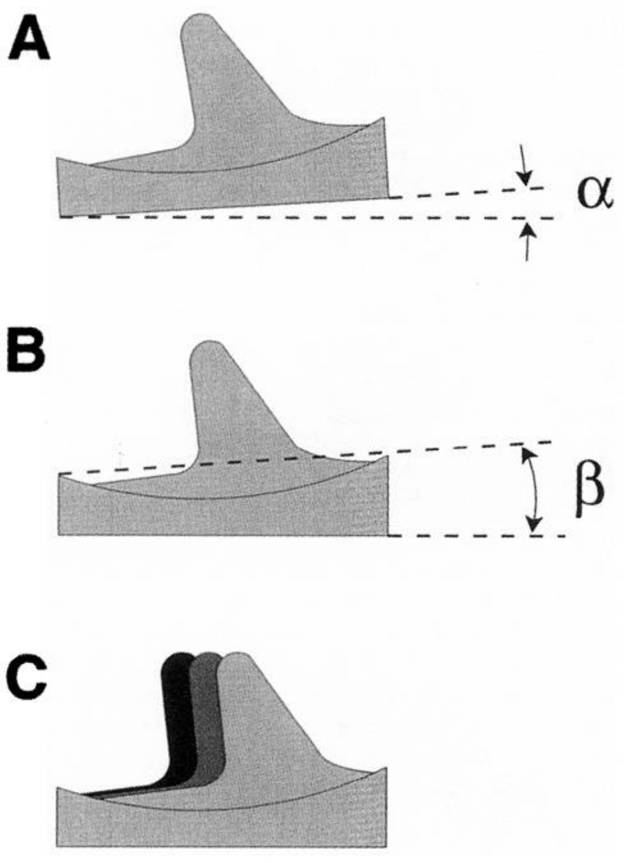

FIG. 2. A posterior cruciate ligament-substituting tibial component tilted by angle α (**A**), with angle β built into the tibial insert (**B**), or with variation of the anteroposterior location of the tibial spine (**C**).

altered component geometry in posterior cruciate ligament-substituting knee replacement (2) was used to examine the influence of component orientation on implant kinematics. In addition to tilt of the entire tibial component, a slope that was incorporated into the tibial insert was considered to study the effects of this common design variation. We sought to analyze the effect of tilt of the tibial component on femoral rollback by examining its effect on the contact between the cam and spine, which drives rollback in posterior cruciate ligament-substituting knee replacement.

METHODS

A computer simulation was developed to predict the motion of a posterior cruciate ligament-substituting knee replacement subject to sagittal plane tilt of the tibial component. Planar implant kinematics were determined from sagittal plane profiles of the component geometry. These profiles (Fig. 1) were derived by fitting cubic B-splines (6) to points sampled from three-dimensional computer-assisted design representations of a posterior cruciate ligament-substituting knee replacement (Advance PS Knee System; Wright Medical Technology, Arlington, TN, U.S.A.). B-splines were chosen to represent implant geometry because they permit the accurate characterization of many different implant profiles, including those composed of circles, ellipses, straight lines, and complex shapes that cannot be defined with simple geometric primitives. A large number of points (n > 50) were sampled from each profile to ensure faithful spline representations of the implant geometry.

Three assumptions were used to simulate implant motion during knee flexion. First, the most inferior point on the femoral condylar profile contacted the tibial well at its most inferior point when the knee was extended. The contact point remained there until the knee was flexed enough for the cam to contact the spine. Second, contact—either condylar or between cam and spine—was maintained, once initiated, as the knee flexed. Third, tangents to sagittal implant profiles at points of contact were collinear. These assumptions were implemented with use of systems of kinematic constraint equations to describe contact between the implants. Vector addition (Fig. 1B) yields

$$\mathbf{p} + \mathbf{f}(v) = \mathbf{t}(u) \qquad \text{(Eq. 1)}$$

where the components of **t** and **f** provide the coordinates of points on the tibial and femoral splines corresponding to the spline parameter values u and v and where **p** is the tibiofemoral position vector. The collinearity of profile tangents yields

$$d\mathbf{t}/du \times d\mathbf{f}/dv = 0 \qquad \text{(Eq. 2)}$$

at the point of contact between the condyles. These vector equations were converted to a system of three scalar nonlinear equations. For small angles of flexion, the femoral component was constrained to sit in the bottom of the tibial well by fixing the tibial spline parameter u and solving for the components of the tibiofemoral position vector **p** and the location of contact on the femoral condyle (represented by the spline parameter v) as the angle of knee flexion (θ) was increased from full extension (θ = 0°) in 1° increments. Equations similar to Eqs. 1 and 2 described contact between the cam and spine; the resulting system of six equations was solved to determine the angle of knee flexion at which the cam initially contacted the spine. Once initiated, contact was maintained by solving the six-equation system for the components of **p** and the four spline parameters (one parameter each for the tibial well, femoral condyle, tibial spine, and femoral cam spline) after the initial contact between cam and spine, until 120° of flexion was reached. All systems of equations were solved with use of an iterative Newton-Raphson algorithm (11). The anteroposterior location of the condylar contact point (distance x [Fig. 1A]) was recorded throughout each simulated flexion.

The tibial component was considered oriented neutrally when its base-plate was horizontal. Tilt of the tibial component was prescribed by rotating the implant profiles representing the tibial spine and well in the sagittal plane. Tibial component tilt (angle α [Fig. 2A]) was varied in 0.5° increments between 5° posterior and 5° anterior, and a simulation of knee replacement kinematics was performed for each orientation.

The angle between the line connecting the posterior and anterior edges of the tibial well and the horizontal (angle ß [Fig. 2B]) was prescribed to be 0, 3, and 6° (the approximate original value for the prosthesis studied) to investigate the effects of building a slope into the tibial component. For these simulations, the spine was relocated in the anteroposterior direction to preserve its position relative to the bottom of the well. The anteroposterior location of the tibial spine relative to the bottom of the well has been found to affect the angle of flexion at which the spine and cam engage (2). Therefore, spine location was moved 3 mm both anterior and posterior to its original position (Fig. 2C) in conjunction with varied tibial tilt, so that the effects of the interplay of spine location and tibial tilt (both component tilt and built-in slope) on implant kinematics could be investigated.

To investigate the generality of our results, we constructed a simple geometric model that was used to examine the basic mechanism by which tilting affects rollback in posterior cruciate-substituting knee replacement. The femoral and tibial condyles were each represented by a single circular arc in the simplified

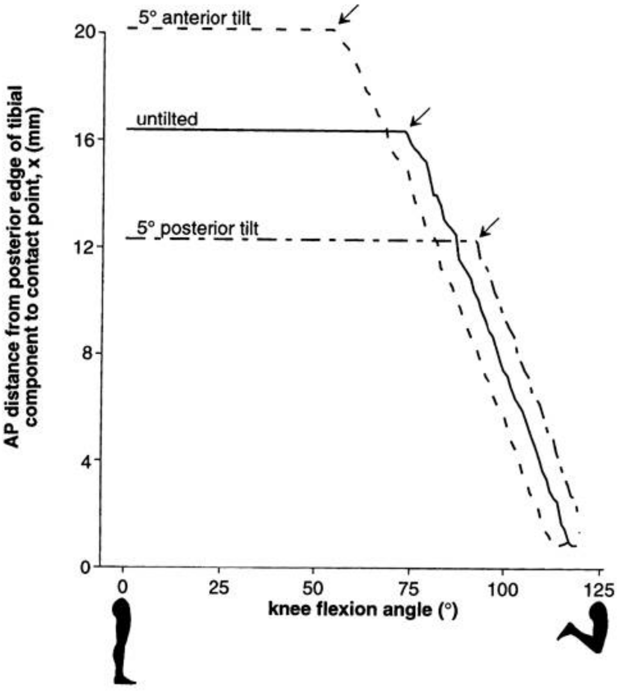

FIG. 3. Anteroposterior (AP) location of the tibiofemoral condylar contact point relative to the posterior lip of the tibial well (x [Fig. 1A]), subject to sagittal plane tilt of the tibial component. Posterior tilting of the tibial component moved the contact point posteriorly in extension but caused the initiation of rollback (caused by cam-spine contact in the simulation and indicated by arrows here) to occur at a higher angle of flexion.

geometric model, and the femoral cam and posterior aspect of the spine were assumed to be a point and a line segment, respectively. This simple model was used to gain an intuitive understanding of the link between geometry and motion that is common to many posterior cruciate ligament-substituting designs; all the quantitative analyses described earlier, however, were carried out with use of the actual implant geometry (Fig. 1).

RESULTS

Posterior tilting of the tibial component moved the condylar contact point closer to the posterior edge of the component in extension and reduced the range of flexion over which the cam contacted the spine (Fig. 3). Because rollback is caused by contact between the cam and spine in the simulation, this loss of cam-spine interaction resulted in less posterior travel of the contact point, and the contact point was located farther anterior (with respect to the posterior edge of the tibial component) in deep flexion. Posterior tilt of the tibial component by 5° caused the angle of flexion at which cam-spine contact occurred to increase by 18° (at 92° of flexion compared with 74° in the untilted component). Anterior tilting of the component produced effects opposite to those produced by posterior tilting. Contact between the cam and spine occurred at 55° of flexion when the component was tilted 5° anteriorly.

When a posterior slope was introduced into the tibial component geometry while the orientation of the spine and its position relative to the bottom of the well were maintained, the condylar contact point moved posteriorly for small angles of flexion but the angle of cam-spine contact was unaffected (Fig. 4).

The angle of knee flexion at which the cam contacted the spine was found to vary with the anteroposterior position of the spine (Fig. 5). Displacement of the spine anteriorly by approximately 2 mm and posterior tilting of the tibial component by 3° were both found to increase the angle of cam-spine contact by 12°. The angle of contact was shown to depend linearly on the angle of tibial component tilt over the range of tilts studied, with each degree of component tilt changing the angle of cam-spine contact by approximately 4°.

Analysis of the simplified geometric model illustrates the mechanism by which posterior tilting of the tibial component causes rollback to occur at a larger angle of knee flexion (Fig. 6A). In this simple model, contact between the cam and spine occurs at 90° of flexion (at point Cu) in the untilted component. If the tibial component is then tilted posteriorly by some angle θ, contact between the cam and spine occurs at an angle of knee flexion that is larger than 90° by δ (at point Ct). The offset angle δ introduced by tilting

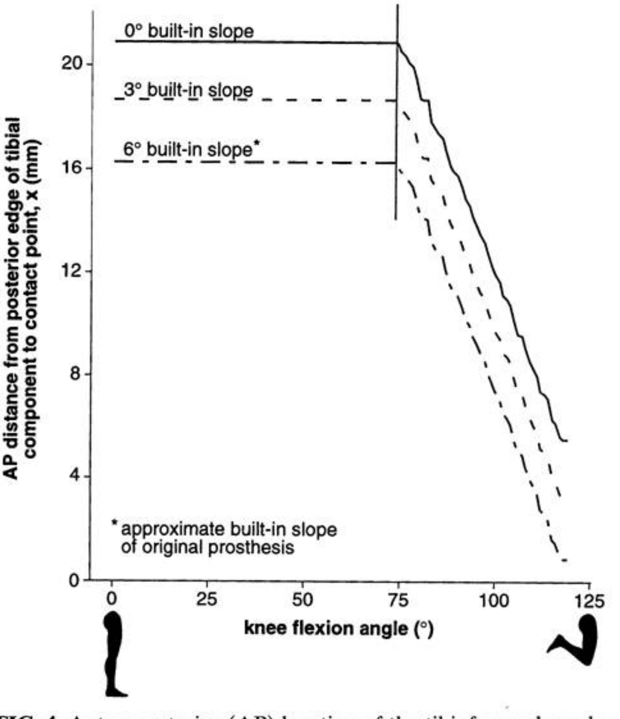

FIG. 4. Anteroposterior (AP) location of the tibiofemoral condylar contact point relative to the posterior lip of the tibial well (x [Fig. 1A]), subject to variation in the slope built into the tibial component. Introducing posterior slope into the tibial insert while maintaining the anteroposterior location of the spine relative to the tibial well caused the contact point to be located posteriorly in extension but had no effect on the angle of cam-spine contact. The tibial component studied has a built-in posterior slope of about 6°; the bottom curve is identical to the untilted curve in Fig. 3.

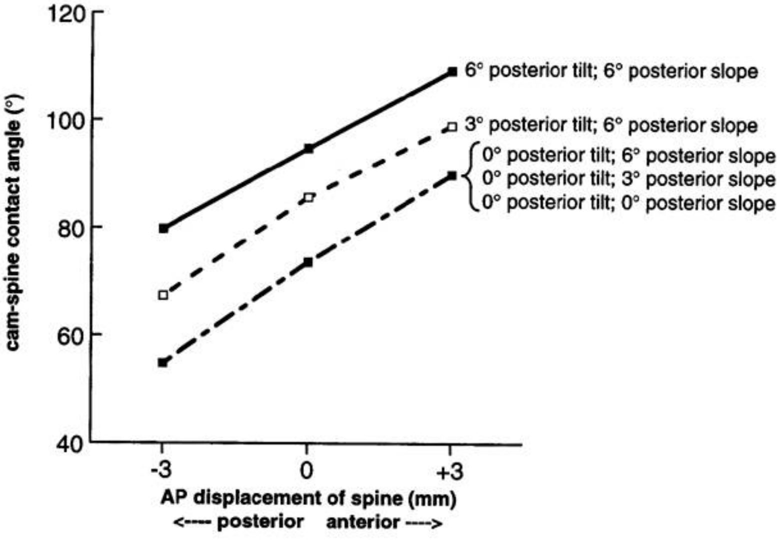

FIG. 5. Dependence of the angle of cam-spine contact on component tilt and anteroposterior (AP) placement of the spine relative to the bottom of the tibial well. Variation in the slope built into the tibial component did not affect the angle of cam-spine contact when spine position relative to the well bottom was preserved (bottom curve).

must be larger than the tilt angle θ as long as the tibial radius R is larger than the femoral radius r (Fig. 6B). This result suggests that the angle of knee flexion at which cam-spine interaction occurs is more sensitive to changes in component tilt for implants whose surfaces do not conform (i.e., for which the difference between R and r is large).

DISCUSSION

These simulations demonstrate that posterior tilting of the tibial component in posterior cruciate ligament-substituting knee replacement alters the function of the cam-spine mechanism meant to substitute for the posterior cruciate ligament. Because the mechanisms that produce femoral rollback in posterior cruciate ligament-substituting and ligament-retaining knee replacement are different, it is likely that tilting the tibial component would affect the kinematics of each differently. In posterior cruciate ligament-retaining knee replacement, rollback is mediated by tension in the posterior cruciate ligament, but in posterior cruciate ligament-substituting knee replacement the femoral component is designed to roll back when its cam contacts the tibial spine. In our simulations, even a small posterior tilt of the tibial component caused large changes both in the angle of flexion at which cam-spine contact occurred and in the anteroposterior location of the condylar contact point in extension.

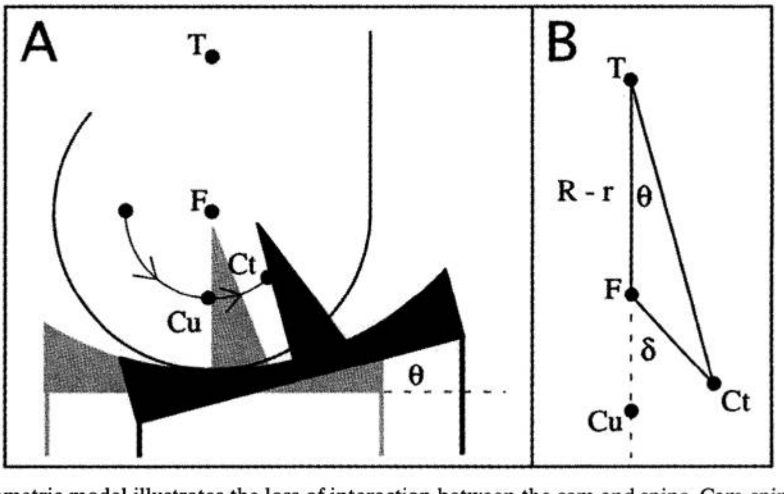

FIG. 6. A: A simplified geometric model illustrates the loss of interaction between the cam and spine. Cam-spine contact occurs at 90° of knee flexion (at Cu) in the untilted component (gray); when the tibial component (black) is tilted posteriorly by angle θ, the location of the tibial well bottom relative to the spine effectively moves posteriorly, and the femoral component must rotate through an angle larger than 90° before the cam contacts the spine (at Ct). **B:** Cam-spine contact in the tilted component occurs at 90° + δ; the offset angle δ is shown to be larger than the tilt angle θ if the tibial well radius (R) is larger than the femoral condyle radius (r). Points T and F are the centers of the circular arcs representing the tibial well and femoral condyle, respectively.

Simulations in the present study also indicate that building a posterior slope into the tibial polyethylene, combined with a neutral placement of the tibial component, may capture some of the benefits of posterior tilting seen in posterior cruciate ligament-retaining knee replacement (such as lowering the posterior lip of the component) without diminishing the role of cam-spine interaction in producing femoral rollback.

It is important to note several limitations when considering the findings of the present study. Different posterior cruciate ligament-substituting designs have varied degrees of condylar conformity, and contact between the cam and spine is intended to occur at various angles. We simulated implant motions by analyzing a single implant design, and our specific kinematic findings (for example, that cam-spine contact occurs at 74° without tibial component tilt) will not apply to all posterior cruciate ligament-substituting designs. However, analysis of the simple geometric model presented earlier (Fig. 6) suggests that one of our findings is true in general: posterior tilt reduces cam-spine interaction in any posterior cruciate ligament-substituting knee replacement that relies on a cam-spine mechanism to effect rollback.

Another limitation of this study is that implant kinematics were assumed to be determined by component geometry alone. This assumption was based on the hypothesis that, for posterior cruciate ligament-substituting implants with conforming tibial condyles, geometry outweighs other factors that may contribute to motion. Muscle and ligament forces, not considered in this kinematic model, are likely to influence implant motions; this is especially true when the knee replacement is less conforming.

An examination of knee motion with use of a mechanical simulator (5) and a recent cinefluoroscopic study (3) have confirmed that the normal knee exhibits rollback of the femur with knee flexion. If normal functions of the muscle and collateral ligaments are to be achieved after knee replacement, then it is important to avoid the loss of femoral rollback that was found to occur in our simulations when a posterior cruciate ligament-substituting tibial component was placed with posterior tilt. In addition to delaying rollback in the simulation, posterior tilting of posterior cruciate ligament-substituting tibial components confined the femoral component to the rear of the tibial plateau throughout the range of flexion, possibly promoting wear in the polyethylene by restricting contact to a smaller region of the plateau.

The simulation results suggest that the design and surgical placement of posterior cruciate ligament-substituting knee components should be decoupled. The implant designer can define the tibiofemoral contact point in extension by building a posterior slope into the tibial component geometry; the angle of flexion at which rollback is to begin may then be prescribed through the anteroposterior placement of the tibial spine. By contrast, a surgeon who posteriorly tilts a tibial component that has been designed to be implanted with neutral orientation may jeopardize femoral rollback by limiting interaction between the cam and spine. The surgeon, unlike the designer, lacks the ability to independently control both the tibiofemoral contact point location in extension and the angle of flexion at which cam-spine contact occurs. If some aspects of the performance of an implant can be improved by posteriorly tilting the tibial component surgically, then posterior slope should be incorporated into the design to preserve prosthetic function (contact between the cam and spine, in this case) that may be lost by tilting the entire component.

Orientation of the components in total knee replacement surgery has been reported to be subject to errors of as great as 4° (13). Because even small changes in component alignment can substantially alter the interaction between the cam and spine, it is important to minimize surgical error in sagittal plane tilt when placing a posterior cruciate ligament-substituting tibial component.

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