Kinematic Comparison of Posterior Cruciate Sacrifice Versus Substitution in a Mobile Bearing Total Knee Arthroplasty

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Abstract: Interest in mobile bearing total knee arthroplasty (TKA) has increased significantly. The objective of this in vivo study was to analyze 2 different mobile bearing TKAs during gait and during a knee bend from 0° to 90° flexion. Femorotibial contact positions for 10 subjects, implanted by a single surgeon, were analyzed using videofluoroscopy. Five subjects were implanted with a posterior-stabilized mobile bearing TKA (PS), and 5 subjects were implanted with a posterior cruciate–sacrificing mobile bearing TKA (PCS). Each subject, while under fluoroscopic surveillance, performed 2 weight-bearing activities: i) normal gait and ii) deep-knee bend. This study showed that the kinematic patterns for subjects having either a PS or PCS mobile bearing TKA were similar during gait but different during a deep-knee bend. Subjects having a PS TKA experienced more posterior femoral rollback of the lateral condyle during the deep-knee bend. Findings of kinematic similarities in gait and differences in a deep-knee bend between these 2 mobile bearing designs are similar to previously published findings of fixed bearing posterior cruciate–retaining and PS TKA. Key words: in vivo, fluoroscopy, kinematics, total knee arthroplasty.

Long-term clinical experience with the total condylar knee prosthesis has been satisfactory with survivorship rates of 91% to 94% at 15 to 21 years [1–3]. Insall, Lachiewicz, and Burstein [4] sought to improve clinical results and range of motion by adding a cam-and-post mechanism to the total condylar design. Published series confirmed satisfactory outcome of the Insall/Burstein design with survivorship of 94% to 98% at 14 to 16 years’ follow-up [5–8]. Callahan and Drake et al [9] evaluated multiple total knee arthroplasty (TKA) prostheses using a meta-analysis and found clinical results improved with the posterior-stabilized (PS) implant, and range of motion averaged 115°, which was statistically greater than that of the total condylar design.

Andriacchi, Galante, and Fermier [10] evaluated gait and stair climbing with posterior cruciate–sacrificing (PCS) and PS designs and found decreased flexion on stair climbing, suggesting a diminished extensor moment. Lesser constrained posterior cruciate–retaining (PCR) TKAs had more normal gait on stair climbing. Wilson and McCann et al [11] used more comprehensive electromyography data with gait analysis, however, and found that PS
designs were comparable to PCR prostheses but superior to PCS implants. Similarly, Mahoney and Noble et al [12] performed a cadaver mechanical study and found that the extensor mechanism efficiency was decreased 15% by posterior cruciate retention, 19% by cruciate sacrifice, and 12% by cruciate substitution.

Videofluoroscopy studies analyzed three-dimensional kinematic function of various TKA techniques, including posterior cruciate retention, sacrifice, and substitution. PCR unconstrained prostheses showed deviations from normal including posterior femorotibial contact in extension, anterior translation with flexion, and diminished weight bearing flexion compared with PCS designs [13–15]. In a follow-up study, a mobile bearing PCS design was evaluated using the same fluoroscopic technique, revealing that the femoral component remains midline during gait and each subject experienced a similar kinematic pattern [16]. It also has been determined that subjects having a PCS design experience a neutral or anterior position of the femoral component at full extension, with progressive posterior femoral rollback (PFR) being achieved with increasing knee flexion [14,15]. The purpose of this study was to compare the kinematics for subjects having either a PCS or PS mobile bearing TKA having the same geometrical features, implanted by the same surgeon with the same surgical technique.

**Methods**

Ten subjects, having either a PCS or PS mobile bearing TKA (LCS; DePuy, a Johnson & Johnson Co, Warsaw, IN), were asked to perform normal gait and a deep-knee bend from 0° to 90° knee flexion under fluoroscopic surveillance. All patients were examined using a high-frequency pulsed fluoroscopy unit (Radiological and Data Solutions, Minneapolis, MN) (Fig. 1). All 5 subjects who were implanted with a PCS TKA were male, and 4 of the 5 subjects (80%) implanted with a PS TKA were male. The average age for the subjects having a PCS TKA was 70 years (range, 71 to 79 years) and for subjects having a PS TKA was 70.2 years (range, 64 to 80 years). All subjects implanted with the LCS PS were diagnosed with osteoarthritis, and 3 of the 5 subjects (60%) in the PCS group were diagnosed with osteoarthritis. Subjects having a PCS TKA were implanted using a surgical technique that sacrifices the anterior and posterior cruciate ligaments, whereas the 5 subjects having a PS TKA received a modification of the PCS implant, in which posterior cruciate prosthetic substitution in the form of a cam-and-post mechanism was included. The articular geometries of the femoral component and the tibial inserts for the 2 different implants are identical. Each subject also was implanted using the same tibial base plate. The PS TKA was designed for the cam-and-post mechanism to engage at approximately 50° knee flexion, guiding posterior translation of the femoral component from 50° knee flexion to maximal flexion.

The surgical technique was standardized and required excision of the anterior and posterior cruciate ligaments. Ligament balancing was conducted during the surgery, and the proximal tibia was the first bone cut. The flexion space was prepared using an anterior cortical referencing guide and cutting block, which was positioned with a spacer. The distal femoral bone was cut last, using an intramedullary alignment guide. All implants were inserted with cement, and patellae were resurfaced.

All TKAs evaluated had a minimum of 6 months’ follow-up and were judged clinically successful with Knee Society clinical scores >90 with no evidence of clinical laxity, pain, or swelling. Each subject was asked to perform 2 weight-bearing activities while under fluoroscopic surveillance. Initially the subjects were asked to flex their prosthetic knee to maximal flexion (deep-knee bend), then to walk on an elevated platform while performing their normal gait. While performing the deep-knee bend, each subject was asked to stand and place the foot on a designated marker to position the knee correctly for imaging with the knee in full extension. The subject was asked to perform normal gait while the fluoroscopy unit was moved manually to capture the knee throughout the stance phase of gait.

![Fig. 1. Subject performing gait (left) and a deep-knee bend (right) while under fluoroscopic surveillance.](image-url)
Intensity-Based Image Registration Technique

The fluoroscopy images were stored on videotape for subsequent redigitization using a frame grabber. The contact position between the femur and tibia was determined using a 3-dimensional model-fitting technique [17–19]. The fluoroscopic images were captured onto a workstation computer. The 3-dimensional computer-aided design solid models of the femoral and tibial components were overlaid onto the 2-dimensional fluoroscopic perspective images using the intensity-based, 3-dimensional to 2-dimensional image registration (Fig. 2). When the computer had determined the best 3-dimensional fit of the femoral and tibial components, the components were rotated to pure sagittal views to determine the anteroposterior positioning of the medial and lateral condyles with respect to the midline of the tibia in the sagittal plane. A position anterior to the midline was denoted as positive, and a position posterior was denoted as negative. Axial rotation of the femoral component with respect to the tibial component was assessed in the coronal plane, with increasing internal rotation of the tibial component denoted as a positive rotation and external rotation as negative. Condylar lift-off of the femoral component was assessed in the frontal plane.

Two different error analyses were conducted to evaluate the accuracy of the model-fitting technique [17–19]. Using an apparatus that allowed for femoral translation and rotation to be dialed in at varying increments of knee flexion, it was determined that the translational accuracy was <0.5 mm and the rotational accuracy <0.5°. Using a fresh cadaver, 90 images were analyzed to determine if bone and soft tissue increase the error of the model-fitting process. The results from this study determined the accuracy of the model-fitting process to be <0.5 mm and <0.5° [18,19].

Results

Anterior-Posterior Femoral Tibial Translation

During the deep-knee bend, on average, subjects having the LCS rotating platform TKA showed PFR of their lateral condyle, while the medial condyle remained in a similar contact position (Fig. 3). On average, subjects having an LCS rotating platform TKA experienced 1.3 mm of PFR. During gait, on average, the same subjects experienced minimal motion of their medial and lateral condyles (Fig. 4 and Table 1). Although the anteroposterior contact position did move for both condyles, the actual motion was due to axial rotation of the mobile bearing polyethylene because the amount of medial condyle translation was offset by the same amount of lateral condyle motion in the opposite direction (Fig. 5 and Table 1).

During the deep-knee bend, on average, subjects having the LCS rotating platform PS TKA showed...
PFR of the medial and lateral condyles, occurring more with the lateral condyle (Fig. 6 and Table 2). On average, subjects having an LCS rotating platform PS TKA experienced 7.1 mm of PFR. During gait, on average, subjects having an LCS rotating platform PS TKA also experienced minimal motion of the medial and lateral condyles (Fig. 7 and Table 2). Similar to subjects having an LCS rotating platform TKA, subjects having the PS version also experienced axial rotation of the condyles, rotating through the center of the tibial stem.

**Tibiofemoral Axial Rotation**

The average amount of axial rotation for subjects having an LCS rotating platform TKA was 3.3° (range, 9.5° to −0.6°; SD, 4.7) of normal rotation (tibia internal rotation with increased knee flexion) during a deep-knee bend and −2.5° (range, 3.7° to −13.2°; SD, 6.4) of reverse rotation (tibia external rotation with increased knee flexion) during gait. The average amount of axial rotation for subjects having an LCS rotating platform PS TKA was 5.2° (range, 11.4° to −2.7°; SD, 7.2) of normal rotation during the deep-knee bend and 3.0° (range, 10.9° to −0.4°; SD, 4.6) of normal rotation during gait. Tables 3 and 4 summarize axial rotation values.

**Condylar Lift-Off**

All 5 subjects having an LCS rotating platform TKA and 4 of 5 subjects having a PS TKA experienced femoral condylar lift-off during both activities (Table 5). The maximal amount of condylar lift-off was 2.2 mm and 1.8 mm for subjects having an LCS rotating platform TKA during gait and a deep-knee bend. Subjects having an LCS rotating platform PS TKA experienced a maximal amount of lift-off of 2.1 mm and 3.3 mm during gait and a deep-knee bend (Fig. 8). The incidence of medial or lateral condylar lift-off was similar for both implant types. Tables 5 and 6 summarize femoral condylar lift-off values.

**Discussion**

The PS design used in this study is a prototype device that was developed using the original LCS femoral and tibial condylar geometries, with the only modification being the addition of a cam-and-post mechanism. From prior knowledge, the pri-
mary goals of this new design were to increase range of motion, improve extensor kinematics, and eliminate bearing spinout resulting from flexion instability. Except for the posterior stabilizer, the tibial polyethylene insert is interchangeable with the original rotating platform implant. The important advantage of the present study is that the only variable tested is the influence of the cam-and-post mechanism because all other variables are controlled.

Several studies have used in vivo, weight-bearing fluoroscopy to evaluate femorotibial kinematics after TKA. Dennis and Komistek et al [14] evaluated lateral condylar motion of PCS TKAs using a three-dimensional inverse perspective technique during a deep-knee bend and found that the lateral condyles started slightly anterior to the midline of the tibial sagittal plane in extension and had PFR with flexion similar to normal knees. They reported an average PFR of 7.7 mm, with the maximal amount being 12.3 mm. Stiehl and Dennis et al [16] evaluated the LCS PCS rotating platform implant with the same fluoroscopic technique and analysis and found that the implant showed minimal rollback from 0° to 60° flexion followed by mild anterior translation with increased knee flexion. All implants were noted to start posterior to the sagittal midline at full extension.

Banks, Markovich, and Hodge [20,21] evaluated a PCS design during a step-up activity and found a small amount of condylar translation (average, 2.9 mm). During gait, they reported that the condylar translations were more variable, but there were cases that exhibited kinematics similar to PCR TKAs with anterior translation before heel-strike followed by posterior translations during stance. They were not able to confirm posterior translations consistent with PFR.

Using a more sophisticated technique that accurately determined medial and lateral condylar positions of PS TKAs, Dennis and Komistek et al [15] found that the lateral condyle experienced consistent rollback, whereas the medial condyle often showed anterior translation from about 30° to 60° flexion. After that point, cam engagement with further flexion caused posterior condylar translation of the medial condyle. Crossett and Komistek et al [22] used in vivo fluoroscopy during the gait cycle for 2 different PS designs and found average anterior-posterior translation of 4.8 mm for the Congruency (DePuy, Inc, Warsaw, IN) and 5.5 mm for the Insall Burstein II (Zimmer, Warsaw, IN). Stiehl and Komistek et al [13] studied PCR TKAs and suggested the presence of lateral condylar lift-off in many subjects. This early study used a two-dimensional vector method, however, and evaluated only lateral condylar motion. Dennis and Komistek et al [23], using fluoroscopy, evaluated

### Table 2. Anteroposterior Femoral Tibial Translation for LCS RP PS (mm)

<table>
<thead>
<tr>
<th>Position</th>
<th>Deep-Knee Bend</th>
<th>Gait</th>
<th>Toe-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Extension</td>
<td>90° Flexion</td>
<td>Heel-Strike</td>
</tr>
<tr>
<td>Lateral</td>
<td>-0.6 (1.5 to 3.2)</td>
<td>-6.5 (-4.1 to 11.3)</td>
<td>-0.7 (1.1 to 1.7)</td>
</tr>
<tr>
<td>Medial</td>
<td>-0.5 (2.6 to 3.4)</td>
<td>-2.5 (1.3 to -6.5)</td>
<td>-1.0 (1.6 to -3.5)</td>
</tr>
</tbody>
</table>

NOTE. Values are mean (range).

### Table 3. Average Axial Rotation for Both Implant Types During Gait (°)

<table>
<thead>
<tr>
<th>Knee Type</th>
<th>Heel-Strike</th>
<th>Midstance</th>
<th>Toe-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCS RP</td>
<td>-2.3</td>
<td>-2.4</td>
<td>-3.8</td>
</tr>
<tr>
<td></td>
<td>(1.2 to -5.9)</td>
<td>(4.5 to -8.4)</td>
<td>(1.2 to -13.4)</td>
</tr>
<tr>
<td>LCS RP PS</td>
<td>-0.3</td>
<td>-1.5</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>(4.1 to -3.8)</td>
<td>(2.9 to -9.8)</td>
<td>(6.7 to -1.5)</td>
</tr>
</tbody>
</table>

NOTE. Values are mean (range).
bicondylar lift-off for subjects having PCR or PCS TKAs and found the occurrence of lateral or medial condylar lift-off for both implant types. Lateral condylar lift-off was seen at 0°, 30°, 60°, and 90° of flexion, and the maximal lateral lift-off was 1.4 mm. Medial condylar lift-off was seen at all degrees of flexion, and the greatest amount was 2.6 mm.

Stiehl and Dennis et al [24] evaluated condylar lift-off and screw-home rotation with the LCS rotating platform mobile bearing implant. Condylar lift-off was seen in 90% of cases, and medial condylar lift-off was more frequent than lateral. The greatest medial lift-off was 2.1 mm, whereas the greatest lateral lift-off was 3.5 mm. Screw-home rotation ranged from 9.6° (tibial internal rotation with knee flexion) to −6.2°. In at least 50% of patients, medial condylar lift-off was unexpectedly greater than lateral lift-off. There was no consistent relationship with either lift-off or rotation, and considerable variability was present. The lift-off values for the subjects in the present study were similar to the results previously published for subjects having the LCS rotating platform TKA [24]. Subjects in the present study experienced either medial or lateral condylar lift-off, which seems plausible because the anterior and posterior cruciate ligaments are sacrificed during surgery for both TKAs evaluated in this study. It has been hypothesized by Dennis and Komistek et al [23] that the anterior cruciate ligament resists lateral condyle lift-off because this ligament attaches to the lateral condyle of the femur, and the posterior cruciate ligament resists medial condyle lift-off because the ligament attaches to the medial condyle.

In the current study, subjects having either the LCS rotating platform or LCS PS TKA showed a contact position near the midline tibia in extension. Throughout stance phase of gait, subjects experienced axial rotation relative to the center of the tibial stem, which resulted in anteroposterior motion of the medial and lateral condyles, in the opposite direction of each other. During a deep-knee bend, subjects having an LCS rotating platform TKA experienced an anterior slide of the femoral component occurring at either 30° or 60° knee flexion. In contrast, subjects having an LCS rotating platform PS TKA experienced PFR of the medial and lateral condyles with increasing knee flexion. Subjects routinely experienced more PFR of their lateral condyle, which resulted in subjects achieving normal axial rotation patterns.

The LCS implant has high conformity to 30° flexion, which would explain the relatively neutral positioning in extension and gait. Femoral geometry changes on the posterior condyles with a diminishing radius of curvature, causing the tendency toward anterior translation in deeper flexion. Similar to PCR implants experiencing anterior translation with increased knee flexion, this movement could lead to extensor mechanism deficiency and diminished range of motion, but Kobori and

### Table 4. Average Axial Rotation for Both Implant Types During a Deep-Knee Bend (°)

<table>
<thead>
<tr>
<th>Knee Type</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCS RP</td>
<td>−4.8 (3.3 to −12.0)</td>
<td>−1.4 (6.7 to −10.7)</td>
<td>−0.1 (7.7 to −12.2)</td>
<td>−1.4 (8.9 to −10.9)</td>
</tr>
<tr>
<td>LCS RP PS</td>
<td>0.1 (2.2 to −3.4)</td>
<td>2.1 (6.1 to −2.3)</td>
<td>3.8 (8.8 to −2.2)</td>
<td>5.3 (16.6 to −2.8)</td>
</tr>
</tbody>
</table>

NOTE. Values are mean (range).

### Table 5. Maximum Amounts of Condylar Lift-Off for Both Implant Types During Gait (mm)

<table>
<thead>
<tr>
<th>Knee Type</th>
<th>Heel-Strike</th>
<th>Midstance</th>
<th>Toe-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCS RP</td>
<td>2.2</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>LCS RP PS</td>
<td>1.8</td>
<td>1.6</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Fig. 8. Maximal amount of condylar lift-off, occurring at 30° knee flexion during a deep-knee bend.
Komistek et al [25] reported range-of-motion values of 162° for Japanese subjects implanted with this TKA. Regarding articular wear and interface loading, the midline positioning for subjects having the LCS rotating platform and PS TKA, during gait, could be considered optimal.

The LCS implant analyzed in this study has a central cone-shaped peg that allows rotation about the center of the tibia but constrains any sagittal or coronal plane translation. Normal axial screw-home rotation was seen with the PS implant during the deep-knee bend and gait. The tibial implant rotated externally with increasing knee flexion, although there was a degree of lateral condylar translation in deep flexion. Subjects having the LCS rotating platform TKA experienced a normal axial screw-home rotation during a deep-knee bend but experienced reverse screw-home or tibial internal rotation during gait.

Both implants showed medial and lateral condylar lift-off. Because both implant types require sacrificing the anterior and posterior cruciate ligaments, the results from this study are similar to previous studies involving PCS or PS TKAs. PCR implants typically have shown a lesser tendency for the occurrence of medial condylar lift-off. Certain subjects in the present study had a tendency for lateral condylar lift-off to occur, whereas others were more susceptible to medial condylar lift-off.

### Conclusion

This study analyzes the kinematic performance of a mobile bearing TKA and compares the in vivo kinematics for subjects having either a cruciate-sacrifice or cruciate-substituting (with a cam-and-post mechanism) implant. The positioning of the femoral component for both implant types during gait tended to remain midline. During the deep-knee bend, subjects having a PS TKA experienced PFR, whereas subjects having a PCS TKA experienced paradoxical sliding of the femoral component in flexion to 90°. The addition of the cam-and-post mechanism seemed to induce the occurrence of PFR with increasing knee flexion. It could be assumed that the absence of femoral component sliding during gait for both implant types would lead to lower contact stress, which could lead to increased implant longevity. The inclusion of a cam-and-post mechanism for a mobile bearing TKA leads to better PFR with increased flexion, which may lead to better range of motion and more consistent knee kinematics during knee flexion activities.

### References


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**Table 6. Maximum Amounts of Condylar Lift-off for Both Implant Types During a Deep-Knee Bend (mm)**

<table>
<thead>
<tr>
<th>Knee Type</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCS RP</td>
<td>1.2</td>
<td>1.6</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>LCS RP PS</td>
<td>1.7</td>
<td>3.3</td>
<td>1.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>