Kinematics of the Patellofemoral Joint in Total Knee Arthroplasty

James B. Stiehl, MD,* Richard D. Komistek, MD,† Douglas A. Dennis, MD,† and Peter A. Keblrish, MD‡

Abstract: Sagittal plane patellofemoral kinematics was determined for 81 subjects while performing a weight-bearing deep knee bend under fluoroscopic surveillance. Fourteen normal knees, 12 anterior cruciate ligament (ACL)–deficient knees, and 55 total knee arthroplasties (TKAs) were assessed. Of TKAs, 39 had resurfacing with a dome-shaped patella, 8 had resurfacing with an anatomic mobile-bearing patella, and 8 were unresurfaced. TKA patellae experienced more superior patellofemoral contact and higher patellar tilt angles compared with the normal knees and ACL-deficient knees (P < .05). Patellofemoral separation at 5° (+3°) extension was seen in 86% cruciate-retaining and 44% cruciate-stabilized TKAs and 8% ACL-deficient knees but not in the normal knees or mobile-bearing TKAs (P < .05). The patellar kinematic patterns for subjects having a TKA were more variable than subjects having either a normal knee or an ACL-deficient knee. Kinematic abnormalities of the prosthetic patellofemoral joint may reduce the effective extensor moment after TKA. Key words: total knee arthroplasty, patella, kinematics, biomechanics.

Complications resulting from patellofemoral resurfacing are an important cause of revision in total knee arthroplasties (TKAs) [1–12]. In many cases, poor TKA kinematics and abnormal forces exerted on the prosthetic components may play a key role in wear, malalignment, or accelerated failure from associated design flaws [13–22]. Such complications have induced many surgeons to avoid patellar resurfacing in patients with osteoarthritis and good remaining articular cartilage [23–27]. Studies indicate, however, an increased incidence of revision without resurfacing, and secondary resurfacing may prove inferior to resurfacing at the time of TKA [28–32].

Mechanical analysis of the extensor mechanism of the knee indicates that the levering action of the patella is as important as its function as a spacer. Models have predicted substantial changes in force transmission through knee flexion by altering patellar ligament length and rotation in relation to the tibial axis. The effective moment arm of the extensor mechanism reflects not only the magnitude of forces in the quadriceps and patellar ligaments, but also their orientation [33–37].

Most previous experimental studies of the patella have involved in vitro analyses or have not tested the knee in the weight-bearing mode. The present study investigates in vivo weight-bearing patellofemoral kinematics in normal knees and in knees after TKA with and without patellar resurfacing by determining patellofemoral contact positions and angular patellar tilt in relation to the sagittal axis of the proximal tibia.
Methods

Using dynamic in vivo fluoroscopy with a 2-dimensional computer digitization technique, patellofemoral contact position, patellar tilt angle, and patellofemoral separation were determined for 81 patients [38,39]. Fourteen subjects had normal knees, 12 had anterior cruciate ligament-deficient (ACLD) knees, and 55 patients had TKAs. Of the TKA group, 14 had been implanted with a posterior cruciate-retaining (PCR) TKA, 25 had a posterior cruciate-substituting (PS) TKA, and 16 had a mobile-bearing posterior cruciate-sacrificing (MB) TKA. All PCR TKAs and PS TKAs had patellar resurfacing, whereas 8 MB TKAs were resurfaced, and 8 were unresurfaced. The prosthetic designs chosen for the study were the Press Fit Condylar PCR and PS designs (Johnson & Johnson, Inc, Raynham, MA) and the Low Contact Stress (LCS) rotating platform prosthesis (Depuy, Inc, Warsaw, IN). Great care was taken to make symmetric cuts of the patella to a hockey puck shape with an average thickness of 14 to 15 mm. The final patellar thickness after resurfacing was within 2 mm of the presection distance.

All surgical implantations were performed by 2 surgeons (P.A.K., D.A.D.) using standardized surgical techniques. All patients with TKA were considered clinically successful with excellent clinical rating scores and without significant pain or measurable instability. Fluoroscopic analysis was done by asking patients to stand with the knee in full extension and perform 3 weight-bearing deep knee bends. Sagittal plane fluoroscopy was done as the radiology technician carefully centered the knee on the screen.

Patellofemoral Contact Position

The contact position between the femur and patella was determined in the sagittal plane using 2-dimensional computer digitization. Designated points on the femoral, tibial, and patellar components were digitized with respect to the newtonian reference frame (Fig. 1). Initially, points P1, P2, P3, and P4 were digitized on the patella at 0°, 30°, 60°, and 90° of knee flexion. Two lines were constructed, the first line connecting points P1 and P2 and the second line connecting points P3 and P4. The midpoints of the lines P1–P2 and P3–P4 were found and denoted as points P5 and P6. After a line was constructed between points P5 and P6, the midpoint of this line was determined and denoted as the patellar mass center, point Pmass.

Fig. 1. A schematic detailing the points digitized on each fluoroscopic image. See text for details.

The contact point between the patella and the femur was determined by initially magnifying the fluoroscopic image by a factor of 3.5. The closest distance between the most anterior portion of the femoral component and the most posterior osseous portion of the patella was denoted as the contact point, point PF. The fluoroscopic image was reduced back to normal size, and the distance between the patellar mass center and the patellofemoral contact point was measured. This measured distance was scaled by a 1-inch metal ball attached to the patient’s leg. This calibrated distance was denoted as Q, the actual distance of the contact point from the patellar mass center. A patellofemoral contact point superior to the patellar mass center and the patellofemoral contact point was measured. This measured distance was scaled by a 1-inch metal ball attached to the patient’s leg. This calibrated distance was denoted as Q, the actual distance of the contact point from the patellar mass center. A patellofemoral contact point superior to the patellar mass center was denoted as positive, and contact inferior to the patellar mass center was denoted as a negative distance. Although there are 2 contact regions observed on the lateral and medial condyles as knee flexion proceeds, the patellofemoral contact, point PF, represented the estimated midpoint of the contact regions in the sagittal plane.
Patellar Tilt Angle

At 0°, 30°, 60°, and 90° of flexion, points T1 and T2 were digitized at the anterior margin of the tibial plateau and the anterior cortex of the tibial shaft. A line connecting points T1 and T2 was denoted as the longitudinal axis of the tibia. The angle between the longitudinal axes of the patella and tibia was measured and denoted as the patellar tilt angle. If the longitudinal axis was anterior to the longitudinal axis of the tibia, the patellar tilt angle was denoted as positive and referred to as patellar extension. If the longitudinal axis of the patella was posterior to the longitudinal axis of the tibia, the patellar tilt angle was denoted as negative and referred to as patellar flexion.

Patellofemoral Separation

Patellar components were fixed in the trochlear groove of femoral components. The distance between the most anterior portion of the femoral condyle and the dorsal portion of the flat-surfaced patellar component was measured and denoted as distance D (Fig. 2). Fluoroscopy images at full extension only were analyzed by measuring the distance (Δ) between the most posterior portion of the patellar component and the most anterior portion of the femoral component. The amount of patellofemoral separation was determined from the equation, Δ = D, then multiplied by the magnification conversion factor of 3.5. Patellar prosthetic thickness was known in all cases but was not figured into this calculation. When patellofemoral separation was observed in a subject, subsequent fluoroscopy images were viewed to determine the angle of knee flexion when the patella comes into contact with the femur.

Fig. 2. Implant components (left) and a fluoroscopic image (right) showing the technique used to determine patellofemoral separation.

Error Analysis

An error analysis was conducted using an apparatus that allowed for angles and distances to be changed in increments of 0.01° and 0.01 mm. Five implanted cadaver patellae were oriented into 18 different combinations of patellar tilt, separation, and patellofemoral contact points (Fig. 3). Although the analysis determined 2-dimensional patellar kinematics, the cadaver patellar and femoral components were abducted, adducted, internally rotated, and externally rotated relative to each other to simulate the out-of-plane rotations of the in vivo knee. The determined errors were 0.52° for patellar tilt, 0.71 mm for patellofemoral contact, and 0.38 mm for patellar separation.

Results

Patellofemoral Contact Position

The patellofemoral contact patterns were similar for all knee types (Fig. 4, Table 1). At full extension, the patellofemoral contact position was inferior to the mass center of the patella for all knees except for the resurfaced MB TKA (P < .05). For the normal and ACLD knees, the average distance from the contact position to the patellar mass center was −8 mm, whereas subjects having a PCR and PS fixed bearing and MB resurfaced TKAs were more superior at −1, −2 and 2 mm (P < .05; PCR fixed bearing and MB unresurfaced compared with normal). During knee flexion, the average contact position for all groups translated in the superior direction. There was greater variability in patellofemoral contact patterns for the implanted knees and the ACLD knees than normal knees, but the ACLD
contact positions were most similar to normal. For the dome-shaped devices of the PCR and PS TKAs, the average contact positions were more superior, at 90° flexion, compared with the normal, ACL-deficient and MB knees, but these results were not statistically different ($P > .05$). The MB resurfaced and unresurfaced TKAs experienced a significantly different patellofemoral contact position at 30° of knee flexion compared with the normal patella ($P < .05$). On average, from 30° to 90° of knee flexion, subjects having PCR and PS TKAs experienced similar contact positions, whereas subjects having either an unresurfaced or resurfaced patella experienced similar contact positions (Table 1).

**Patellar Tilt Angle**

On average, the patellae for all knee types were flexed in full extension and progressively extended (most inferior portion of the patella extending from the tibia) with increased knee flexion (Fig. 5, Table 2). There was not a statistical-difference in the patellar tilt angles for the 6 knee groups. At full extension, the normal ($-7°$), ACLD ($-6°$), PCR fixed bearing ($-6°$), and MB unresurfaced ($-7°$) patellae experienced the most similar patellar tilt angle. Although the PS fixed bearing and MB resurfaced patellae experienced a different average patellar tilt angle, the results were not statistically different ($P > .05$). The patellae of normal knees experienced an increase in extension with increasing knee flexion. The average patellar tilt angles for the normal knee were 0°, 5°, and 7° at 30°, 60°, and 90° of knee flexion. The ACLD knees had slightly greater patellar tilt angles than normal knees, which were 2°, 7°, and 12° at 30°, 60°, and 90° ($P > .05$). On average, subjects having an unresurfaced MB TKA patella experienced similar patellar tilt angles compared with the normal patella at 0°, 30°, and 60° but experienced a more extended angle of 14° at 90° of knee flexion. The average change in patellar tilt angle compared with the normal patella was substantially greater for the fixed bearing PCR and PS TKAs at 30°, 60°, and 90° of knee flexion ($P < .05$), and at 90° of knee flexion for subjects having a MB resurfaced patella ($P < .05$). The most significant difference in the patellar tilt angles, compared with the normal patella, occurred at 90° of flexion, where the angle for PCR and PS total knees was 25° and 26°, whereas the tilt angle for the resurfaced MB TKA was 20° (Fig. 6).
Patellofemoral Separation

At full extension, there was no measurable separation distance between the patella and femur for any normal knees or the MB TKAs, whether resurfaced or unresurfaced. Separation was seen in 1 of the ACLD knees, 86% of PCR TKAs ($P < .05$, compared with normal), and 44% of PS TKAs ($P < .05$, compared with normal). The maximum measured separation was 12.2 mm and 6.2 mm for PCR TKAs and PS TKAs (Fig. 7, Table 3). The average amount of separation for knees experiencing patellofemoral separation was 3.9 mm and 1.1 mm for PCR TKAs and PS TKAs. In knees showing patellofemoral separation, the patella contacted the trochlear groove of the femoral component at a mean of 5° ($\pm 3°$) of knee flexion.

Discussion

Numerous biomechanical studies have analyzed the patellofemoral joint and have suggested an important levering function as opposed to a simple pulley spacer [33-36]. Factors related to patellar kinematics are the comparison of the femorotibial and patellofemoral contact, the angular orientation of the patella, and the patellar ligament. The effective extensor moment arm increases with early flexion of the knee related to the posterior translation of femorotibial contact with rollback and the relative inferior patellofemoral contact position. With increasing flexion, the effective moment arm decreases because the patellar ligament swings posteriorly as the patella falls into the median femoral groove, reducing the actual moment arm. The patellofemoral contact migrates superiorly, decreasing the mechanical force advantage of the patella lever [34]. Increasing patellar thickness is important at <35° because most of the force is taken up by the quadriceps tendon. Conversely a thick patella does not affect the levering action of the patella at higher degrees of flexion. Patellar tendon length is important because increasing this length moves patellofemoral contact inferiorly, causing a greater moment arm and enhancing the levering of the quadriceps tendon. As a result, there is a higher patellar force concentration and a greater transmis-

![Fig. 5. Average patellar tilt angles versus knee flexion angle. (ACLD, anterior cruciate ligament deficient; PCR, posterior cruciate retaining; PS, posterior cruciate substituting.)](image)

<table>
<thead>
<tr>
<th>Flexion</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>−8 mm</td>
<td>−2 mm</td>
<td>5 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>ACLD</td>
<td>−8 mm</td>
<td>−4 mm</td>
<td>4 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>PCR fixed</td>
<td>−1 mm</td>
<td>3 mm</td>
<td>8 mm</td>
<td>9 mm</td>
</tr>
<tr>
<td>PS fixed</td>
<td>3 mm</td>
<td>6 mm</td>
<td>9 mm</td>
<td>$P &lt; .05$</td>
</tr>
<tr>
<td>MB unresurfaced</td>
<td>−6 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>MB resurfaced</td>
<td>2 mm</td>
<td>4 mm</td>
<td>4 mm</td>
<td>5 mm</td>
</tr>
</tbody>
</table>

NOTE. Statistically different values compared with normal are in **bold** and significance is shown in the last column. ACLD, anterior cruciate ligament deficient; PCR, posterior cruciate retaining; PS, posterior cruciate substituting; MB, mobile bearing; NS, not significant.
sion to the patellar ligament. At 82° of flexion in normal knees, the quadriceps tendon wraps around the distal femur, which rapidly reduces the amount of force transmitted through the patella and patellar tendon [37].

In TKA, in vitro studies evaluated sagittal plane patellofemoral contact area in normal knees and TKAs. Huberti and Hayes [40] evaluated 12 human cadaver knees finding distal patellofemoral contact at 20° flexion and proximal migration to the most...
proximal portion of the patella at 120° flexion. Takeuchi et al [41] studied patellofemoral contact in cadavers with 6 TKA types, finding an inconsistent superior or inferior shift of the contact area with flexion.

Stiehl et al [42] used dynamic videofluoroscopy under weight-bearing conditions to investigate sagittal plane patellofemoral kinematics in TKA. Patellar ligament rotation, which measures the angle formed by the patellar tendon and the longitudinal axis of the tibia, started at 16° extension in normal knees and progressed to 0°. Prosthetic knees had a decreased angle in extension, which also progressed to 0° with flexion. Patellar axis rotation, which compared the angle between the patellar tendon and the sagittal axis of the patella, increased with knee flexion in normal knees and TKAs but was greater than normal in TKAs in full flexion. Two abnormalities first identified in that study included abnormal patellar separation in full extension and a pie-shaped or wedge gap opening at the distal pole of the patella as the patellar prosthesis articulated on the more superior surface of the dome.

Stiehl et al [43] previously investigated the MB anatomic patella used in the current study, comparing the results with or without posterior cruciate ligament sacrifice. Patellofemoral contacts of both MB implants were similar to normal but tended to be more inferior with higher degrees of flexion, which contrasted with the superior position seen on dome-shaped implants. Patellar ligament rotation was lower than normal in the MB implants reflecting the posterior femorotibial contact in extension and anterior translation beyond 60° flexion. Patellar axis rotation angles were similar for normal knees and TKAs.

The analysis in the current study focused on the abnormalities identified in TKA from prior in vivo fluoroscopic weight-bearing studies (ie, altered patellofemoral contact, patellar tilt angle, and patellofemoral separation in early flexion). We chose to measure patellar tilt angle, which determines patellar axis rotation with respect to the longitudinal axis of the tibial as opposed to the patellar ligament. Prior studies showed little change in patellar axis rotation but significant alterations in the patellar ligament angle and the tendency for the distal patella to gap open from the distal femur, both of which could be shown by the patellar tilt angle [42].

In our study, patellofemoral contact position moved superiorly in normal and ACLD knees in virtually identical fashion. This finding is not surprising because the joint line is unchanged, the patella is anatomic for both, and the patellar retinacular ligaments remain normal. Abnormal ACLD femorotibial kinematics with posterior contact positioning may explain the patellofemoral separation seen in 1 case. Neither this posterior femorotibial contact nor the anterior translation with flexion seemed to affect patellofemoral contact position, however.

All TKAs experienced a more superior contact position at full extension through 30° of knee flexion, and this pattern continued for subjects having a fixed-bearing PCR or PS TKA at 60° and 90° of knee flexion. We can speculate that with PS TKAs, whether fixed or MB, that joint line elevation resulting from posterior cruciate disruption could cause a more superior contact, at least with early flexion. The MB resurfaced and unresurfaced patellae with the PS LCS implant had contact positions similar to normal knees at 60° and 90° flexion.

On average, the most superior overall patellofemoral contact pattern was determined for subjects having a PCR TKA. This observation is puzzling but may reflect the spherical shape of the dome prosthesis and concurrently certain nonanatomic features of the prosthetic femoral component. Another factor may be the relative line contact of domed implants that leads to a balancing of this contact position relative to the length of the patellar tendon and the joint line. Prior kinematic studies of PCR TKAs have shown consistently posterior femorotibial contact in extension and erratic anterior translation of the femorotibial contact with flexion, which may cause more superior patellofemoral contact [43,44]. It is known that the effective extensor moment arm is reduced in TKAs, but the exact roll of diminished patellar levering resulting from superior patellofemoral contact is unknown [34,35,45].

The patellar tilt angles of the domed patellae were similar with PCR or PS TKAs and were greater than normal knees or ACLD knees. This finding may reflect joint line elevation with posterior cruciate

### Table 3. Patellar Separation

<table>
<thead>
<tr>
<th>Separation</th>
<th>% of Total</th>
<th>Maximum Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ACLD</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>PCR fixed</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>PS fixed</td>
<td>11</td>
<td>25</td>
</tr>
<tr>
<td>MB unresurfaced</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>MB resurfaced</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>

ACLD, anterior cruciate ligament deficient; PCR, posterior cruciate retaining; PS, posterior cruciate substituting; MB, mobile bearing.
sacrifice or abnormal posterior femorotibial contact positioning seen with PCR knees. The patellar tilt angles of unresurfaced MB TKAs were most similar to normal knees. Subjects having a resurfaced MB TKA experienced larger patellar tilt angles compared with subjects having an unresurfaced MB TKA, but the values were lower than those determined for fixed-bearing TKAs having dome-shaped patellae. This difference may reflect the relative anatomic shape of the MB patella. In general, it could be stated that patellar tilt angles produced trends comparable to patellofemoral contact analysis with higher patellar tilt angles correlating with more superior patellofemoral contact. We have not accounted for alteration in patellar thickness or patellar tendon length after TKA, and the amount of joint line elevation was not determined.

Patellofemoral separation is a phenomenon that may be explained in part by femorotibial contact, which tends to be more posterior for TKAs and some ACLD knees. The highest incidence and magnitude of separation was seen in PCR TKAs, which may reflect absence of the anterior cruciate ligament and posterior femorotibial contact in extension. PS TKAs showed a substantial number with this finding, but only half the number seen with posterior cruciate retention. Dennis et al. [44] showed that femorotibial contact with PS TKA, on average, is more anterior than PCR TKA, which could explain this difference. None of the unresurfaced or resurfaced anatomic MB TKAs showed separation, comparable to normal knees. The clinical implication of patellofemoral separation is unknown but could explain certain clunks that some patients experience.

Conclusion

This study compared patellofemoral contact patterns and patellar tilt angles of patients with normal knees, ACL-deficient knees, and TKAs using an in vivo weight-bearing fluoroscopic analysis. Dome-shaped patellar prostheses showed the most abnormal results, with more superior patellofemoral contact and greater patellar tilt angles. These findings may be related to kinematic abnormalities and certain technical changes, such as joint line positioning and precise placement of the patellar prosthesis. Results of ACL-deficient knees and TKAs that retained normal patella or resurfaced with an anatomic shaped prosthesis were comparable to normal. This information is enlightening regarding the in vivo performance of the patella in TKA and will guide future studies that investigate problems with prosthetic patellar resurfacing.

References