Kinematic Analysis of a Posterior Cruciate Retaining Mobile-Bearing Total Knee Arthroplasty

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Abstract: Using video fluoroscopy, 10 subjects having a mobile-bearing posterior cruciate–retaining total knee arthroplasty were analyzed to determine their in vivo kinematic patterns. Under weight-bearing conditions, while in extension, the average contact position was posterior to the mid-tibia sagittal plane with posterior translation of both condyles to 60° of flexion, followed by anterior translation to 120° of flexion. Under non–weight-bearing conditions, the average condylar contact positions were significantly more anterior from full extension to 90° of knee flexion ($P=.01$). The average range of motion was 129° under non–weight-bearing conditions and 119° during weight-bearing. Although subjects in this study exhibited variable motion patterns, they are accommodated by the unconstrained optimized articulation of this highly conforming mobile-bearing implant. Key words: knee, kinematics, mobile bearing, cruciate retention.
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Mobile bearings have been used in total knee arthroplasty (TKA) to reduce elevated contact stresses known to be a factor in causing tibial polyethylene wear [1–7]. Surfaces were made to be highly conforming creating a more favorable, increased area of contact. The unconstrained mobility of these implants was desirable to reduce stresses and strains across fixation interfaces. The Low Contact Stress (LCS) knee prosthesis (DePuy, Warsaw, IN), the subject of this report, was originally designed with a tibial component that allowed for posterior cruciate retention (PCR) (meniscal bearing) or sacrifice (rotating platform) [3]. The femoral component was designed with polycentric radii of curvature that approximated the condylar shape of the normal distal femur. Clinical reports have demonstrated comparable midterm clinical results with either PCR or sacrifice using this implant, and osteolysis has been a rare event [2,4,5,7]. With longer follow-up beyond 10 years, investigators found increasing rates of fracture, wear, and dislocation of the original meniscal bearings as compared with the rotating platform tibial insert [1,3]. The rotating platform originally was developed for more difficult cases, and early clinical results with this implant may have been biased from that factor [7]. However, the implant gained increasing popularity because long-term results have been shown to be durable even in younger patients, and the surgical technique is generally simpler with less technical challenge [7,8].

The LCS anteroposterior (AP) glide tibial insert was a later modification of the rotating platform that incorporated a control-arm mechanism to articulate with the cone-shaped insert tibial stem. By
allowing unconstrained sagittal plane motion, this device could then be inserted with PCR, which continues to be a desirable technique for preservation of function while minimizing anatomical alterations such as joint line elevation. Clinical investigations with this implant have been favorable, although few published reports exist at this time. Because of the unique mechanical design, we believed that further kinematic studies were needed before widespread use could be advocated.

Video fluoroscopy, skeletal pin placement with gait analysis, and computer photogrammetry have been used to characterize in vivo joint kinematics [8–19]. We have used computer vector analysis to determine femoral-tibial contact points through weight-bearing range of motion [20]. More recently, we have used automated 3-dimensional computer-aided design matching of the particular implants, resulting in more accurate spatial resolution with regard to AP femorotibial contact, condylar rotation, and condylar liftoff [10,16,18]. The purpose of this study was to evaluate the kinematics of the LCS AP-glade mobile-bearing TKA with retention of the posterior cruciate ligament under in vivo weight-bearing and non-weight-bearing conditions, using fluoroscopy and our current iterative model-fitting technique. Patients were chosen on the basis of satisfactory clinical outcomes, being judged as stable and having well-aligned components.

Materials and Methods

Knee kinematics were assessed for 10 subjects implanted with a LCS AP Glide mobile-bearing TKA (DePuy International, Leeds, England), which was designed for PCR. All TKAs were judged clinically successful (Hospital for Special Surgery Rating Scores >90), with no ligamentous laxity or pain. The operative procedures were performed by one surgeon (R.J.O.), who used an identical technique previously described for this PCR system. All surgeries were performed using a PCR technique with initial resection of the proximal tibia, followed with ligament and soft-tissue balancing in extension. The tibial cut used an extramedullary guide and was determined to be perpendicular to the longitudinal axis of the lower extremity with the posterior slope parallel to the original anatomy. The insertion of the posterior cruciate ligament was protected with a preserved bone block. A femoral anterior cortical reference and a positioner and spacer that referenced the cut tibial surface determined the femoral rotation and balanced the ligaments in flexion. The 15° posterior sloped distal femoral cut and the femoral valgus angle were set by an intramedullary alignment guide. The sloped distal femoral cut is necessary to accommodate the unique shape of the LCS femoral component. The technique requires careful attention to matching the flexion to the extension gap using block spacers [4,5,7].

Each subject was asked to perform 2 activities: (1) weight-bearing deep knee bends to maximum flexion, and (2) a non-weight-bearing bend to maximum flexion. During the weight-bearing deep knee bend, each subject placed the foot of the leg to be studied on a designated marker. The subjects were initially fluoroscopyed at full extension and throughout the flexion cycle (Fig. 1A). While under non-weight-bearing conditions, the leg to be analyzed was passively manipulated to maximum knee flexion (Fig. 1B). Patients were examined using a Siemens Siremobil 2000 Digital X-ray image intensifier.
system (Iselin, NJ). The fluoroscopic images were stored on videotape for subsequent redigitization using a frame grabber. Weight-bearing and non-weight-bearing knee kinematics was analyzed for all 10 subjects using the RMMRL model-fitting software package. Using a model-fitting approach, the relative pose of knee implant components was determined in 3 dimensions from a single-perspective fluoroscopic image by manipulating a CAD model in 3-dimensional (3D) space [10,20,21].

Individual fluoroscopic frames at specified degrees of flexion were digitized. The images were projected onto the image plane and the corresponding implant models added to the scene. The operator manipulated the models to create an accurate fit. The correct fit was achieved when the silhouettes of the femoral and tibial implant components perfectly matched the corresponding components in the fluoroscopic image (Fig. 2). The pose of each component then was recorded and each measurement of interest was extracted using a CAD-modeling program. The process was performed at the flexion angles of 0°, 30°, 60°, 90°, and 120° to determine knee kinematics (AP contact, axial rotation, and condylar lift-off). The distances from the medial and lateral condyles to the tibia plateau were measured, and the difference between these 2 measurements was used to determine condylar lift-off.

An error analysis was conducted using a fresh cadaver [22,23]. Discrete points were defined on the femoral and tibial components. Using an Optitrack system, these points were digitized and the femur was defined relative to the tibia, in the tibial reference frame. Each orientation of the femur, relative to the tibia, was fluoroscopyed. Using the 3D model-fitting software package, the relative orientation of the femur with respect to the tibia was predicted and compared with the known orientation determined using the Optitrack system. The relative error, derived for 75 orientations, was consistently <0.5° in rotation and 0.5 mm in translation.

**Results**

**AP Translation**

Under weight-bearing conditions, on average, the subjects experienced a posterior contact of the medial (average, −2.7 mm; range, 2.0 mm to −6.7 mm) and lateral (average, −6.3 mm; range, 0.2 mm to −12.3 mm) condyles at full extension (Fig. 3). From full extension to 30° of knee flexion, on average, both condyles moved in the posterior direction to a medial contact position of −5.5 mm (−1.5 to −10.2) and lateral of −9.3 mm (−5.6 to −12.8). At 60° of knee flexion, both condyles moved in the anterior direction to an average medial position of −4.1 mm (1.8 to −8.3) and lateral position of −7.9 mm (−4.2 to −10.2). At 90° of knee flexion, on average, both condyles experienced minimal motion change with a medial condyle contact position of −4.5 (1.2 to −19.3) and lateral position of −7.2 mm (−3.6 to −16.0). At 120° of knee flexion, on average, both condyles experienced an anterior change in contact position to a final medial position of −1.1 mm (2.6 to −3.3) and lateral position of −4.0 mm (−0.3 to −6.8). Nine of 10 subjects were able to achieve at least 120° of knee flexion under weight-bearing condi-
tions. Only 4 of the subjects experienced a posterior motion of their medial condyles from full extension to 120° of knee flexion, whereas all subjects experienced an anterior motion of their lateral condyles.

Under non–weight-bearing conditions, on average, subjects experienced a posterior contact of the medial (average, −1.8 mm; range, 1.7 mm to −4.1 mm) and lateral (average, −3.2 mm; range, 0.7 mm to −7.3 mm) condyles at full extension (Fig. 4). From full extension to 30° of knee flexion, on average, the medial contact position moved in the anterior direction to −1.2 mm (3.5 to −4.1), whereas the lateral condyle contact position moved in the posterior direction to −3.4 mm (2.3 to −9.8). At 60° of knee flexion, both condyles moved in the anterior direction. Both condyles experienced an anterior contact position, where the average medial contact position was 3.4 mm (14.9 to −3.2) and lateral contact position was 0.2 mm (6.9 to −5.1).

At 90° of knee flexion, on average, both condyles again experienced an anterior contact position. On average, the medial condyle contact position was 3.5 mm (15.7 to −4.3) and lateral position was 0.5 mm (6.9 to −4.7). At 120° of knee flexion, on average, both condyles experienced a posterior change in contact position to a final medial position of −0.3 mm (12.6 to −11.2) and lateral position of −3.0 mm (4.4 to −8.2). All of the subjects were able to achieve at least 120° of knee flexion under non–weight-bearing conditions. Five of the subjects experienced a posterior motion of their medial condyles from full extension to 120° of knee flexion, and 6 of the 10 subjects experienced posterior femoral rollback of their lateral condyles.

From full extension to 90° of knee flexion, the average AP contact position for the subjects in this
study were significantly more anterior under non-weight-bearing conditions compared with weight-bearing conditions (Figs. 5 and 6). At 120° of knee flexion, the average contact positions during weight-bearing and non-weight-bearing conditions were similar. Using a Student t-test, the AP position data were statistically different for the lateral condyle at full extension ($P=0.02$), the medial ($P=0.009$) and lateral ($P=0.003$) at 30° of knee flexion, the medial ($P=0.0002$) and lateral ($P=0.0001$) at 60° of knee flexion, and the medial ($P=0.001$) and lateral ($P=0.001$) condyles at 90° of knee flexion. There was no statistical difference in the position data at 120° of knee flexion. The average variance for the weight-bearing data was 14.07 compared with an average variance of 19.58 for the non-weight-bearing data.

**Axial Tibial-Femoral Rotation**

On average, the subjects experienced normal axial rotation during non-weight-bearing knee flexion, but opposite axial rotation during a weight-bearing deep knee bends. During non-weight-bearing knee flexion, the average axial rotation from full extension to 120° of knee flexion was 1.8° ($-9.1$ to $10.8$) (Fig. 7). Under weight-bearing conditions, the average axial rotation was $-2.0°$ ($-11.9$ to $1.6$) (Fig. 8). Under non-weight-bearing conditions, 7 of 10 subjects experienced a normal axial rotation pattern from full extension to 120° of knee flexion, whereas under weight-bearing conditions, only 4 of 9 subjects (1 subject did not achieve 120° of knee flexion) experienced a normal axial rotation pattern. Under non-weight-bearing condi-

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**Fig. 5.** Example of a subject under weight-bearing conditions displaying a posterior contact position. Shown is (A) the fluoroscopic image, (B) the 3D overlay, and (C) the sagittal view.

**Fig. 6.** Example of a subject under non-weight-bearing conditions displaying an anterior contact position. Shown is (A) the fluoroscopic image, (B) the 3D overlay, and (C) the sagittal view.
tions, on average, subjects experienced a normal axial rotation pattern from full extension to 30° of knee flexion (1.1°), from 30° to 60° of knee flexion (1.4°) and from 90° to 120° of knee flexion (1.0°). From 60° to 90° of knee flexion, on average, these subjects experienced −0.4° of opposite axial rotation while performing non–weight-bearing knee flexion. Under weight-bearing conditions, on average, subjects experienced a normal axial rotation pattern from full extension to 30° of knee flexion (0.3°). From 30° to 90° of knee flexion, subjects experienced no axial rotation. From 60° to 90° of knee flexion, subjects experienced an average opposite axial rotation pattern of −1.4°, and from 60° to 90° of knee flexion, on average, opposite axial rotation pattern of −2.6°.

Using a Student t-test, the axial rotation was statistically different for weight-bearing vs non–weight-bearing conditions at full extension ($P=0.03$), but was not statistically different at the other flexion angles ($P=0.31$ at 30°, $P=0.58$ at 60°, $P=0.74$ at 90°, and $P=0.69$ at 120°).

### Condylar Lift-off

Nine of 10 subjects experienced condylar lift-off during weight-bearing and non–weight-bearing conditions. Under non–weight-bearing conditions, the maximum amount of condylar lift-off was 2.5 mm, which was lateral condyle lift-off occurring at 60° of knee flexion. Under weight-bearing conditions, the maximum amount of condylar lift-off was
3.3 mm, which again was lateral condyle lift-off, occurring at 30° of knee flexion. Under non-weight-bearing conditions, 4 subjects experienced >1.0 mm of condylar lift-off just after full extension, 3 of 10 subjects at 30° of knee flexion, 3 of 10 subjects at 60° of knee flexion, 2 of 10 subjects at 90° of knee flexion, and 5 of 10 subjects at 120° of knee flexion. Under weight-bearing conditions, only 1 subject experienced >1.0 mm of condylar lift-off just after full extension, 4 of 10 subjects at 30° of knee flexion, no subjects at 60° of knee flexion, only 1 of 10 subjects at 90° of knee flexion, and only 1 of 10 subjects at 120° of knee flexion. Therefore, although 1 subject experienced >3.0 mm of condylar lift-off during weight-bearing conditions, the incidence and magnitude of condylar lift-off was greater during non-weight-bearing conditions.

**Range of Motion**

The average non-weight-bearing range of motion was 129.3° (120°–138°). The average weight-bearing range of motion was 118.8° (84°–135°). If the 1 subject who only achieved 84° of weight-bearing range of motion was removed, the average weight-bearing range of motion increased to 122.7°.

**Discussion**

PCR as a surgical technique in TKA has been advocated to improve clinical function, optimize transmission of forces across interfaces, and limit anatomical distortion such as joint line elevation [24–33]. However, recent concern has grown regarding articular surface wear of certain “flat-on-flat” PCR TKAs [34]. Line contact in these designs can cause high contact stress known to aggravate articular surface wear, particularly if increased sliding distances occur with function. Kinematic studies of femoral tibial contact using video fluoroscopy and Roentgen photogrammetry have demonstrated significant aberrations from the normal condition [16,17] Stiehl et al. defined abnormal lateral condyle motion in PCR TKAs with femoral tibial sagittal plane contact found to be posterior in extension followed by abnormal anterior translation with flexion on deep knee bend [19].

Dennis et al. refined the 2D method to a 3D computer-iterative, model-fitting method that allowed both condyles to be measured in each position [10]. Again, the lateral femoral tibial contacts were noted to be posterior in extension with irregular anterior translation on weight-bearing flexion. The primary cause of this alteration was reasoned to be anterior cruciate ligament deficiency as demonstrated by similar changes in anterior cruciate–deficient knees. In a subsequent study that evaluated both medial and lateral condyle position, Dennis et al. found anterior translation of both condyles >3 mm in the majority. Furthermore, these abnormalities were not diminished with the addition of a more dished or lipped insert [11]. Banks et al., using slightly different in vivo fluoroscopic analysis, confirmed that virtually all femoral tibial contact positions were posterior of the sagittal plane tibial midline [9]. When evaluating motion from flexion to extension with gait, most PCR total knees showed posterior translation.

Stiehl et al. evaluated the LCS meniscal-bearing PCR prosthesis and found posterior contact in extension compared with normal, but some degree of posterior femoral rollback up to 60° of flexion [8,15] With deep knee bend, there was anterior translation of femoral tibial contacts from 60° to 90° of flexion. The early femoral rollback seen with the meniscal-bearing prosthesis was attributed to the high articular conformity noted from 0° to 40° flexion. Nilsson et al., using RSA with 15-N joint loads, found a similar result with a posterior contact in extension, followed by gradual anterior translation with flexion to 50° [14].

The LCS AP-glide prosthesis demonstrated a posterior position of both condyles at full extension, followed by mild posterior translation or femoral rollback to 30° flexion, followed by anterior translation up to 120° flexion. This anterior position and translation was significantly greater from 0° to 90° flexion in non-weight-bearing knees. We hypothesize that this difference reflects the posterior tibial shear force exerted with active weight-bearing. With a flexion position of 120°, the femoral tibial contact points were similar under weight-bearing and non-weight-bearing conditions.

Stiehl et al. found significant condylar lift-off and screw home rotation with the LCS posterior cruciate-sacrificing rotating platform TKA [18]. They found a maximal medial condyle lift-off of 2.1 mm, whereas the greatest lateral lift-off was 3.5 mm. Screw home rotation was variable, ranging from 9.6° of tibial internal rotation with knee flexion to 6.2° of external rotation. Nilsson et al. investigated the LCS meniscal-bearing total knee prosthesis and found that initial extension started with a more externally rotated tibia than normal and had minimal internal rotation during flexion [14]. As previously suggested by Jonsson et al. and Karrholm et al., this may represent an alteration demonstrated by anterior cruciate–deficient total knees [35–36].
In the current study, the greatest amount of condylar lift-off occurred with the lateral condyle at 30° flexion, and 9 of 10 patients experienced condylar lift-off. For screw home rotation, a similar variability was noted as compared with the previous LCS rotating platform study. Under non-weight-bearing conditions, the total knees analyzed in this study had a range of 10.8° of internal tibial rotation to 9.1° of external tibial rotation, with increasing flexion. Under weight-bearing conditions, only 4 of 9 subjects experience normal axial rotation, with 1 knee having external tibial rotation of 11.9°. The important findings of altered rotation and condylar lift-off relate to the need for contemporary total knee designs to accommodate these kinematic functions. The LCS AP-glide prosthesis is rotationally unconstrained and allows for condylar lift-off in the frontal plane without sacrificing conformity or developing edge loading.

Dennis et al. previously evaluated non–weight-bearing versus weight-bearing range of motion with posterior cruciate and posterior stabilized fixed-bearing TKA [37]. The average weight-bearing flexion in that study was 103° for the PCR fixed-bearing TKA and 113° for the posterior stabilized fixed-bearing TKA. The present study demonstrated substantially greater flexion compared with a fixed-bearing PCR TKA with an average non-weight-bearing flexion of 130° and weight-bearing of 119°. We attribute this finding to at least 2 potential factors. The surgical technique was optimized by a highly experienced surgeon with subtle balancing of each knee. This may be confirmed by the fact that none of our knees were tight in flexion with persistent posterior femoral tibial contact, and all demonstrated laxity to allow anterior translation. Secondly, patient selection for this study was optimized where patients with severe deformity and decreased postoperative motion were not considered. From our previous studies, it is likely that greater range of motion may be expected with a well-done PCR technique compared with the cruciate-sacrificing rotation platform prosthesis [20].

The final issue of this analysis is the potential safety of the AP-glide prosthesis compared with earlier devices. Anterior soft-tissue impingement has been noted anecdotally by European surgeons who have used this implant, which has led to the recommendation of fat pad excision. The AP-glide prosthesis is totally unconstrained in the sagittal plane, and this study has shown the potential for anterior translation in the non–weight-bearing condition. Flexion space balancing must be accurate and not too tight to allow adequate flexion; however, if it is too loose, it may allow for abnormal anterior translation. Another problem has been potential instability that may result from posterior cruciate disruption. Surgeons have preserved a bone block at the insertion of the posterior cruciate ligament to prevent late ligament failure. From the current study, such an abnormally increased flexion gap could lead to abnormal AP motion and clinical symptoms requiring revision.

In conclusion, this study has investigated the kinematics of a PCR mobile-bearing total prosthesis, finding typical abnormal AP translation, condylar lift-off, and screw home rotation compared with other reports [15,18]. Range of motion and potential instability were greater under non–weight-bearing conditions, clearly demonstrating the difference that load bearing adds to these functions. Because this prosthesis is unconstrained with sagittal plane translation or rotation and relies primarily on ligamentous balancing for proper articulation, surgical technique with appropriate extension and flexion spacing must be performed. We have shown that goal to be achievable with this prosthesis.

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