In Vivo Determination of Total Knee Arthroplasty Kinematics

A Multicenter Analysis of an Asymmetrical Posterior Cruciate Retaining Total Knee Arthroplasty

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Abstract: The objective of this study was to determine if consistent posterior femoral rollback of an asymmetrical posterior cruciate retaining (PCR) total knee arthroplasty was mostly influenced by the implant design, surgical technique, or presence of a well-functioning posterior cruciate ligament (PCL). Three-dimensional femorotibial kinematics was determined for 80 subjects implanted by 3 surgeons, and each subject was evaluated under fluoroscopic surveillance during a deep knee bend. All subjects in this present study having an intact PCL had a well-functioning PCR knee and experienced normal kinematic patterns, although less in magnitude than the normal knee. In addition, a surprising finding was that, on average, subjects without a PCL still achieved posterior femoral rollback from full extension to maximum knee flexion. The findings in this study revealed that implant design did contribute to the normal kinematics demonstrated by subjects having this asymmetrical PCR total knee arthroplasty. **Key words:** knee, arthroplasty, kinematics, in vivo, fluoroscopy, implant design.

Under fluoroscopic analysis, normal knee kinematic patterns varied considerably in subjects having a total knee arthroplasty (TKA). These findings are supported in studies using in vitro analyses or those using external markers associated with gait laboratory systems [1-20]. It has been reported that the normal knee experiences more posterior motion of the lateral condyle and internal rotation of the tibia with respect to the femur with increasing knee flexion [4,18,19]. In contrast to the normal knee, in vivo kinematic analyses have reported that subjects having an implanted prosthetic knee, especially those having a posterior cruciate retaining (PCR) TKA with symmetrical condylar radii, often experience a motion pattern opposite of the normal knee where the condyles slide in the anterior direction [4,6-9,11,15,17,21,22]. These previous in vivo kinematic studies have also documented the occurrence of axial rotational patterns that are opposite of the normal knee [16,17], shown that condylar liftoff can occur in TKA [4,5,8,10,12], and determined that subjects having a TKA experience a decreased weight-bearing range of motion compared with that of the normal knee [20].

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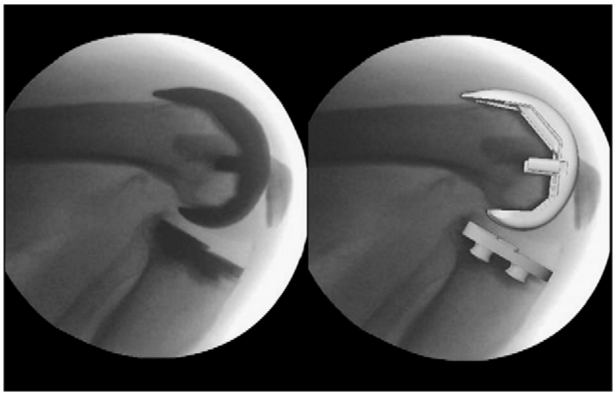

Fig. 1. The fluoroscopic image is brought into the computer scene (left), and the 3D femoral and tibial components are overlaid onto the 2D fluoroscopic image (right).

Although previous in vivo analyses of TKA kinematics have reported variable kinematic patterns that can be opposite in pattern to those derived for the normal knee, a single-surgeon analysis conducted on subjects implanted with a PCR TKA having asymmetrical condyles reported kinematic patterns more similar to the normal knee [13]. The prosthesis analyzed in this single-surgeon series had asymmetrical condylar radii, with the lateral condyle having a larger radius than the medial condyle. Therefore, the main difference between the PCR TKA analyzed in the above-mentioned single-surgeon series study compared with other PCR TKAs is the asymmetrical femoral condylar radii [23]. In the previous single-surgeon study, a null hypothesis was chosen that subjects having an asymmetrical condylar knee would achieve similar kinematic patterns to those subjects having a symmetrical condylar knee. Unexpectedly, the results from this study revealed a high incidence of posterior femoral rollback (PFR), leading to the acceptance of the alternative hypothesis that the subjects having an asymmetrical condylar knee routinely achieved PFR [13]. The results from this study revealed an important finding but led to new questions as to what factors most influenced the kinematic patterns that were more similar to the normal knee than those previously determined for subjects having a PCR TKA with symmetrical condyles.

Therefore, the objective of this present study was to conduct a follow-up analysis to verify if the results in subjects having a PCR TKA implanted by multiple surgeons would be similar to those reported in our earlier single-surgeon study. This present follow-up study was conducted to determine which of the following factors contribute to more normal kinematic patterns for subjects having a PCR TKA with asymmetrical condyles: (1) surgical technique, (2) implant design, (3) surgeon experience, (4) the effectiveness of the posterior cruciate ligament (PCL), or (5) a combination of numerous factors. A null hypothesis is initially chosen for statistical purposes that the implant design does not influence PFR and the kinematics for subjects in this study will mainly be influenced by surgical technique and/or surgeon experience.

Materials and Methods

In vivo knee kinematics was assessed for 80 subjects who were implanted with a PCR TKA having asymmetrical condylar radii (NexGen CR, Zimmer, Warsaw, Ind). This was a multicenter study involving 3 surgeons. Each of the 3 surgeons provided 20 subjects having the same asymmetrical PCR TKA, implanted with a well-functioning PCL; and one surgeon also contributed 20 subjects having the same PCR TKA, but without a PCL. In 20 subjects, this surgeon chose to use a PCR TKA, although the PCL was removed at the time of surgery. The PCL was removed in these cases because it was excessively tight or associated with a fracture of the tibial island at the PCL insertion sight. In the other 60 subjects, the PCL was deemed functional at the time of surgery through a clinical assessment of PCL tension and overall knee motion, resulting in PFR of the condyles during passive flexion. Institutional review board approval was obtained for each of the centers involved, as well as informed consent for all patients participating in the study (IRB# 1122, 02-ORTHO2, and 02101102). The flexion and extension gaps were balanced, and a standard cruciate retaining prosthesis was implanted. All subjects had well-func-

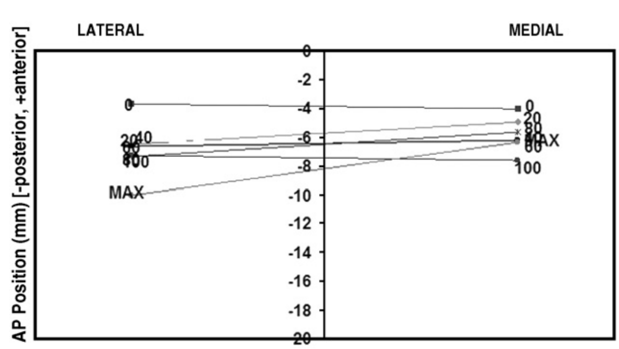

Fig. 2. Average A/P contact position for subjects implanted by surgeon 1 (with a PCL).

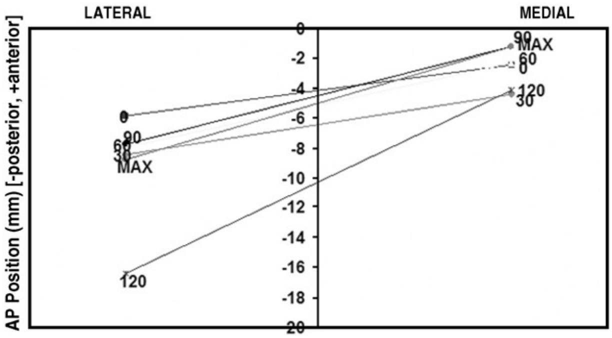

Fig. 3. Average A/P contact position for subjects implanted by surgeon 2.

tioning TKAs and were judged clinically successful (Hospital for Special Surgery scores >90) [24], with no ligamentous laxity or pain. Each subject was at least 6 months postoperation, weighed 250 lb or less, and was able to flex their knee to at least 115° under passive conditions. The average preoperative range of motion was 115° (90° to 135°), 103° (80° to 120°), and 110° (90° to 130°) for surgeons 1, 2, and 3, respectively.

Fluoroscopic evaluations were performed on all 80 subjects, while performing a deep knee bend to maximum knee flexion, at the 3 chosen sites previously described [4-16]. One research engineer traveled to the designated sites and conducted the fluoroscopic examinations. Each subject was asked to perform successive deep knee bends. Patients were examined using a C-arm type fluoroscopic unit. The fluoroscopic images were stored on videotape for subsequent redigitization and analysis.

Model Fitting

Using a three-dimensional (3D) model-fitting approach, the relative pose of knee implant components was determined in 3D from a single-perspective fluoroscopic image by manipulating a computer-aided design model in 3D space [25]. A 3D scene of the fluoroscopic unit was created on a Silicon Graphics Indigo (Mountain View, Calif) workstation in C++ using the Open Inventor Toolkit (Silicon Graphics) library. AutoCAD (San Rafael, Calif) was used to extract measurements. The scene consisted of a light source (x-ray), an image plane on which to project the fluoroscopic image (image intensifier), an area to manipulate a 3D model (subject area), and a camera to view the entire scene.

Individual fluoroscopic frames at specified degrees of flexion were digitized. The images were projected onto the image plane, and the corresponding implant models were added to the scene. Initially, the operator manipulated the models into position; and then the computer determined an accurate fit. The correct fit was achieved when the silhouettes of the femoral and tibial implant components best matched the corresponding components in the fluoroscopic image (Fig. 1). The pose of each component was then recorded, and measurements of interest were extracted using a computer-aided design modeling program. The process was performed at full extension, 30° of knee flexion, 60° of knee flexion, and 90° and maximum knee flexion. Anterior/posterior (A/P) contact positions for both the medial and lateral condyles and the axial rotation of the femoral component relative to the tibial component were assessed. Femorotibial contact anterior to the midcoronal plane of the tibial articular surface was denoted as positive, and posterior contact was denoted as negative [15]. To determine *axial rotation*, which was defined as the amount of femorotibial rotation from full extension to maximum knee flexion, a line was created from the medial condylar contact point to the lateral condylar contact point. A second line was then constructed, bisecting the center of the tibial plateau in the coronal plane. The angle created between these 2 lines was measured and denoted as the axial rotation angle. If the lateral condylar contact position was more anterior than the medial condylar contact position, then the axial rotation angle was denoted as negative. If the medial condylar contact point was more anterior than the lateral condylar contact point, the axial rotation angle was denoted as positive [16].

Error Analysis

An error analysis was conducted using a fresh cadaver. Discrete points were defined on the femoral and tibial components. Using an Optotrack system

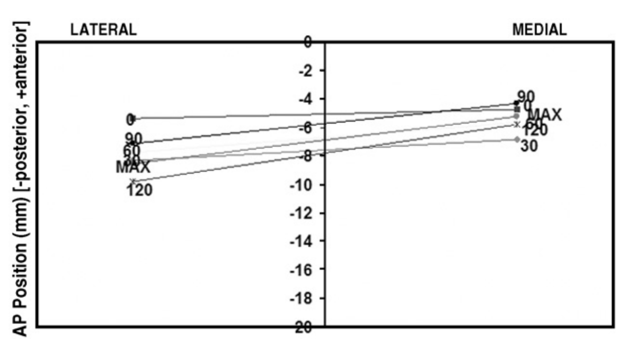

Fig. 4. Average A/P contact position for subjects implanted by surgeon 3.

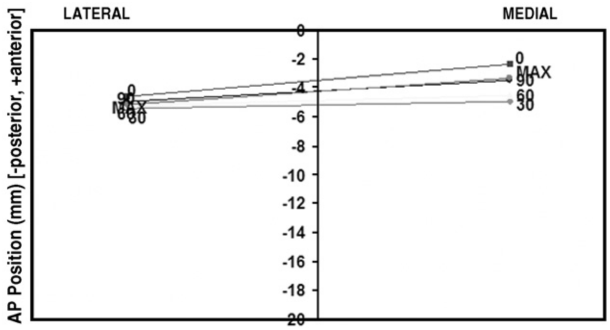

Fig. 5. Average A/P contact position for subjects implanted by surgeon 1 (no PCL).

(Northern Digital, Inc, Waterloo, Ontario, Canada), 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 fluoroscoped. 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 Optotrack system. The relative error derived for 75 orientations was consistently less than 0.5° in rotation and 0.5 mm in translation [25].

Statistical Methods

A statistical analysis was conducted using the nonparametric Kruskal-Wallis method, which makes no assumptions of the sample distribution. Two statistical tests were conducted to determine statistical differences in the data. The first statistical analysis was conducted to determine if the role of the PCL is statistically significant, influencing TKA kinematics. This analysis was conducted using data from the 2 groups implanted by surgeon 1: (1) the well-functioning PCL subjects and (2) the subjects not having a PCL. The second analysis was conducted to determine if the role of the surgeon is statistically significant, influencing TKA kinematics. This analysis was conducted using all 3 groups of subjects having a well-functioning PCL implanted by 3 different surgeons.

Using the statistical data, the following will be assumed:

1. If the patients of surgeons 2 and 3 experience significantly different kinematic results compared with the patients of surgeon 1 (from our previous single-surgeon series), then it will be assumed that the surgeon does influence the kinematics for subjects having this asymmetrical PCR TKA design.
2. If the patients of surgeon 1 without a PCL experience significantly different kinematic patterns compared with the patients of surgeon 1 with a PCL, then it will be assumed that the PCL does play a significant role in the kinematics for subjects having this asymmetrical PCR TKA design.
3. If the results for the design test (1 above) and the PCL test (2 above) do not lead to statistical differences, then it will be assumed that the implant type chosen for this study does significantly contribute (may not be the only factor, but the most likely of 3 tested in this study) to subjects achieving more normal kinematic patterns.

Results

Anteroposterior Translation

On average, subjects having an asymmetrical PCR TKA experienced PFR of their medial and lateral condyles, albeit less than those previously reported for the normal knee (Figs. 2-5; Tables 1 and 2). At full extension, the average medial and lateral condyle contact positions for all 4 groups of subjects were posterior of tibial midline in the coronal plane (Table 1). In addition, at full

Table 1. Average PFR of the Medical and Lateral Condyles

	Medial Condyle				Lateral Condyle			
	Full Extension (mm)	Maximum Flexion (mm)	Posterior Rollback (mm)	Standard Deviation	Full Extension (mm)	Maximum Flexion (mm)	Posterior Rollback (mm)	Standard Deviation
PCL 1	−4.0	−6.2	−2.2	4.4	−3.7	−9.9	−6.2	4.2
PCL 2	−2.5	−1.2	1.3*	1.8	−5.8	−8.8	−3.0	3.0
PCL 3	−4.8	−5.2	−0.4	1.9	−5.4	−8.5	−3.1	3.0
No PCL	−2.4	−3.3	−0.9	2.6	−4.6	−5.1	−0.5	4.2

* Represents an anterior slide rather than posterior femoral rollback.

Table 2. Amount and Percentage of PFR for the Medial and Lateral Condyles

	Medial Condyle				Lateral Condyle			
	Maximum PFR (mm)	Maximum Slide (mm)	PFR >0.0 mm (%)	PFR >3.0 mm (%)	Maximum PFR (mm)	Maximum Slide (mm)	PFR >0.0 mm (%)	PFR >3.0 mm (%)
PCL 1	−11.5	7.6	65	35	−17.1	N/A*	100	70
PCL 2	5.1	−2.1	30	0	−10.3	3.6	90	50
PCL 3	−3.3	3.4	65	10	−7.4	3.9	80	60
No PCL	−4.8	7.2	65	15	−7.4	9.8	65	25

* Represents that no subjects experienced an anterior slide.

extension, there was no statistical difference in the data for the lateral condyle ($P = .054$) for patients having a well-functioning PCL implanted by 3 different surgeons; but the position of the medial condyle ($P = .002$) was statistically different. Knees implanted by surgeon 2 experienced a more anterior contact position than those knees implanted by surgeon 1 or 3. Interestingly, there was no statistical difference in the position of the lateral ($P = .665$) or medial condyles ($P = .601$) for the PCL versus no PCL subjects implanted by the same surgeon.

At maximum knee flexion, the average medial condyle contact positions for all 4 groups of subjects remained in a similar position to the contact positions derived for the subjects at full extension; but the lateral condyle for the subjects in the 3 groups having a well-functioning PCL moved to a more posterior position (Table 1). Subjects having a PCR TKA without a PCL experienced a contact position of their lateral condyle at maximum flexion that was similar to the contact position at full extension, although the overall motion was in the posterior direction (0.5 mm) (Table 1). No statistical difference was detected for the lateral condyle of the 3 groups having a well-functioning PCL ($P > .5$), but the position of the medial condyle at maximum flexion demonstrated a statistical difference ($P < .001$). Subjects having a well-functioning PCL implanted by surgeons 1 and 3 experienced a more posterior contact position of their medial condyle than the subjects implanted by surgeon 2 at maximum knee flexion. At maximum knee flexion, the subjects having a well-functioning PCL also experienced a statistically more posterior position of their lateral condyle at maximum knee flexion than the subjects not having a PCL ($P = .003$). Interestingly, the statistical difference in condylar position between these 2 groups (well-functioning PCL vs no PCL) began at 90° of knee flexion, where the position of the medial and lateral condyles was also statistically different ($P < .005$)

Therefore, from full extension to maximum knee flexion, all 4 groups experienced PFR of differing amounts (Tables 1 and 2). Only subjects implanted by surgeon 2 experienced an average anterior motion of either condyle. The subjects implanted by surgeon 2 experienced an anterior motion of their medial condyle from full extension to maximum knee flexion. Subjects implanted by surgeon 1 not having a PCL experienced the least amount of PFR of their condyles (Table 1). Interestingly,

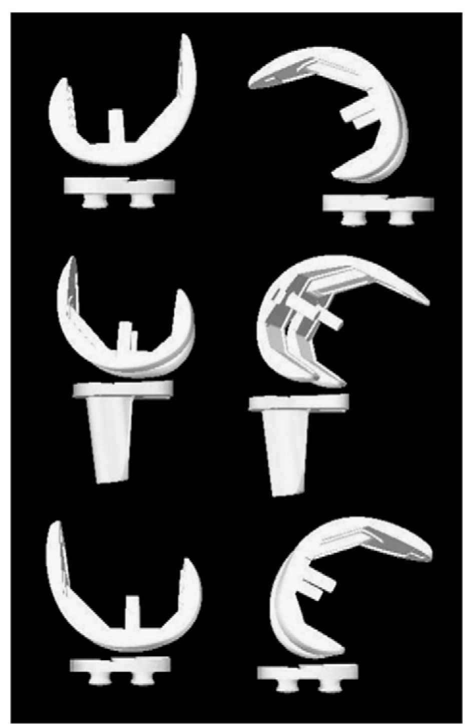

Fig. 6. Example of femorotibial contact positions demonstrating PFR. The top subject was a patient of surgeon 1 (functioning PCL), middle a patient of surgeon 2, and the bottom a patient of surgeon 3.

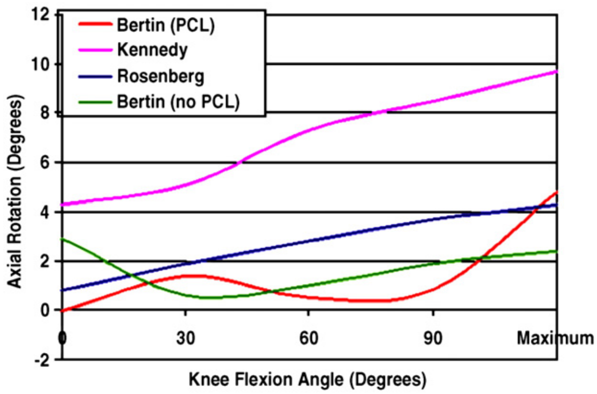

Fig. 7. Average axial tibiofemoral rotation for subjects implanted by the 3 surgeons.

during the test of the 3 groups having a well-functioning PCL from full extension to 90° of knee flexion, there was no statistical difference in the amount of lateral condyle rollback (P = .417). Further analysis revealed that there was a statistical difference in the amount of PFR achieved from full extension to maximum knee flexion for both the lateral (P = 0.016) and the medial (P = .002) condyles. Subjects having a well-functioning PCL implanted by surgeon 1 experienced statistically greater PFR from 90° of flexion to maximum knee flexion than those subjects implanted by surgeons 2 and 3. In addition, from full extension to 90° of knee flexion, subjects having a well-functioning PCL did not experience a statistically greater amount of PFR of their lateral (P = .068) or medial (P = .272) condyles compared with the subjects not having a PCL. From full extension to maximum knee flexion, subjects having a functional PCL experienced a statistically greater amount of lateral condyle rollback (P = .005) than those subjects not having a PCL; but there was no statistical differences for the medial condyle (P = .317).

Most subjects having a well-functioning PCL experienced PFR, especially for the lateral condyle (Fig. 6). Overall, the number of subjects experiencing PFR of both condyles was 12 of 20, 12 of 20, 11 of 20, and 8 of 20 for subjects implanted by surgeon 1 having a well-functioning PCL, subjects implanted by surgeon 2, subjects implanted by surgeon 3, and subjects implanted by surgeon 1 not having a PCL, respectively. The greatest amount of variability in the anteroposterior data occurred for patients of surgeon 1 patients having a functioning PCL (standard deviation = 4.4), whereas the least variability occurred for patients of surgeon 2 (standard deviation = 1.8) and surgeon 3 (standard deviation = 1.9) (Table 1). There was no statistical difference in the number of subjects experiencing PFR for the 3 groups having well-functioning PCL ($P < .05$). Overall, from full extension to maximum knee flexion, 54 of 60 (90%) subjects having a well-functioning PCL experienced PFR of their lateral condyle and 31 of 60 (53%) of their medial condyle. Furthermore, in this present study, 13 of 20 (65%) subjects not having a PCL experienced PFR of their lateral and medial condyles.

Axial Tibiofemoral Rotation

On average, subjects having an asymmetrical PCR TKA with a functional PCL experienced normal axial rotation patterns, albeit less in magnitude than the normal knee, from full extension to maximum knee flexion (Fig. 7, Table 3). The average amount of axial rotation was 5.1° (20.1° to −8.5°), 5.4° (13.7° to −4.5°), and 3.5° (10.0° to −9.3°) for subjects having a well-functioning PCL implanted by surgeons 1, 2, and 3, respectively. On average, subjects not having a PCL implanted by surgeon 1 experienced −0.5° (5.5° to −9.7°) of reverse axial rotation from full extension to maximum knee flexion. In the normal knee, the lateral condyle rolls in the posterior direction with increasing knee flexion. At full extension, the lateral condyle is anterior of the medial condyle; and in deep flexion, the lateral condyle is posterior of the

Table 3. Axial Rotation Data

	Average (°)	Standard Deviation	Normal Rotation (%)	Reverse Rotation (%)	Normal >3.0° (%)	Normal >6.0° (%)	Reverse > −3.0° (%)	Maximum Normal (°)	Maximum Reverse (°)
PCL 1	5.1	6.9	80	20	65	40	15	20.1	−8.5
PCL 2	5.4	4.3	85	15	75	45	5	13.7	−4.5
PCL 3	3.5	5.0	75	25	65	45	10	10.0	−9.3
No PCL	0.5*	4.0	50	50	25	0	25	5.5	−9.7

* Represents −0.5° of opposite axial rotation.

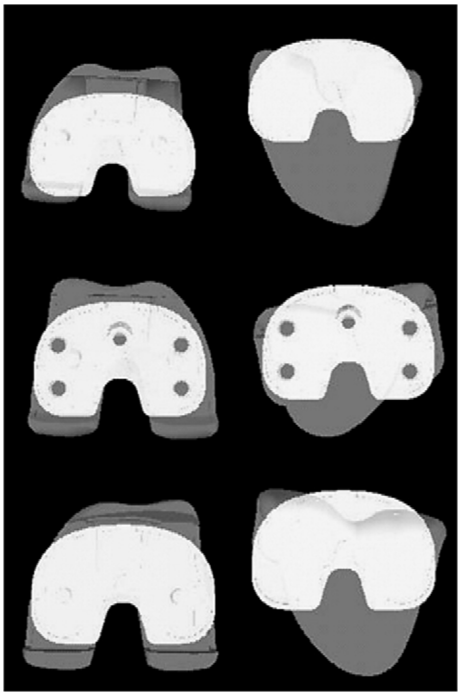

Fig. 8. Examples of subjects demonstrating normal axial rotation, where the lateral condyle rolled more posteriorly than the medial condyle. The top subject was a patient of surgeon 1, the middle surgeon 2, and the bottom surgeon 3.

medial condyle. Because the medial condyle of the normal knee moves significantly less posterior than the lateral condyle, a rotation of the lateral condyle relative to the medial condyle occurs with increased knee flexion.

In this study, a high percentage of subjects having a well-functioning PCL experienced a normal axial rotation pattern, but less in magnitude compared with the normal knee (Table 3, Fig. 8). About 43.3% of the subjects (surgeon 1 = 40%, surgeon 2 = 45%, and surgeon 3 = 45%) experienced at least 6.0° of normal axial rotation from full extension to maximum knee flexion; and 65%, 75%, and 65% of the subjects implanted by surgeons 1, 2, and 3, respectively, experienced at least 3.0° of normal axial rotation. There was no statistical difference in the axial rotation data for the 3 groups having a well-functioning PCL implanted by 3 different surgeons from full extension to 90° of knee flexion (P = .100) and from full extension to maximum knee flexion (P = .621). From full extension to 90° of knee flexion, there was no statistical difference in the axial rotation data for the subjects with and without a PCL implanted by surgeon 1 (P = .176); but from full extension to maximum knee flexion, the amount of rotation was statistically different (P = .005).

Discussion

In this present analysis, the in vivo kinematics was determined for 4 groups of subjects implanted with an asymmetrical PCR TKA. Three groups of subjects had a well-functioning PCL, whereas one group of subjects did not have a PCL, although they were implanted with a PCR TKA. Inclusion of the group of subjects without a PCL allows for the determination of knee kinematics for a PCR without a PCL and a further understanding of the role of the PCL. If in vivo kinematics is reported, it should be compared also with that determined for the normal knee. Komistek et al conducted a fluoroscopic analysis of 10 normal knees using computed tomographic scans to recover 3D bone geometry and the same 3D model-fitting approach to determine the in vivo kinematics for the normal knee [14]. In this study, they reported that the lateral condyle achieved significantly more posterior motion than the medial condyle with increasing knee flexion (19.2 mm vs 3.4 mm in the posterior direction). They also reported that these knees experience 16.5° of internal tibial rotation with respect to the femur with increasing knee flexion.

Previously published fluoroscopic studies of different designs of TKA have determined that subjects having a PCR TKA having symmetrical condylar radii experience a paradoxical anteroposterior motion opposite of the normal knee [4,7,9,17]. A multicenter analysis composed of various TKA types compared with the normal knee was conducted using fluoroscopy, and it was concluded that subjects having a normal knee experience significantly more PFR than that in all TKA knees and that most PCR fixed-bearing TKAs with symmetrical condylar radii experience a motion pattern opposite of the normal knee [16]. Other studies using various approaches including roentgen stereophotogrammetric analysis have found similar findings where PFR did not routinely occur in subjects having a PCR TKA [26-28]. In a single-surgeon fluoroscopic evaluation, average femorotibial contact patterns of PCR TKA with symmetrical condylar radii and anterior cruciate ligament deficient knees were determined to be similar, having abnormal posterior contact in full extension, with a substantial number of these knees having paradoxical anterior femoral translation in midflexion and terminal flexion ranges [5]. Erratic femorotibial contact patterns were evident in both of these knee groups. In a weight-bearing analysis comparing femorotibial contact patterns of PCR TKA designs having symmetrical condylar radii with either a posterior lipped (relatively flat) or curved polyethylene tibial insert, only minimal differences in overall kinematic patterns were observed, suggesting that changes in sagittal curvature of these polyethylene inserts had little effect [7]. Other studies conducted by Stiehl et al and Oakeshott et al have also determined that PCR mobile-bearing TKAs experience similar motion patterns to those derived for subjects having a fixed-bearing TKA [6,29].

Contrary to previously conducted fluoroscopic studies for subjects having a PCR TKA, 54 of 60 (90%) subjects having a PCR TKA in this study, with a functional PCL, experienced PFR of their lateral condyle. Furthermore, 32 of 60 (53%) subjects experienced PFR of their medial condyle with increasing knee flexion, from full extension to maximum knee flexion. In the normal knee, subjects achieve posterior motion of their lateral condyle, but not necessarily with their medial condyle; so the patterns evident for subjects in this present study are consistent with the documented findings for the normal knee [14]. Therefore, subjects implanted with the asymmetrical PCR TKA in this study experienced a higher incidence of PFR compared with those subjects evaluated having a PCR TKA with symmetrical condylar radii [7,9,15,29]. Although most subjects in this study did experience PFR of their lateral condyle, the amount of rollback was less than the normal knee.

Inasmuch as the subjects in this study achieved a normal PFR pattern of the medial and lateral condyles and the lateral condyles rolled further in the posterior direction, it would be expected that, on average, the subjects would experience a normal axial rotation pattern, although less in magnitude than the normal knee. In this study, on average, subjects in the 3 groups having a functional PCL achieved 5.1°, 5.4°, and 3.5° of normal axial rotation. Patients without a PCL achieved a −0.5° reverse axial rotation, which may be due to the absence of both cruciate ligaments. Previous fluoroscopic studies have determined that patients with PCR TKA routinely experienced opposite axial rotation, where the tibia externally rotates with respect to the femur with increasing knee flexion. In this study, from full extension to maximum knee flexion, 48 of 60 (80%) subjects having a well-functioning PCL experienced a normal axial rotation pattern, whereas 12 of 60 (20%) subjects experienced an opposite rotation pattern. In comparison with the group of patients with no PCL, the group with an intact PCL achieved more normal axial rotation from 90° of flexion to maximum flexion. This would indicate that the PCL is most influential in contributing to normal kinematic patterns in terminal flexion more than 90°.

The more normal kinematic patterns achieved for subjects in our first, single-surgeon series study lead to the assumptions that the PFR, with increasing knee flexion, could be due in part to (1) the surgeon chosen for the study; (2) the surgical technique used for implantation; (3) the implant chosen, which has asymmetrical condyles; and/or (4) a combination of the above. It was difficult to postulate that one surgeon is so dramatically different than surgeons performing other designs of TKA that such an appreciable difference would arise. Therefore, this follow-up analysis was conducted to determine if a PCR TKA designed with the lateral condyle having a larger radius of curvature will be more normal in its kinematic function. The results from this multicenter analysis revealed that subjects having a well-functioning PCL, implanted by 3 different surgeons, experience PFR of their lateral condyle and normal axial rotation patterns. Although subjects implanted by surgeon 1, who was the surgeon used in our previous single-surgeon study, experienced more PFR of the lateral condyle compared with the patients of the 2 other surgeons from this present study, the amount of motion from full extension to 90° of knee flexion was not statistically different (P = .4168). Surgeon 1 did experience progressive rollback of the lateral condyle from 90° of knee flexion to maximum flexion, leading to statistically greater PFR from full extension to maximum knee flexion than surgeon 2 (P = .02). The overall motion of the medial condyle was also statistically greater for surgeon 1 compared with those of the other 2 surgeons from full extension to 90° of knee flexion (P = .02), but only statistically greater than that of surgeon 2 from full extension to maximum knee flexion (P = .002). In addition, subjects not having a PCL did achieve, on average, minimal PFR of their lateral condyle, although less in magnitude than the subjects implanted by the same surgeon having a functional PCL. Therefore, a functional PCL could lead to more PFR, but not necessarily statistically different results in pattern. Lastly, it can be assumed that the implant design having asymmetrical condyles does contribute to greater PFR of the lateral condyle throughout knee flexion. Therefore, the prosthesis design tested in this study provided consistent lateral condyle motion; and it seems, at least in part, that the asymmetrical condyles in this design is an important factor in achieving PFR. It must be noted though that from full extension to maximum flexion, subjects having a well-functioning PCL did achieve statistically more PFR; but from full extension to 90° of knee flexion, the leading factor for more normal kinematic patterns did seem to be the implant design. This finding revealed that the PCL does play a greater role in implant kinematics from 90° to maximum knee flexion.

The present multicenter fluoroscopic evaluation showed that traditional PFR demonstrated by the normal knee that did not routinely occur in our previous studies involving PCR TKA with symmetrical condylar radii did occur for subjects in this study, although less in magnitude than the normal knee. Furthermore, these subjects having an asymmetrical condylar PCR TKA experienced a higher incidence and magnitude of normal axial rotation than subjects having a symmetrical condylar PCR TKA. The main difference between the PCR TKA analyzed in this study compared with other PCR TKA designs is the asymmetrical condyles. In this study, we used the null hypothesis that implant design does not influence PFR. It was assumed that the kinematics for subjects in this follow-up analysis will mainly be influenced by surgical technique or the surgeon. The results from this present study defeat the null hypothesis, leading to the acceptance of the alternative hypothesis that asymmetrical condylar radii do significantly influence PFR and axial rotation (at least for the 3 surgeons tested in this study). The comparison of knees without a PCL and knees with a PCL all having the same prosthesis implanted by the same surgeon shows that the PCL improves the quality and consistency of the kinematics results, especially from 90° of flexion to maximum knee flexion.

The results further document that if the PCL is kept in its best functional condition, the kinematics of TKA can be similar to the normal knee in pattern. If the ligament is completely released, the kinematic patterns are good but not as consistent or nearly as normal in pattern as that if the PCL is completely intact. These data are a strong encouragement for surgeons to try to keep the PCL integrity intact during the reconstruction. It is also motivation to develop new techniques to achieve a balanced knee without having to release the intact PCL during reconstruction with a PCR TKA. These results from this study revealed that knees with an intact PCL have more PFR of the lateral femoral condyle, especially occurring from 90° to maximum knee flexion. This fact may have implications for prosthesis design where a higher degree of flexion is the goal. To achieve higher flexion, rollback is necessary to prevent impingement of the femur on the posterior aspect of the tibia at maximal flexion.

In summary, the results from this study suggest the following factors influence knee kinematics:

1. The prosthetic design is the primary factor that contributes to knee kinematics.
2. A functional PCL provides the best results for a subject having a PCR TKA, in harmony with the prosthetic design.
3. Some minor differences were determined between surgeon groups that could lead to a more objective method of soft-tissue balancing allowing all knees to be implanted with the same ligament tension.

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