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Original Research

Effect of Posterior Tibial Slope on Knee Kinematics After Bicruciate-Retaining Total Knee Arthroplasty

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ABSTRACT

Background: Following total knee arthroplasty (TKA), normal knee kinematics are rarely replicated. Retention of both cruciate ligaments (bicruciate retaining TKA) has helped this. Postoperative posterior tibial slope (PPTS) may further affect ligament tension and kinematics. The objective of this study is to determine how changes between the preoperative posterior tibial slope (PTS) and PPTS affect knee kinematics.

Methods: Twenty bicruciate retaining TKAs were performed using standard instrumentation. Fluoroscopic kinematic data were obtained during gait and a single knee bend. Differences (Δ) between radiographic measurements of preoperative and PPTS were correlated with in-vivo knee kinematics. Patients were separated into 2 groups based on their Δ values. Group I consisted of Δ values less than 0.7, indicating either a similar PPTS compared to preoperative PTS or a slightly flatter PPTS. Group II consisted of Δ values above 0.7, indicating a steepened PPTS.

Results: Preoperative PTS values ranged from −0.5° to 11.2°, with an average of 5.0° ± 3.4°. PPTS values ranged from 3.0° to 12.1°, with an average of 7.1° ± 3.1°. Weight-bearing range of motion (WBROM) measured from 94° to 139°, and femorotibial axial rotation ranged from −2.9° to 17.3°. A *t*-test revealed average values for WBROM in Group I_T ($\Delta < 0.7$) to be significantly greater than those for Group II_T ($\Delta > 0.7$) ($P = .01$).

Conclusions: These findings indicate that either a PPTS approximating the preoperative PTS or a slightly flattened PPTS in comparison ($\Delta < 0.7$) is associated with WBROM greater than 130°. Values for axial rotation and anterior sliding were not significantly associated with changes to the PTS.

Introduction

Anatomic posterior tibial slope (PTS) varies considerably among individuals and between the medial and lateral tibial plateaus [1,2]. In a population of 1024 patients, PTS values ranged from 2.1°-18.7°, with an average of 8.4° [3]. The desired or targeted postoperative posterior tibial slope (PPTS) in surgery may be based on the patient's anatomical preoperative PTS, a set value for a particular implant design, or posterior cruciate retaining total knee arthroplasty (PCR TKA), which is dependent upon posterior cruciate ligament tension. Surgical techniques intended to reproduce the desired or target PTS include intramedullary or extramedullary mechanical guides, computer navigation, and robotics, which are generally considered more accurate than mechanical guides [4]. For these reasons, there can be considerable variability in PTS following TKA, creating differences between the anatomic preoperative PTS and PPTS. We believe these differences between PPTS and preoperative PTS may have an effect on postoperative knee kinematics.

During TKA, an increase in PTS increases the size of the flexion gap, while a decrease in PTS reduces the size of the flexion gap [5]. An increase in PTS can be helpful to increase knee flexion after TKA [6]. Xiaojun Shi et al. suggest that this increase in knee flexion may result from less posterior tibiofemoral impingement occurring as a

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result of a greater PPTS. An increased flexion space can also be associated with instability after TKA [7]. Mid-flexion stability has been recognized as an important factor that influences knee function after TKA [8]. However, the effect of PPTS on mid-flexion stability is not clear. In the normal knee, the femur rolls posteriorly and externally rotates with respect to the tibia during knee flexion [9]. After PCR TKA, paradoxical motion typically occurs in which the femur rolls forward during knee flexion [10]. In PCR TKA, changes in PTS may have the greatest impact on the mid-flexion anteroposterior (AP) translation [11]. Increased PTS appears to result in more posterior contact of the femoral condyles on the tibial component and decreased femoral rollback [12].

In bicruciate retaining (BCR) TKA, more normal kinematics and rollback occur, likely as a result of anterior cruciate ligament (ACL) retention [13]. However, the optimal PPTS for BCR TKA and the effect of PPTS on weight-bearing knee flexion after BCR TKA have not been established. For this study, we formed a hypothesis stating that more normal or even optimal knee kinematics can be achieved through making intraoperative tibial cuts, which allowed for the PPTS to be either equal to or nearly equal to the anatomic, preoperative PTS. Furthermore, we predicted that post-TKA patients would achieve a greater degree of knee flexion at PPTS values that were similar to their preoperative PTS angles. The objective of this study is to determine how changes between the preoperative PTS and PPTS affect postoperative knee kinematics. Additionally, the authors sought to determine if there was a specific value for the difference between PPTS and preoperative PTS that would yield optimal kinematic outcomes for patients following BCR TKA. Lastly, this study aims to determine a PPTS value that may be best for a surgeon to strive for in order to obtain favorable values for the 3 kinematic parameters included in this study.

Material and methods

Demographics

BCR TKA (Smith and Nephew, Journey XR) was performed using mechanical guides and standard instrumentation in 16 patients (20 knees). At the time of participation in the study, all subjects had well-functioning BCR TKAs and were judged clinically successful without any postoperative complications.

Kinematic and radiographic measurements were taken between 1.6 and 3.6 years following surgery. Of the subjects, 9 were men and 7 were women. The mean age and body mass index of the subjects were between 64 and 74 years and between 23 and 31 kg/m^2, respectively (Table 1). Institutional review board approval was obtained, and all subjects signed an informed consent form prior to participating in this study.

Kinematic data collection

Study participants were asked to perform a weight-bearing, single-leg, deep knee bend (DKB) activity while the subject's knee was under fluoroscopic surveillance. Subjects were instructed to begin at full extension and flex as deep as they could in order to obtain a maximum flexion value. Kinematics were measured at full extension, maximum flexion, and 30° increments of the entire flexion/extension cycle. Study participants were examined while performing these activities using a C-arm fluoroscopic unit (GE OEC 9600). The fluoroscopic videos were stored for subsequent redigitization and analysis.

Three-dimensional model fitting

Previously published 3-dimensional (3D) to 2-dimensional (2D) image registration techniques were used to overlay the 3D models of the implanted components on their projection in the 2D fluoroscopic image. Specifically, the fluoroscopic space is virtually modeled within a computer graphical user interface. This graphical user interface (Fig. 1) allows the user to virtually view the fluoroscopic space between the X-ray source and the image intensifier. Three-dimensional computer-aided design (CAD) models of the components are virtually placed in the space between the camera and the image, which allows the user to superimpose the CAD model silhouettes on top of the implant component silhouettes from the X-ray image. By matching a 3D CAD model of the implant component to each fluoroscopic frame of interest in the video, 3D in vivo kinematics can be extracted from a 2D image. In general, the errors associated with this model fitting technique are less than 0.65 mm for in-plane translations and 1.5° for rotations, out of plane errors are normally higher [14].

Table 1
Patient demographic information.

Knee identifier	Surgery date	Time between surgery and data collection (years)	Patient age at the time of data collection (years)	BMI (kg/m^2)
1	12/3/2018	2.64	69.7	22.0
2	7/25/2019	2.00	71.2	29.5
3*	3/7/2019	2.38	71.6	19.0
4	7/1/2019	2.06	67.2	25.3
5	11/5/2018	2.72	55.8	28.4
6*	4/10/2017	4.29	73.6	24.1
7	9/26/2018	2.82	66.8	32.4
8*	7/20/2020	1.01	64.9	22.0
9	10/5/2017	3.80	68.1	29.4
10	11/27/2019	1.65	72.5	30.8
11	2/18/2019	2.43	70.1	27.8
12	8/9/2018	2.96	73.3	33.7
13	10/23/2017	3.75	72.0	27.8
14	11/7/2019	1.71	76.5	33.3
15*	9/7/2017	3.88	73.5	26.4
16	6/4/2020	1.13	68.6	27.1
Average		2.58	69.47	27.43
Standard deviation		0.98	4.84	4.21

Data marked with an asterisk indicate bilateral knee measurements for that patient.
BMI, body mass index.

Figure 1. Interface of the custom-developed software that was used to perform the registration process.

Weight-bearing range of motion (WBROM) was extracted directly from the fluoroscopic images by digitally measuring the angle between the long axis of the tibia and the long axis of the femur at the point of maximum flexion. Other kinematic parameters of interest include the lateral anterior/posterior (LAP) and medial anterior/posterior positions of the femoral condyles, measured in millimeters with respect to the midline of the geometric bounding box containing the tibial baseplate. Axial orientation of the femur is measured with respect to the tibial baseplate as the angular difference between bodies about the long axis (superior/inferior axis) of the tibia. LAP and medial anterior/posterior values are denoted as positive if they occur anterior to the tibial origin and are denoted as negative if they occur posterior to the tibial origin. External rotation of the femur with respect to the tibia is denoted as positive, and internal rotation of the femur with respect to the tibia is denoted as negative (Fig. 2).

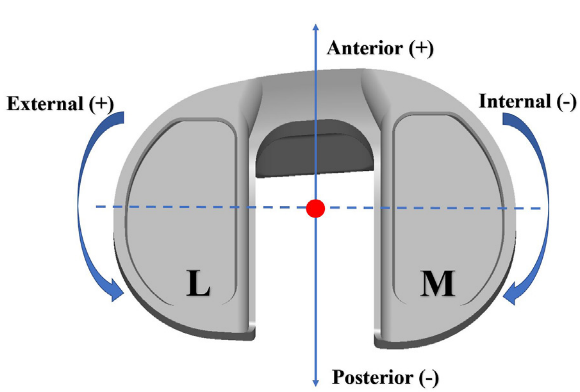

Figure 2. Schematic diagram highlighting the defined directions used for the analysis of the kinematic variables.

Radiographic analysis

Standard digitized anteroposterior, lateral, and patellar radiographs were obtained within 6 weeks of surgery and at the time of participation in the study. Preoperative PTS and PPTS values were determined using lateral radiographs and radiographic viewing software (Inteleviewer; Intelerad, Montreal, Quebec). Two coauthors independently collected 3 rounds of these measurements for each knee. Values were taken in reference to the anatomical axis of the tibia based upon support from literature [15]. This axis was determined using the proximal anatomic axis (PAA) method from lateral radiographs, as outlined by Ho Yoo et al. [16]. Utilizing the PAA, PTS values were collected using Inteleviewer software measurement tools following methodology outlined by Kizilgöz et al. [17]. Preoperative and postoperative representations of both the PAA and PTS angular measurements can be referenced in Figure 3.

The 3 rounds of preoperative PTS values collected by observer one were averaged to form a mean preoperative PTS value for each knee. The 3 rounds for PPTS values were averaged in an equivalent manner. The same approach to preoperative and PPTS values was taken with the data collected by observer 2. These mean values from both observers for preoperative and PPTS were averaged together to form the final PTS values for each knee. These final

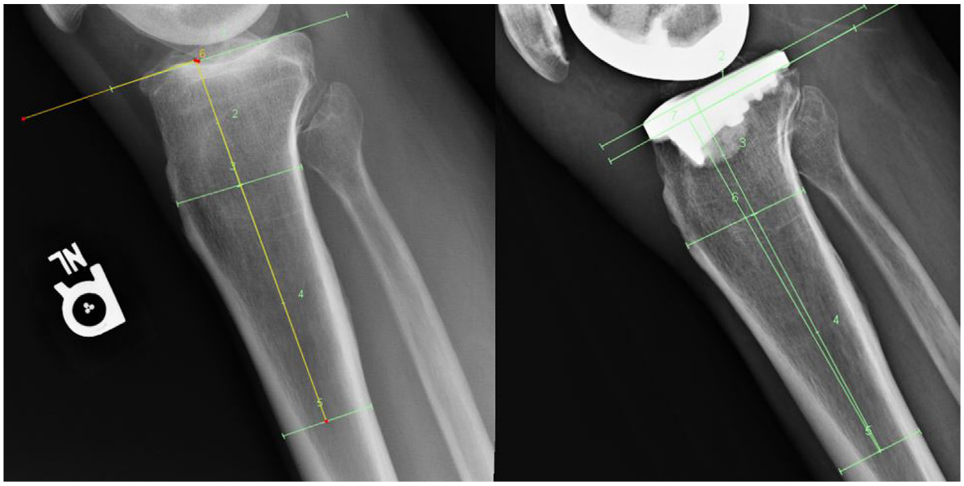

Figure 3. Demonstration of how PTS values were determined utilizing the proximal anatomic axis in preoperative and postoperative lateral radiographs.

averages for the preoperative and postoperative PTS values were used to calculate a “delta” (Δ) variable for each knee, which was accomplished via the following equation:

$$\Delta = (\textit{final postoperative PTS}) - (\textit{final preoperative PTS})$$

Statistical analysis

All statistical analysis was accomplished using either SPSS (V24.0; IBM, Armonk, NY) or integrated statistical components of Microsoft Excel.

The reliability of measurements was assessed via the intraclass correlation coefficient (ICC) and interpreted according to values of 0.5-0.75 indicative of moderate reliability, 0.75-0.9 indicative of good reliability, and greater than 0.9 indicative of excellent reliability. A value lower than 0.5 was indicative of poor reliability [18].

Once Δ values were calculated, 2 groups (groups I and II) were formed for *t*-test analysis. Group I for *t*-test (Group I_t) consisted of Δ values less than 0.7, which meant PPTS values were relatively similar to preoperative PTS values or they were slightly flattened in comparison (n = 5). Group II_t consisted of Δ values above 0.7, meaning PPTS for this group was steeper in comparison to preoperative PTS measurements (n = 15). Being deemed as most clinically relevant, the kinematic results for WBROM, axial rotation (AR), and LAP of each knee were paired with their respective Δ values. A student’s *t*-test compared the averages of the respective kinematic data for WBROM, AR, and LAP in each of the groups based on their Δ values. Averages for mid-flexion anterior sliding for Groups I_t and II_t were compared utilizing the LAP kinematic data collected between flexion angles at 30 and 90 degrees. A positive LAP indicates forward translation of the lateral femoral condyle with respect to the tibia. Another *t*-test was used to compare those averages between Groups I_t ($\Delta < 0.7$) and II_t ($\Delta > 0.7$).

Results

In concordance with the ICC levels defined by Koo et al., the intrarater reliability for the determination of Δ values from preoperative imaging achieved good reliability, ICC = 0.82 (95% confidence interval (CI), 0.62-0.92) and moderate reliability, ICC = 0.70 (95% CI, 0.39-0.87) for raters one and 2, respectively. Determination of Δ values from postoperative imaging demonstrated excellent intrarater reliability in both raters with ICC = 0.98 (95% CI, 0.95-0.99) and ICC = 0.97 (95% CI, 0.94-0.99) for raters one and 2, respectively. Interrater reliability was deemed as good for the determination of Δ values from preoperative imaging, ICC = 0.81 (95% CI, 0.64-0.92) and excellent for postoperative imaging, ICC = 0.94 (95% CI, 0.89-0.97). Summary results can be referenced in Table 2.

Preoperative PTS values for all knees ranged from −0.5° to 11.2°, with an average of 5.0° ± 3.4°, compared to postoperative values ranging from 3.0° to 12.1°, with an average of 7.1° ± 3.1°. The values for Δ, WBROM, AR, and mid-flexion LAP values for Groups I_t and II_t used in the *t*-test analysis can be referenced in Table 3. A comparison between kinematic outcomes for Groups It and IIt with their associated *t*-test *P*-values can be referenced in Table 4. Postoperative WBROM ranged from 94.0° to 139°, and AR ranged from −2.9° to 17.3°. A 2-sample student *t*-test revealed the average WBROM for Group I_t (129°) was significantly greater than that for Group II_t (116°) ($P = .01$). A similar *t*-test for average AR for Group I_t (6.9°) did not differ significantly from Group II_t (6.4°) ($P = .4$). A *t*-test for LAP did not show a significant difference in mid-flexion LAP between Group I_t and Group II_t ($P = .08$).

Discussion

Anatomic PTS varies considerably between individuals. PTS in TKA is determined by the orientation of the tibial bone cut and may result in a change from preoperative anatomic PTS to PPTS. Adequate PTS is necessary to facilitate femoral rollback during knee flexion and provide adequate knee laxity in flexion [5,6]. Excessive PTS can result in flexion instability [7]. Pan et al. studied the effect of differences in PTS before and after TKA in 5 groups of patients

Table 2
Interclass and intraclass correlation coefficient.

Measurement recorded	Intraobserver		Interobserver
	Observer 1	Observer 2	
Preoperative PTS measurement	0.820 (0.622-0.923)	0.704 (0.388-0.872)	0.811 (0.642-0.915)
Postoperative PTS measurement	0.978 (0.954-0.991)	0.970 (0.937-0.987)	0.941 (0.890-0.973)

Data are reported as interclass or intraclass correlation coefficient (95% confidence interval).
PTS, posterior tibial slope.

Table 3
Two groups are used in *t*-test analysis.

Knee identifier (right/left)	Delta (Δ)	WBROM	AR	Mid-flexion LAP
Group I_t (Δ < 0.7)				
3 (left)	0.11	137	5.09	5.73
4	−1.93	126	7.28	3.87
8 (right)	−2.28	117	8.61	0.80
10	0.67	137	1.94	1.08
15 (left)	−1.41	128	11.7	1.18
Average	−0.97	129	6.92	2.53
Standard deviation	1.29	8.40	3.66	2.18
Group II_t (Δ > 0.7)				
1	1.92	94	17.27	−1.26
2	4.75	101	7.89	1.13
3 (right)	2.46	139	4.9	−0.33
5	6.95	111	−2.9	1.45
6 (right)	4.38	119	7.5	−0.59
6 (left)	4.35	123	8.13	1.07
7	1.42	110	3.98	5.87
8 (left)	1.05	113	5.14	3.88
9	4.30	118	9.57	−7.31
11	4.91	116	4.4	1.39
12	6.47	123	8.05	1.6
13	0.96	101	3.04	2.21
14	1.10	130	3.19	−0.28
15 (right)	2.66	129	6.15	−0.74
16	1.34	120	9.9	2.27
Average	3.27	116	6.41	0.69
Standard deviation	2.02	12.02	4.40	2.90

Directionality is noted for data that were collected bilaterally in patients.

(Group 1, >5°; Group 2, 3°-5°; Group 3, 0°-3°; Group 4, −3° to 0°; Group 5, < −3°) on Knee Society and Western Ontario and McMaster Universities Arthritis Index scores [19]. The authors found that an increase or decrease in PTS can have an impact on the postoperative recovery of knee function. This finding is consistent with our observation that demonstrates greater weight-bearing knee flexion when PPTS is similar to the preoperative PTS. Additionally, our findings indicate that in BCR TKA, a more anatomic PPTS (Δ < 0.7) was associated with greater WBROM and deeper flexion than knees, which had an increase in or a steepened angle of PPTS when compared to preoperative PTS (Δ > 0.7). Since changes in preoperative PTS compared to PPTS can affect ligament tension and knee kinematics, it should be noted that the ideal PPTS may be different for PCR TKA and posterior stabilized designs [20].

Cruciate retaining knees demonstrate anterior femoral translation during knee flexion and posterior femoral translation during knee extension (paradoxical motion), which has been attributed primarily to loss of ACL function [10]. Posterior stabilized knees demonstrate posterior femoral translation during knee extension, but during flexion, the cam postengagement causes femoral rollback during flexion [10]. Considerable variability in rotational motion during knee flexion has been observed after both cruciate retaining and posterior stabilized TKA. BCR designs have been shown to have more normal femoral posterior rollback and external rotation during knee flexion than ACL-sacrificing designs [13,21,22]. However, variability in kinematic patterns has also been reported after BCR TKA [22]. This suggests that factors other than ligament integrity may affect kinematics after BCR TKA such as PTS, articular congruity of the medial and lateral articular surfaces, joint line orientation, limb alignment, and muscle function.

Table 4
Statistical comparison between groups.

Statistical measure	GI_t-WBROM	GII_t-WBROM	GI_t-AR	GII_t-AR	GI_t - mid-flexion LAP	GII_t - mid-flexion LAP
Average	129	116	6.92	6.41	2.53	0.69
Standard deviation	8.40	12.02	3.66	4.40	2.18	2.9
P-value	.01		.40		.08	

Kinematic data and associated *t*-test *P*-values were provided for comparison between Group I_t (Δ < 0.7) and Group II_t (Δ > 0.7).

In the normal knee, the femur externally rotates during knee flexion. However, we did not find an association between our Δ variable, PPTS, and AR during knee flexion. Previous kinematic studies have demonstrated considerable variability in AR during knee flexion [23]. Many factors likely affect the differences in AR before and after TKA, aside from PTS. Although BCR TKA preserves both cruciate ligaments, there are other anatomic differences between the normal and replaced knee including loss of menisci, changes in articular surface geometry, and joint line orientation, which could have an effect on knee kinematics and AR during knee flexion [23].

It is possible to consider anterior translation in vivo as theoretically being affected by many factors, including cruciate ligament and soft tissue tension, implant conformity, and dynamic extra-articular joint forces. We found considerable variability in AP sliding in our patient population. AP sliding during DKB activity did not correlate with WBROM, while our Δ variable and an overall flattened PPTS did correlate with WBROM.

This study may be limited by the relatively small number of knees examined. A high importance can be placed on future studies with a greater number of knees and thus more power to further our current understanding regarding PTS cuts made intraoperatively for BCR knees. It is important to consider that there may be inaccuracies in measurements of preoperative PTS and PPTS values from lateral knee radiographs. However, multiple measurements were made, and radiographs were taken with a standardized procedure by similarly trained technicians to minimize rotational errors. Additionally, the results demonstrated relatively positive statistics for relatability. Although the number of patients in our study was low, the accuracy of fluoroscopic measurements of weight-bearing flexion has been established in previous studies [10]. In addition, all patients contained in this study had a single prosthetic device manufacturer and were BCR designs, so the results may not necessarily extrapolate to other implant designs. Patient variables such as overall health and other orthopaedic impairments may contribute to each patient's ability to perform a single DKB activity. Our study population also had an average preoperative PTS of approximately 5 degrees, and our results may not apply to other patient populations with greater anatomic preoperative PTS values.

Conclusions

WBROM is an important clinical outcome and was considerably higher in our patients, particularly with relatively anatomic PPTS, in comparison to prior studies with conventional ACL sacrificing TKA [24]. This may reflect the benefit of more normal proprioception and mid-flexion stability associated with ACL retention in TKA. Our results suggest that to attain an optimal WBROM in BCR TKA, the surgeon should strive to make a PTS cut intraoperatively that creates a PPTS that is nearly identical or slightly flatter than the anatomic or preoperative PTS (Δ < 0.7) to produce favorable WBROM.

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Conflicts of interest

M. Ries receives royalties from Smith and Nephew and Stryker and is a paid consultant for Smith and Nephew. M. LaCour receives financial/material support from Orthopaedic Innovation Technology Center, Inc.; receives research support from Zimmer-Biomet, Smith & Nephew, Microport, DePuy-Synthes, and Breg; and is a paid consultant for JointVue. All other authors declare no potential conflicts of interest.

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CRediT authorship contribution statement

Jordan Dobrich: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization, Formal analysis, Investigation. **Sawyer Bauer:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Steven Elicegui:** Writing – review & editing, Formal analysis, Data curation. **Michael LaCour:** Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization, Supervision, Resources, Software, Project administration. **Michael Ries:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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