Radiographic Landmarks for Tunnel Positioning in Posterior Cruciate Ligament Reconstructions

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Background: Consistent radiographic guidelines for tunnel placement in single- or double-bundle posterior cruciate ligament (PCL) reconstructions are not well defined. Quantitative guidelines reporting the location of the individual PCL bundle attachments would aid in intraoperative tunnel placement and postoperative assessment of a PCL reconstruction.

Hypothesis: Consistent and reproducible measurements in relation to radiographic landmarks for the entire PCL and its individual bundle attachments are achievable.

Study Design: Controlled laboratory study.

Methods: The femoral and tibial PCL bundle attachment centers of 20 nonpaired fresh-frozen cadaveric knees were labeled using radio-opaque spheres and the attachment areas were labeled using barium sulfate. Anteroposterior (AP) and lateral radiographs of the femur and tibia were obtained, and measurements of the distances between the PCL bundle centers and landmarks were acquired.

Results: On the AP femur view, the anterolateral bundle (ALB) and posteromedial bundle (PMB) centers were 34.1 ± 3.0 mm and 29.2 ± 3.0 mm lateral to the most medial border of the medial femoral condyle, respectively. The lateral femur images revealed that the ALB center was 17.4 ± 1.7 mm and the PMB center was 23.9 ± 2.7 mm posteroproximal to a line perpendicular to the Blumensaat line that intersected the anterior margin of the medial femoral condyle cortex. Anteroposterior tibia images revealed that the ALB and PMB centers were located 0.2 ± 2.1 mm proximal and 4.9 ± 2.9 mm distal to the proximal joint line, respectively. The PCL attachment center was 1.6 ± 2.5 mm distal to the proximal joint line. On the lateral tibia view, the ALB center was 8.4 ± 1.8 mm, the PCL attachment center was 5.5 ± 1.7 mm, and the PMB center was 2.5 ± 1.5 mm superior to the champagne glass drop-off of the posterior tibia.

Conclusion: Radiographic measurements from several clinically relevant views of the femur and tibia were reproducible with regard to the anatomic locations of the ALB and PMB centers. The measurements from the lateral femur and tibia views provided the most clinically pertinent radiographic measurements intraoperatively.

Clinical Relevance: This study established a set of clinically relevant radiographic guidelines for anatomic reconstruction of the PCL. The parameters set forth in this study can be used in both the intraoperative and postoperative settings for both single- and double-bundle PCL reconstructions.

Keywords: posterior cruciate ligament; anterolateral bundle; posteromedial bundle; radiographs; Blumensaat line

A central limitation to the development of successful anatomically based posterior cruciate ligament (PCL) surgical reconstruction is the lack of applying information relating recent advances in knowledge of PCL anatomy[1,6,28] to the surgical methods for tunnel placement. Radiography has been reported to accurately assess tunnel position intraoperatively and postoperatively in ligament reconstructions.[19,21,23,27] Therefore, reproducible and accurate radiographic guidelines to direct tunnel placement during PCL reconstructions are essential to perform anatomic PCL reconstructions.

Recent reports have detailed the anatomy of the individual PCL bundles. At the femoral attachment, the medial intercondylar ridge[1,13] has been reported to mark the proximal border of both the anterolateral bundle (ALB) and

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posteromedial bundle (PMB), whereas the medial bifurcate prominence has been reported to mark the separation between the ALB and PMB.[1] At the tibial PCL attachment, the bundle ridge consistently defines the posterior margin of the ALB and the anterior margin of the PMB.[1] Although awareness of these newly reported landmarks may help to improve tunnel placement intraoperatively, radiographic characterization of these structures may further assist with localization of the individual PCL bundles.

Although the anteromedial and posterolateral bundles of the anterior cruciate ligament (ACL) have been well characterized radiographically,[20] studies on the PCL have not adequately described the radiographic locations of the ALB and PMB attachments separately.[2,4,12,14,21] Anatomic PCL reconstructions have been reported to improve subjective and objective outcomes over nonanatomic reconstruction tunnel placement.[10,14,17] Therefore, further studies to define the ideal radiographic guidelines of the PCL are required.

The purpose of our study was to establish quantitative radiographic guidelines for identifying the anatomic femoral and tibial attachment sites of the entire PCL and its individual anterolateral and posteromedial bundles. We hypothesized that a standardized radiographic protocol could reproducibly describe the radiographic positions of the entire PCL as well as its bundle attachments. These guidelines have the potential to facilitate anatomic placement of PCL reconstruction tunnels intraoperatively, aid in postoperative evaluations of PCL reconstructions, and support preoperative planning of revision surgeries, potentially leading to more successful PCL reconstruction outcomes.

MATERIALS AND METHODS

Specimen Preparation

Twenty nonpaired, fresh-frozen human cadaveric knee specimens (average age, 49.1 years [range, 21-59 years]; 14 men and 6 women) with no history of injury or disease were used. Institutional review board approval was not required for this study since it was performed on cadaveric specimens only. All dissections were performed with the senior author present (R.F.L.). Dissection began with the removal of all soft tissues with the exception of the PCL, collateral ligaments, and menisci. The anterior and posterior meniscofemoral ligaments were identified and excised. After observing the tensioning pattern of the PCL fibers throughout the full range of knee motion, the surgeon carefully separated the ALB and PMB using a blunt-tipped probe. Subsequently, each bundle was sectioned and the peripheries of the femoral and tibial bundle footprints were marked with a permanent ink pen. After sharp dissection of the PCL fibers from their bony attachments, the center of each bundle was immediately marked with a 2-mm stainless steel sphere (Small Parts, Inc, Miami, Florida). In a modification of a previously described technique,[19,30] the spheres were shallowly embedded in bone and fixed in place with glue (Henkel Co, Dusseldorf, Germany). Metal soldering wire (Malin Co, Cleveland, Ohio) was fixed along the medial intercondylar ridge[13] of the distal femur for radiographic imaging. All imaging was conducted with the knee specimen at full extension. After initial femoral anteroposterior (AP) and lateral radiographic imaging, a radio-opaque barium sulfate ($BaSO_4$) (E-Z-EM, Inc, Lake Success, New York) emulsion was applied to each femoral bundle attachment site to denote the bundle attachment area.

On the tibia, 1-mm-diameter t-pins (Swinton Ave Trading Ltd, Inc, Boca Raton, Florida) were used to label the inferolateral corner of the transverse shiny white attachment fibers of the posterior horn of the medial meniscus[1] and the posterior root attachments of the medial and lateral menisci. Metal soldering wire was fixed along the tibial bundle ridge, which has been reported to mark the separation between the ALB and PMB.[1] Preliminary pilot imaging studies on 4 knees revealed that the geometric center point of the PCL attachment remained equidistant from the anterolateral and posteromedial bundle centers and at the bundle ridge. When we attempted to label it, the marker overlapped with the bundle ridge wire marker. Thus, we used the intersection of the bundle ridge and a line connecting the individual bundle centers as a reference point to calculate distances from the geometric center point of the tibial PCL attachment. Measurements from this landmark are referred to as "PCL tibial attachment center" measurements.

Image Collection

A fluoroscopy mini C-arm (Hologic, Inc, Bedford, Massachusetts) was used to obtain femoral and tibial images according to standard radiographic techniques.[14,29] True AP views of the femur were obtained by ensuring minimal margins and maximal overlap between the medial and lateral borders of the condyles. True lateral views of the femur were obtained by aligning the posterior aspects of the medial and lateral femoral condyles. True AP views of the tibia were obtained with the anterior and posterior margins of the medial tibial plateau closely superimposed, the intercondylar eminences of the tibia positioned at the center of the femoral intercondylar notch, and the tibia covering one third of the fibular head. True lateral views of the tibia were obtained with a well-defined joint line and complete overlap of the posterior cortex of the proximal tibia. With the radiographic markers in place, the femoral and tibial radiographs were obtained in full extension for the AP and lateral views.

Measurements

Quantitative radiographic measurements were performed in a digital picture archiving and communication system (PACS) (Stryker, Kalamazoo, Michigan). Distances were calibrated with a metal sphere measuring 2.54 cm in diameter (Stryker) placed directly in the plane of the specimen at the level of the studied structures. Anatomic positioning nomenclature was reported according to standard positioning in the extended knee.[32] Measurements involving structures labeled with the 2-mm spheres were made in reference to the spherical centers, whereas those involving

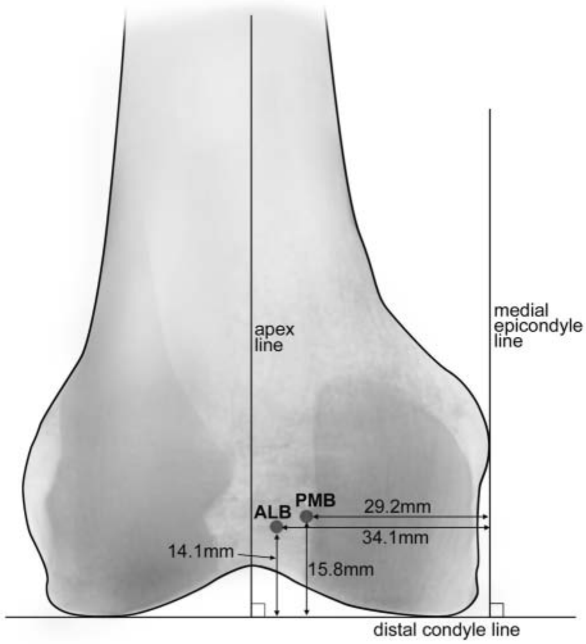

Figure 1. Illustration of the radiographic anteroposterior femur view. The measurement axis generated was based on the distal condyle line. ALB, anterolateral bundle; PMB, posteromedial bundle.

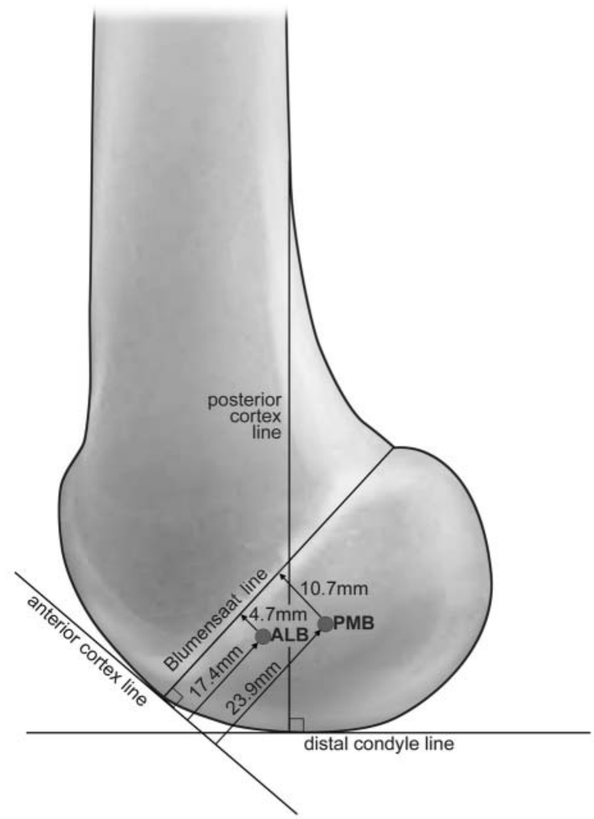

Figure 2. Illustration of the radiographic lateral femur view. The measurements displayed use the Blumensaat line axis. ALB, anterolateral bundle; PMB, posteromedial bundle.

t-pins were made from the proximal end of the pins, which were inserted with the entire pin flush with the bony surface.

On the AP femur radiographs (Figure 1 and Supplementary Figure A1 in the appendix, available in the online version of this article at http://ajs.sagepub.com/supplemental/), the superior/inferior locations of the bundle centers were measured perpendicular to a line that intersected the distal margins of the femoral condyles (distal condyle line). Medial/lateral positions of the bundles were measured from a line drawn perpendicular to the distal condyle line and intersecting the most medial border of the medial femoral condyle (medial epicondyle line) and to a parallel line intersecting the radiographic apex of the intercondylar notch (apex line).

On the lateral femur radiographs (Figure 2 and Supplementary Figure A2, available online), 2 separate axes were used: (1) an axis generated off of a vertical line drawn along the posterior cortex of the proximal femur (posterior cortex line) and (2) an axis generated off of the Blumensaat line. Using the axis based on the posterior cortex line, the AP positions of the individual bundle centers were measured perpendicular to the posterior cortex line, and superior/inferior distances to the distal condyle line and medial intercondylar ridge were measured parallel with the posterior cortex line. Using the second axis based off of the Blumensaat line, distances were measured perpendicular to the Blumensaat line. In addition, a subsequent line was generated that was perpendicular to the Blumensaat line and that intersected the junction of the Blumensaat line with the most anterior margin of cortical bone of the overlapped femoral condyles. Distances from this line posteroproximally to the bundle centers parallel with the Blumensaat line were measured. Following application of the $BaSO_4$, the lateral femoral radiographs were repeated and measurements were acquired from the margins of the bundle attachment areas along the same axes used to measure the bundle centers (Supplementary Figure A3, available online).

On the AP tibia radiographs (Figure 3 and Supplementary Figure A4, available online), a reference line was drawn along the proximal joint line, and subsequent perpendicular lines were drawn intersecting pertinent bony and soft tissue landmarks. Superior/inferior distances were measured from the bundle centers and PCL attachment center to the proximal joint line and to the level of the inferolateral corner of the shiny white fibers of the posterior horn of the medial meniscus.[1] Medial/lateral distances were measured to lines that intersected the apexes of the tibial eminences and to the posterior meniscal root attachments.

On the lateral tibia radiographs, the AP distance of the bundle attachment centers (Figure 4 and Supplementary Figure A5, available online) and margins of the bundle attachment areas (Supplementary Figure A3, available online) were measured perpendicular to a reference line drawn through the center of the long axis of the tibia (long axis of tibia line). Vertical measurements were

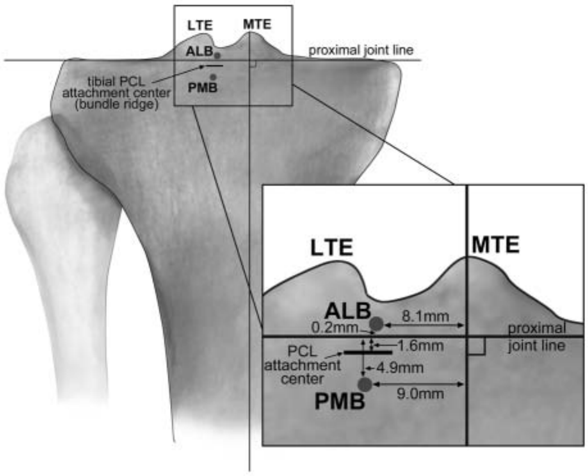

Figure 3. Illustration of the radiographic anteroposterior tibia view. The measurement axis was generated off of the proximal joint line. ALB, anterolateral bundle; LTE, lateral tibial eminence; MTE, medial tibial eminence; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

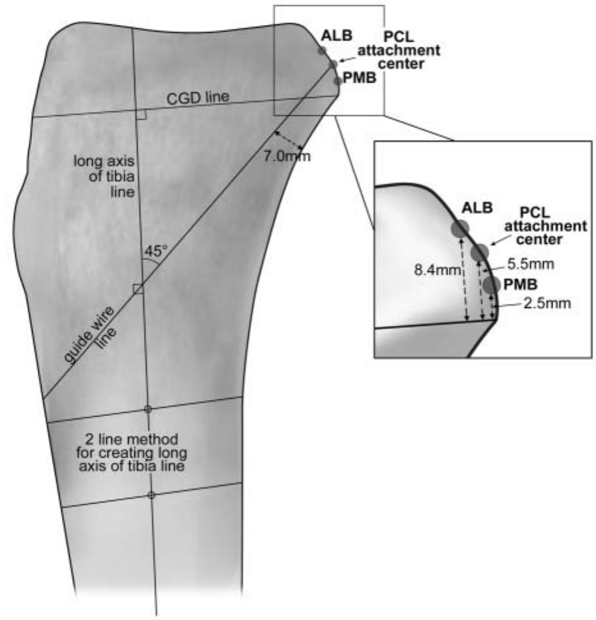

Figure 4. Illustration of the radiographic lateral tibia view. The measurement axis was generated from an estimated long axis of tibia line. ALB, anterolateral bundle; CGD, position depicting the champagne glass drop-off on the tibia; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

made from the bundle centers and the tibial PCL attachment center to a reference line perpendicular to the tibial axis line and intersecting the champagne glass drop-off ridge[1] (CGD line). Next, a line was created to represent the theoretical path of a guide pin according to reports of standard pin placement during drilling of a PCL transtibial reconstruction tunnel.[21,27] To accomplish this, an angled line was superimposed on the lateral tibial radiograph that originated from the tibial PCL attachment center and was directed anteroinferiorly at a 45° angle from the tibial axis line toward the distal anterior tibia (guide wire line). A line parallel to the guide pin line and intersecting the most anterosuperior edge of the concave posterior tibia immediately distal to the champagne glass drop-off was also superimposed (Figure 4 and Supplementary Figure A5, available online). The distance between the guide wire line to the concave posterior tibia was measured to quantify a potential safety margin to avoid posterior wall breakout.[9,15]

Statistical Analysis

To determine the reliability of the distance measurements, 2 reviewers independently measured blinded radiographs using the PACS program. Each reviewer measured the same set of radiographs on 2 separate occasions at least 2 weeks apart to evaluate intraobserver intraclass correlation coefficient (ICC) reproducibility. The measured values were compared between reviewers to evaluate interobserver ICC consistency. Reliability analysis was performed with the use of Predictive Analytics Software (PASW) Statistics version 18.0.0 (SPSS, Inc, an IBM Company, Chicago, Illinois). Two-way mixed, single-measure ICCs were calculated to determine reliability within (intraobserver) and among (interobserver) reviewers for measurement values.[11] Interclass correlation coefficients of >0.75 were considered excellent.[25] Final measurements, percentages, and variations were reported by averaging values from both occasions and reviewers for a single averaged value.

RESULTS

All measurements and percentages are reported in Tables 1 to 6. The main clinically important measurements and standard deviations follow. Percentages in relation to reference lines are listed in the corresponding tables.

AP Femur

Radiographic measurements for the AP view of the femur are reported in Table 1 and illustrated in Figure 1. The ALB and PMB centers were located 14.1 ± 1.2 mm and 15.8 ± 2.0 mm superior to the distal condyle line, respectively. The ALB center was 34.1 ± 3.0 mm lateral to the most medial border of the medial femoral condyle, whereas the PMB center was located 29.2 ± 3.0 mm lateral.

Lateral Femur

Radiographic measurements for the lateral view of the femur are reported in Table 2 and illustrated in Figure 2. The ALB center was located 17.4 ± 1.7 mm posteroproximal to the anterior cortex line of the femoral condyles along a reference line parallel with the Blumensaat line.

TABLE 1
Quantitative Relationships of the Femoral Attachments of the PCL Bundles to Landmarks and Reference Lines on AP Radiographs[a]

Relationship	Distance, mm	Percentage
ALB to:		
Distal condyle line	–14.1 ± 1.2	–152.1 ± 25.3[b]
Apex line	–6.6 ± 1.5	–8.3 ± 1.9[c]
Medial epicondyle line	34.1 ± 3.0	42.8 ± 1.9[c]
Medial intercondylar ridge	6.1 ± 1.9	65.6 ± 24.3[b]
PMB to:		
Distal condyle line	–15.8 ± 2.0	–170.5 ± 31.3[b]
Apex line	–11.4 ± 2.0	–14.4 ± 2.7[c]
Medial epicondyle line	29.2 ± 3.0	36.7 ± 1.7[c]
Medial intercondylar ridge	5.2 ± 1.8	57.1 ± 25.3[b]

[a]Values are reported as the mean ± standard deviation. Measurements made in the superior and medial directions are indicated by positive values. AP, anteroposterior; ALB, anterolateral bundle; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

[b]Percentages were created by normalizing values using the maximum height of the intercondylar notch.

[c]Percentages were created by normalizing values using the maximum medial-lateral width from medial to lateral epicondyle.

TABLE 2
Quantitative Relationships of the Femoral Attachments of the PCL Bundles to Landmarks and Reference Lines on Lateral Radiographs[a]

Relationship	Distance, mm	Percentage
ALB to:		
Posterior cortex line	–0.8 ± 2.6	–2.1 ± 7.4[b]
Anterior cortex line	17.4 ± 1.7	47.7 ± 14.7[b]
Distal condyle line	–13.6 ± 1.3	–50.0 ± 11.8[c]
Blumensaat line	4.7 ± 1.2	17.3 ± 6.1[c]
Medial intercondylar ridge	6.1 ± 1.8	22.1 ± 7.7[c]
PMB to:		
Posterior cortex line	7.9 ± 2.5	22.0 ± 10.1[b]
Anterior cortex line	23.9 ± 2.7	65.6 ± 20.7[b]
Distal condyle line	–14.8 ± 2.0	–54.6 ± 14.0[b]
Blumensaat line	10.7 ± 1.4	39.4 ± 10.0[b]
Medial intercondylar ridge	5.5 ± 1.7	20.0 ± 6.8[b]

[a]Values are reported as the mean ± standard deviation. Measurements made in the anterior and superior directions are indicated by positive values. ALB, anterolateral bundle; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

[b]Percentages were created by normalizing values using the total cortex-to-cortex length of the Blumensaat line.

[c]Percentages were created by normalizing values using the maximum distance from the Blumensaat line perpendicular to the most inferior femoral condyle margin.

The PMB center was 23.9 ± 2.7 mm posteroproximal to this reference line. The ALB and PMB centers were 4.7 ± 1.2 mm and 10.7 ± 1.4 mm posteroinferior from the Blumensaat line. Radiographic measurements for the lateral view of the femur with $BaSO_4$ labeling are reported in Table 3 and displayed in Supplementary Figure A3 (available online).

TABLE 3
Quantitative Relationships of the Femoral Attachments of the PCL Bundles to Landmarks and Reference Lines on Lateral Radiographs After the Addition of $BaSO_4$[a]

Relationship	Distance, mm
ALB	
Anterior margin to posterior cortex line	–3.8 ± 2.2
Posterior margin to posterior cortex line	3.6 ± 2.0
Superior margin to distal condyle line	–18.7 ± 1.8
Inferior margin to distal condyle line	–8.2 ± 1.3
Near margin to the Blumensaat line	1.8 ± 1.0
Far margin to the Blumensaat line	9.8 ± 1.8
PMB	
Anterior margin to posterior cortex line	3.4 ± 2.2
Posterior margin to posterior cortex line	13.9 ± 2.0
Superior margin to distal condyle line	–20.1 ± 2.6
Inferior margin to distal condyle line	–9.0 ± 1.8
Near margin to the Blumensaat line	6.1 ± 1.6
Far margin to the Blumensaat line	15.4 ± 1.7
Bundle center to	
Posterior cortex line	4.4 ± 2.1
Distal condyle line	–14.0 ± 1.6
Blumensaat line	8.5 ± 1.4
Medial intercondylar ridge	5.9 ± 1.7

[a]Values are reported as the mean ± standard deviation. Measurements made in the anterior and superior directions are indicated by positive values. ALB, anterolateral bundle; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

AP Tibia

Radiographic measurements for the AP view of the tibia are reported in Table 4 and illustrated in Figure 3. The ALB and PMB centers were located 0.2 ± 2.1 mm proximal and 4.9 ± 2.9 mm distal to the proximal joint line, respectively. The PCL attachment center was 1.6 ± 2.5 mm distal to the proximal joint line. The ALB center was located 2.2 ± 1.0 mm superior and the PMB center 2.9 ± 1.0 inferior to the PCL tibial attachment center.

Lateral Tibia

Radiographic measurements for the lateral view of the tibia are reported in Table 5 and illustrated in Figure 4. The ALB and PMB centers were located 8.4 ± 1.8 mm and 2.5 ± 1.5 mm superior to the champagne glass drop-off, respectively, whereas the PCL attachment center was 5.5 ± 1.7 mm superior to the champagne glass drop-off. The guide wire reference line was 7.0 ± 1.6 mm anterosuperior from the nearest concave edge of the posterior tibia. Radiographic measurements for the lateral view of the tibia with $BaSO_4$ are reported in Table 6 and illustrated in Supplementary Figure A3 (available online).

Data Analysis

Interobserver ICC consistency was assessed among each of the reviewers in the first and second measurement trials. The interobserver ICC values were 0.997 and 0.997 for

TABLE 4
Quantitative Relationships of the Tibial Attachments of the PCL Bundles to Landmarks and Reference Lines on AP Radiographs[a]

Relationship	Distance, mm	Percentage
ALB to:		
Proximal joint line	–0.2 ± 2.1	–0.3 ± 2.6
Lateral tibial eminence	–5.2 ± 2.3	–6.7 ± 2.8
Medial tibial eminence	8.1 ± 2.3	10.5 ± 2.9
Lateral posterior root attachment	–4.2 ± 3.2	–5.3 ± 3.8
Medial posterior root attachment	8.7 ± 1.8	11.4 ± 2.5
Shiny white fibers of PHMM	0.7 ± 1.6	0.9 ± 2.1
Tibial PCL attachment center	–2.2 ± 1.0	–2.8 ± 1.3
PMB to:		
Proximal joint line	4.9 ± 2.9	6.2 ± 3.4
Lateral tibial eminence	–4.4 ± 2.1	–5.8 ± 3.0
Medial tibial eminence	9.0 ± 3.2	11.5 ± 3.7
Lateral posterior root attachment	–3.2 ± 3.3	–4.3 ± 4.2
Medial posterior root attachment	9.6 ± 2.8	12.4 ± 3.3
Shiny white fibers of PHMM	5.8 ± 2.3	7.5 ± 2.7
Tibial PCL attachment center	2.9 ± 1.0	3.7 ± 1.3
Tibial PCL attachment center to proximal joint line	–1.6 ± 2.5	2.1 ± 3.0

[a]Values are reported as the mean ± standard deviation. Measurements made in the superior and medial directions are indicated by positive values. All percentages were created by normalizing values using the maximum medial-lateral width of the tibial plateau. AP, anteroposterior; ALB, anterolateral bundle; PCL, posterior cruciate ligament; PHMM, posterior horn of the medial meniscus; PMB, posteromedial bundle.

TABLE 5
Quantitative Relationships of the Tibial Attachments of the PCL Bundles to Landmarks and Reference Lines on Lateral Radiographs[a]

Relationship	Distance, mm	Percentage
ALB to:		
Long axis of the tibia line	31.4 ± 3.8	59.4 ± 6.5
CGD line	–8.4 ± 1.8	–15.8 ± 3.0
Tibial PCL attachment center	–3.8 ± 1.1	–7.1 ± 1.9
PMB to:		
Long axis of the tibia line	35.8 ± 4.2	67.6 ± 6.7
CGD line	–2.5 ± 1.5	–4.8 ± 2.8
Tibial PCL attachment center	3.6 ± 0.9	6.8 ± 1.6
Tibial PCL attachment center to:		
Long axis of the tibia line	34.1 ± 4.1	64.4 ± 6.6
CGD line	–5.5 ± 1.7	–10.4 ± 3.1
Distance between 45° lines	7.0 ± 1.6	13.2 ± 2.8

[a]Values are reported as the mean ± standard deviation. Measurements made in the anterior and superior directions are indicated by positive values. All percentages were created by normalizing values using the maximum anterior-posterior length of the tibial plateau. ALB, anterolateral bundle; CGD, champagne glass drop-off; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

TABLE 6
Quantitative Relationships of the Tibial Attachments of the PCL Bundles to Landmarks and Reference Lines on Lateral Radiographs After the Addition of $BaSO_4$[a]

Relationship	Distance, mm
ALB	
Anterior margin to long axis of the tibia line	28.3 ± 3.4
Superior margin to CGD line	–11.3 ± 2.3
Superior margin to tibial PCL attachment center	–7.8 ± 2.0
PMB	
Posterior margin to long axis of the tibia line	37.1 ± 3.9
Inferior margin to CGD line	–1.0 ± 2.7
Inferior margin to tibial PCL attachment center	6.0 ± 1.2

[a]Values are reported as the mean ± standard deviation. Measurements made in the anterior and superior directions are indicated by positive values. ALB, anterolateral bundle; CGD, champagne glass drop-off; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

the first and second trials, respectively. These values indicate a high consistency of measurements within a reviewer. The intraobserver ICC values were 0.998 and 0.999 for each reviewer. These values demonstrate that the examiners were able to independently measure reference lines and distance measurements consistently.

DISCUSSION

In this study, we report a reproducible set of clinically applicable radiographic guidelines to assist with intraoperative and postoperative assessment of anatomic tunnel placement in PCL reconstructions. Our study yielded excellent interclass and intraclass correlation coefficients, demonstrating that the methods are highly repeatable and accurate. Because of the frequent reported intraoperative use of lateral radiographs during PCL reconstructions, the most important findings of this study were on the lateral views of the femur and tibia. On the lateral femur view, the measurements to the Blumensaat line and the anterior cortex line are likely the most pertinent findings. This measurement axis is a proven technique, and it has been used in ACL radiographic studies.[19,21] In addition, on the lateral tibia radiographs, the PCL attachment center measurement to the champagne glass drop-off, which has been reported to be an important landmark on lateral tibial radiographs,[27] is a critical finding because it is easily observed both radiographically[27] and arthroscopically.[1] This is an important measurement to ensure anatomic placement of the PCL tibial tunnel. These relationships are critical to proper placement of PCL tunnels intraoperatively and could be used to quickly assess proper tunnel placement after inserting a transtibial PCL reconstruction tunnel guide pin.

Our study contrasted the notion that the tibial PCL tunnel is found 1 cm distal to the joint line, as initially reported by Racanelli and Drez.[22] We found that the PCL attachment center was radiographically located 1.6 mm distal to the joint line. We believe that differences in labeling technique, more accurate and higher resolution images with digital measuring features, and more precise calibration techniques may have made our study results slightly different than their initial landmark study completed. Therefore, our findings indicate that anatomic placement of a single tibial PCL tunnel should be located between 1 and 2 mm distal to the joint line on the AP view. We believe that this important landmark can be readily assessed with intraoperative fluoroscopy or radiographs to verify the correct tibial tunnel guide wire position.

A recent article has also reported on a slightly different review of the radiographic landmarks for the ALB and PMB.[18] In this study, the authors compared 3-dimensional photographic images with the results of radiography and reported similar results. Their radiography results, although comparable, differ from the present study because they refer to radiographic grids and reference lines to delineate the radiographic position of the ALB and PMB. In addition, they do not report on the AP femoral relationships or on the margins of the PCL bundle attachment footprints.

Although few reports have noted obtaining intraoperative femoral radiographs to ensure proper tunnel placement during PCL reconstructions, we believe that both AP and lateral femur views may play important roles during surgery. Because femoral tunnel placement has been reported to be the most important determinant of knee stability in PCL reconstructions,[8,26] one should be confident that he or she is placing the femoral tunnels consistently in the proper anatomic location. Our results demonstrated consistent PCL bundle anatomy and highly repeatable femoral measurements. The findings of the femoral location of the ALB attachment provide guidelines for those opting for a single-bundle PCL reconstruction approach. The ALB is functionally the most critical bundle to reconstruct when placing anatomic femoral tunnels.[27] Therefore, single-bundle reconstruction approaches will likely be most successful by following our guidelines for ALB placement. Although clinical studies are required to confirm the findings presented, these measurements may be directly applied intraoperatively to assist in femoral tunnel placement when required after femoral guide pins are inserted.

Clinically relevant landmarks and reference lines observed via radiography, such as the methods suggested through this study, may have the most clinical applicability for assessment of PCL reconstruction tunnel positioning during surgery. There remains a variety of other methods currently used to determine femoral tunnel position for each PCL bundle, such as the "clock-face" method, measuring from the anterior medial femoral condyle articular cartilage edge, or other arbitrary markings.[2,6,7,24,28] However, subjectivity in applying these methods has reportedly led to inconsistency in the reconstruction of other ligaments, including the ACL.[3,5] Therefore, radiography is likely the most objective and repeatable approach for intraoperative assessment of tunnel placement in knee ligament reconstructions.[2]

Transtibial tunnel reaming for a PCL reconstruction is the most common surgical technique currently used.[21,24] However, it carries the potential risk of neurovascular injury by a reamer breaking through the posterior tibial cortex or overpenetration of the guide pin.[9,15,16,31] Combining our 7.0-mm measurement between the simulated guide pin to the posterior cortex edge with the use of a reported 13-mm diameter PCL tibial tunnel,[27] a residual 1 to 2 mm of posterior tibial cortex remains as a safety margin. Because of the minimal amount of cortex remaining, one should carefully evaluate the position of the guide pin intraoperatively to verify it is sufficiently inferior on the posterior tibial facet not only to anatomically place the tibial tunnel but also to not position it too far posterodistal to risk posterior cortex breakthrough and potential neurovascular injury.[15,31] In addition, although the authors believe that intraoperative AP imaging with the knee in full extension is the most reliable method, it is important to flex the knee to 90° while reaming the tibial tunnel to minimize the risk of neurovascular compromise.[16]

We acknowledge that this study has some limitations. Our study numbers, although one of the largest describing knee radiographic landmarks, are still relatively small. Most important, one should recognize the potential limitations of 2-dimensional radiographic measurements of the complex 3-dimensional femoral PCL attachment site. Thus, it is important to recognize this relationship and be cognizant that both AP and lateral radiographs must be concurrently evaluated to accurately assess the PCL femoral attachment radiographically.

CONCLUSION

This study provides radiographic guidelines to identify the individual bundles and centers of the PCL attachment points with using radiographically pertinent landmarks. On the lateral femur view, the ALB center should be located 17.4 mm posteroproximal to the anterior cortex line of the femoral condyles, whereas the PMB center should be located 23.9 mm posteroproximal to this reference line. Tibial placement of ALB and PMB centers should be located 8.4 mm and 2.5 mm superior to the radiographically visualized champagne glass drop-off of the posteroproximal tibia on the lateral radiograph, respectively, whereas the PCL attachment center should be 5.5 mm superior to it. Contrary to previous reports of placing the PCL tunnel 1 cm distal to the proximal joint line, anatomic placement of a single tibial PCL tunnel should be located between 1 and 2 mm distal to the joint line on the AP view. These findings can be directly applied to proper tunnel positioning intraoperatively during PCL reconstruction and also to assess reconstruction tunnel placement postoperatively.

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