Dynamic Three-Dimensional Computed Tomography Mapping of Isometric Posterior Cruciate Ligament Attachment Sites on the Tibia and Femur: Single- Versus Double-Bundle Analysis

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Purpose: (1) To determine the area of posterior cruciate ligament (PCL) insertion sites on the lateral wall of the medial femoral condyle (LWMFC) that demonstrates the least amount of length change through full range of motion (ROM) and (2) to identify a range of flexion that would be favorable for graft tensioning for single-bundle (SB) and double-bundle (DB) PCL reconstruction. **Methods:** Six fresh-frozen cadaveric knees were obtained. Three-dimensional computed tomography point-cloud models were obtained from 0° to 135°. A point grid was placed on the LWMFC and the tibial PCL facet. Intra-articular length was calculated for each point on the femur to the tibia at all flexion angles and grouped to represent areas for bone tunnels of SB and DB PCLR. Normalized length changes were evaluated. **Results:** Femoral tunnel location and angle of graft fixation were significant contributors to mean, minimum, and maximum normalized length of the PCL (all $p < .001$). Tibial tunnel location was not significant in any case (all $p < .22$). A femoral tunnel in the location of the posteromedial bundle of the PCL resulted in the least length change at all tibial positions (maximum change 13%). Fixation of the anterolateral bundle in extension or at 30° flexion resulted in significant overconstraint of the PCL graft. The femoral tunnel location for a SB PCLR resulted in significant laxity at lower ranges of flexion. **Conclusion:** PCL length was significantly dependent on femoral tunnel position and angle of fixation, whereas tibial tunnel position did not significantly contribute to observed differences. All PCL grafts demonstrated anisometry, with the anterolateral bundle being more anisometric than the posteromedial bundle. For DB PCLR, the

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posteromedial bundle demonstrated the highest degree of isometry throughout ROM, although no area of the LWMFC was truly isometric. The anterolateral bundle should be fixed at 90° to avoid overconstraint, and SB PCLR demonstrated significant laxity at lower ranges of flexion. **Clinical Relevance:** Surgeons can apply the results of this investigation to surgical planning in PCLR to optimize isometry, which may ultimately reduce graft strain and the risk of graft failure. Additionally, DB PCLR demonstrated superiority compared with SB PCLR regarding graft isometry, as significant laxity was encountered at lower ranges of flexion in SB PCLRs. Fixation of the ALB at 90° flexion should be performed to avoid overconstraint in knee extension.

See commentary on page 2885

Posterior cruciate ligament (PCL) injuries may decrease knee joint longevity secondary to degenerative changes from associated biomechanical derangements.[1] Although improvements in single-bundle PCL reconstruction (SB PCLR) tunnel placement, fixation type, and optimal graft fixation angles have been achieved, biomechanical and clinical studies have demonstrated residual laxity after SB PCLR.[2,3] Improved understanding of the anatomy and biomechanics of the PCL and SB PCLR has led to the development of techniques that better replicate the natural PCL anatomy; namely, the double-bundle PCL reconstruction (DB PCLR).[1,4,5]

The DB PCLR seeks to restore normal knee anatomy through reconstructing both the anterolateral bundle (ALB) and posteromedial bundle (PMB). The ALB runs vertically from its attachment on the tibia to the roof of the notch and has a predominant function in controlling posterior tibial translation. The PMB has a more oblique course and attaches to the lateral wall of the medial femoral condyle (LWMFC). A recent systematic review reported that DB PCLR provides significantly greater posterior tibial stability and International Knee Documentation Committee (IKDC) scores compared with SB PCLR in randomized clinical trials.[6] Recent evidence has suggested that the differences in these outcomes may be secondary to increased resistance to posterior tibial translation achieved by reconstructing both the ALB and PMB.[7]

Both the ALB and PMB are naturally anisometric. These bundles are subject to varying forces throughout the arc of motion as a function of having different intra-articular distances from the LWMFC to the tibial plateau. This natural anisometry subjects a graft (or grafts) placed in different positions to significant length changes and forces throughout range of motion (ROM), which can lead to graft elongation and increased risk of failure.[8]

The anisometric nature of PCL grafts should be minimized to obtain ideal stability and decrease the stress transferred to the grafts. Therefore, determining the best flexion angle for fixation of PCL grafts to prevent overconstraint or overtensioning would be of great clinical utility.

The purposes of this study were (1) to determine the area of PCL insertion sites on the LWMFC that demonstrate the least amount of length change through full range of motion and (2) to identify a range of flexion that would be favorable for graft tensioning for SB and DB PCLR. The authors hypothesized that within the femoral footprint, there would be an area that demonstrates minimal length change, and that changes in both tibial and femoral tunnel position would significantly affect the intra-articular isometry. Additionally, it was hypothesized that a SB PCLR would not demonstrate isometric behavior.

Methods

Specimens

Six fresh-frozen cadaveric human knees were used in this study. The cadaveric specimens used in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. Per the tissue bank (Science Care, Phoenix, AZ), the specimens had no history of arthritis, cancer, surgery, or any ligament knee injury. All specimens and computed tomography (CT) images were further examined by 2 sports medicine fellowship-trained orthopaedic surgeons for bony abnormalities before initiation of data collection. The mean age of the donors was 47 years (range 26 to 59). Each knee was preserved at −20°C and thawed for 24 hours before imaging.

Three-Dimensional CT Knee Models

Each knee underwent CT imaging (BrightSpeed; GE Healthcare, Chicago, IL) in the coronal, axial, and sagittal planes by use of 0.625-mm contiguous slices (20-cm field of view, 512 × 512 matrices) at various flexion angles. An external fixation device was used to ensure consistent flexion during scanning by holding the proximal and distal portions of the specimen in place during each scan. The knees were scanned at 0°, 10°, 20°, 30°, 40°, 90°, 110°, and 125° flexion, via previously validated methodology.[9,10] Additional care was taken to ensure neutral alignment of the specimens during fixation: the neutral alignment was independently confirmed visually and by by 2 of the senior authors. Using a previously described method, CT images were imported in DICOM format and segmented with 3-dimensional (3D) reconstruction software (Mimics; Materialise, Leuven, Belgium) to generate the 3D knee models.[9-11]

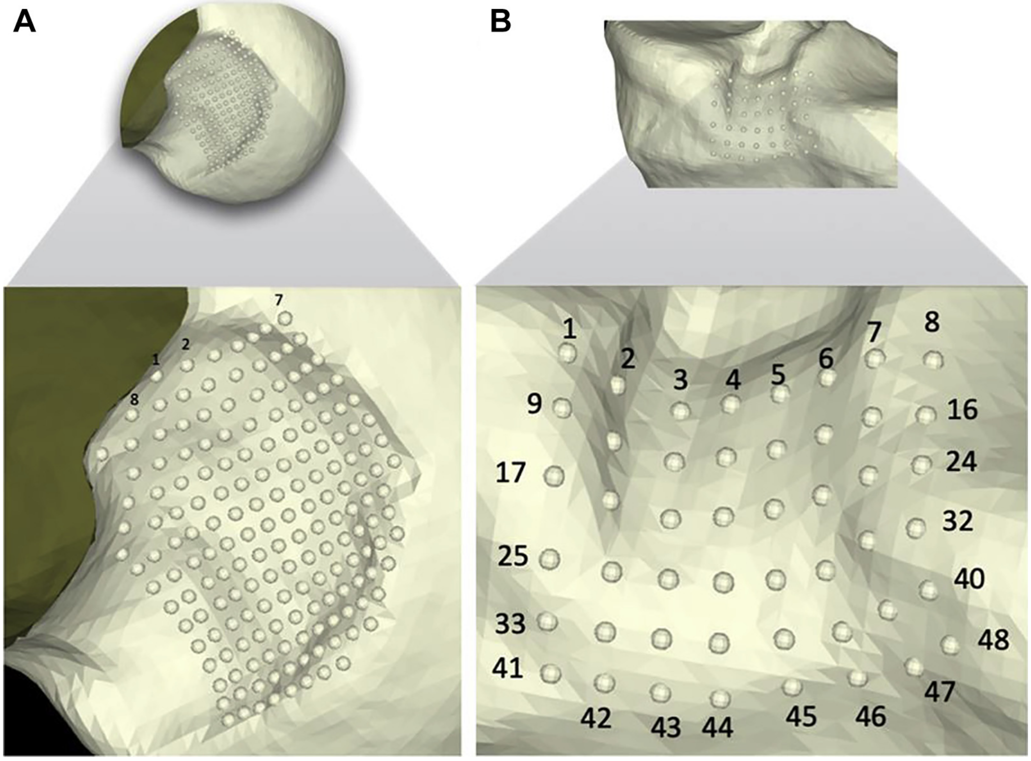

Figure 1. Depiction of femoral posterior cruciate ligament (PCL) footprint and tibial PCL footprint points on a 3-dimensional projection of a right knee. During surgery, the authors' preference is to obtain these views via an anterolateral portal. (A) View of femoral PCL footprint from an anterior view projected obliquely so as looking at the medial wall of the lateral femoral condyle. (B) Anterior view of the tibial PCL footprint, looking inferiorly at the anterior intercondylar region of the tibia.

Determination of Tibial PCL Insertion Sites

A total of 48 virtual tibial insertion sites were determined on the tibial plateau model at 0° flexion (Figure 1). These tibial insertion sites were distributed in an 8- by 6-point grid, which measured 16.8 by 15.0 mm in plane. In the longer axis, points were 2.4 mm apart, and in the shorter axis, they were 3.0 mm apart. Bony landmarks were identified by 2 sports medicine fellowship-trained orthopaedic surgeons, including the bundle ridge, which demarcates the separation between the ALB and PMB.[12] The ALB was located proximal, anterior, and lateral to the bundle ridge, whereas the PMB was distal, posterior, and medial to the bundle ridge. The center of a single PCL tunnel was also identified immediately anterior to the bundle ridge, on the medial side of the PCL facet, 9.8 mm from the lateral cartilage point, as previously described.[12,13]

A planar 48-point grid was then sized and carefully placed to align the 2 bundle locations with the coordinates of the grid. An additional point was set at the midpoint of the ALB and the PMB points. The grid was sized and oriented so that the tunnel locations corresponded to the same relative coordinates for each sample. The grid was projected on the 3D tibial plateau model, and 3D coordinates of each insertion point were obtained. Transformation matrixes from the tibial model at 0° to the tibial models in flexion were calculated by using a 3D-3D registration technique, which ensured each point was maintained in the same position on each model, and the PCL insertion points at 0° of flexion were transformed to the flexed tibial models. This procedure allowed for creating the tibial insertion points in various flexion angles identical to those in 0° of flexion.

Determination of Femoral PCL Insertion Sites

Similar to the tibial PCL insertion site determination, a 152- to 172-point grid (depending on the size of the specimen) was virtually placed on the lateral wall of the medial femoral condyle in the femoral model by referring to the trochlear point, the medial arch point, and the medial bifurcate prominence. The ALB was positioned in the center of these 3 landmarks, as previously described.[12] The PMB was placed halfway from the posterior point and the medial arch point in the femur, distal to the medial intercondylar ridge (Figure 2).

The 100-point grid was then superimposed while ensuring that it encompassed the center point of the ALB and PMB. The grid was then projected on the 3D medial femoral condylar model, and the PCL femoral insertion sites were determined at the grid points on the lateral wall of the medial femoral condyle. An additional point was set at the center of the ALB and the PMB points. The insertion points in the flexed conditions were calculated by the same procedure described above.

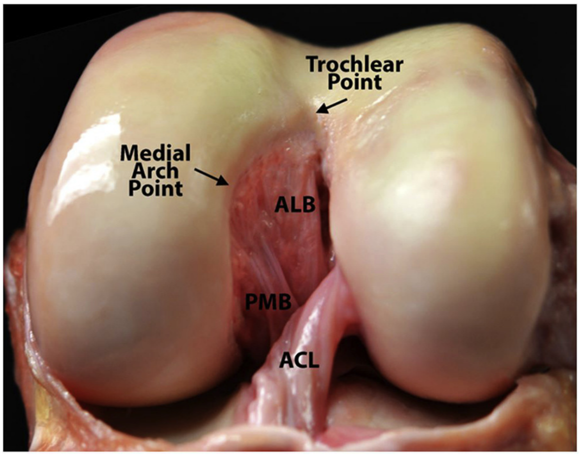

Figure 2. Anatomic dissection of a left knee demonstrating the femoral attachments of the anterolateral bundle (ALB) and posteromedial bundle (PMB) of the posterior cruciate ligament (PCL) and the osseous landmarks: the trochlear point and medial arch point. Note that the ALB attaches adjacent to the cartilage margin and that the PMB's most distal aspect is 5 mm proximal to the articular cartilage margin. ACL, anterior cruciate ligament.

PCL Length Calculation

The PCL length L_{ijk} between the tibial insertion point j and the femoral insertion point k at the femoral flexion angle i was calculated as a virtual 3D distance between these 2 points using the distance formula derived from the Pythagorean theorem:

$$L_{ijk} = \sqrt{\left(x_{tij} - x_{fik}\right)^2 + \left(y_{tij} - y_{fik}\right)^2 + \left(z_{tij} - z_{fik}\right)^2},$$

where x_{tij}, y_{tij}, and z_{tij} are the coordinates of the tibial insertion point j at the femoral flexion angle i; and x_{fik}, y_{fik}, and $_{zfik}$ are the coordinates of the femoral insertion point k at the flexion angle i. Isometry at the femoral flexion angle i between the tibial insertion point j and the femoral insertion point k was evaluated by an increment of the length change, Δ in reference to the length at 0° of flexion, calculated by $\Delta = L_{ijk} - L_{0jk}$. The use of 0° flexion as the reference point was chosen by convention, in agreement with previous works completed with similar methodology. Establishing this as a consistent reference point allowed for a consistent framework to interpret changes. Therefore, a zero value of Δ indicates isometry, a positive value indicates elongation of the PCL, and a negative value indicates shortening of the PCL during femoral flexion. All lengths from all tibial points to each of the femoral points were calculated at all flexion angles.

Determination of Tunnel Locations

After PCL length changes were calculated from all femoral to tibial coordinates, 3 groupings of points were used for isometry analysis. These groupings were determined by systematically placing 3 circles on the femoral grids. Because a standard size grouping would vary with respect to the different specimen sizes, the circles were sized relative to the previously described morphologic landmarks. Two circles were placed about the center points of the ALB and PMB, matching the native anatomy (11-mm diameter for ALB, 7-mm for PMB), to replicate tunnel locations in a DB PCLR (referred to as DB-ALB and DB-PMB). A line perpendicular to half the distance between the center of the ALB and PMB bundles was marked, and a third circle of 12 mm was placed over the intersection of this line and the lateral intercondylar ridge, to replicate the tunnel for a SB PCLR (referred to as SB).

The points encompassed by the 3 circle groupings on the femur were identified. If the circle encompassed a point outside the medial wall of the medial femoral condyle, this specific point was not included. The distances from 3 tibial sites (ALB bundle center point, PMB bundle center point, and the center of these) to the points encompassed by the circle groupings were retrieved for all flexion angles. Mean distances were calculated for each potential combination of tunnel locations (3 femoral to 3 tibial, 9 total per knee) and at each angle of knee flexion. Next, the maximum ligament length through the knee range of motion was defined for each tunnel combination. Ligament lengths at each flexion angle were then normalized to this maximum length to allow for more direct comparisons between subjects.

Characterization of Isometry

The percentage change in ligament length over the full range of motion was determined for each tunnel combination to determine which tunnels resulted in the greatest degree of isometry. Factors affecting length of the PCL were then determined by use of analysis of variance (ANOVA). Additionally, to assess differences at each angle of graft fixation, ligament strain was plotted against each flexion angle, with a hypothetical fixation angle set at 0°, 30°, and 90° knee flexion. For these plots, 0° flexion was considered the reference point, and strain was reported as incremental change from this value. Finally, for each femoral tunnel location (DB-ALB, DB-PMB, and SB), pairwise comparisons were made across fixation angles (0° versus 30°, 0° versus 90, and 30° versus 90°).

Statistical Analysis

Statistical analyses were performed with Excel (Microsoft Corp., Redmond, WA) and Stata 14 (StataCorp, College Station, TX). Three different factorial ANOVA models were constructed to determine whether femoral tunnel position, tibial tunnel position, or angle of graft fixation (0°, 30°, and 90°) had significant interactions in affecting (1) normalized ligament length, (2) minimum normalized length, and (3) maximum normalized length.

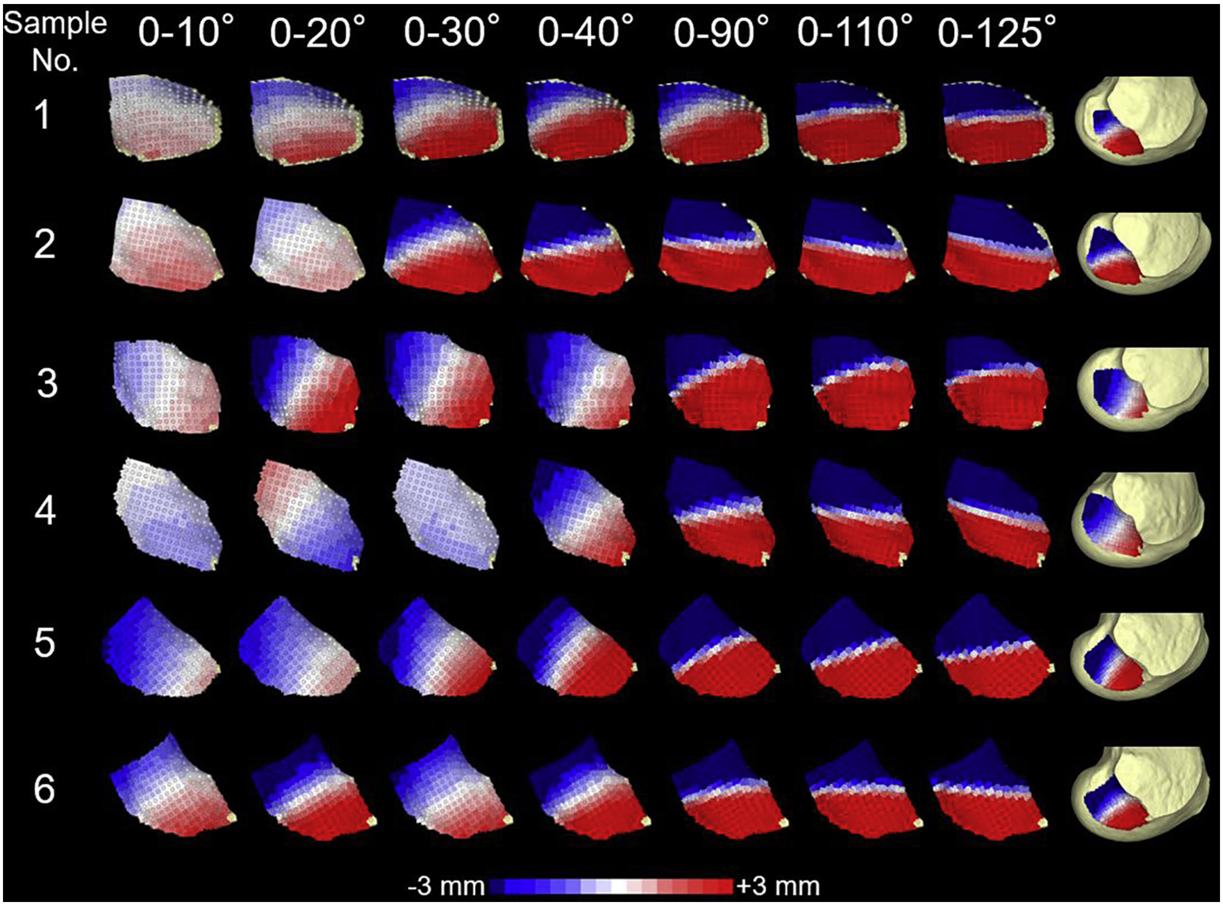

Figure 3. Length-change maps through full range of motion from every coordinate on the lateral wall of the medial femoral condyle to the tibial central of the PCL attachment, for all included specimens. With 0° as reference, red (+3 mm) indicates lengthening of the PCL, blue (−3 mm) indicates shortening, and white (0 mm) indicates minimal change.

Results of the ANOVA analysis are presented with F values, which represent the variance between groups divided by the variance within groups. Results of pairwise comparisons are reported with contrast values. Statistical significance was defined as $p < .05$ for all analyses.

Results

Intra-articular Length Changes

A heatmap of length changes throughout the range of knee flexion from all included samples is displayed in Figure 3. This representation uses full extension as the reference measurement and displays the length changes from all femoral points for a given sample to the center of the PCL attachment on the tibia, as determined by a previous investigation on PCL anatomy by Anderson et al.[12] White areas indicate minimal length changes, or areas of the greatest isometry. No area of the lateral wall of the medial femoral condyle was truly isometric throughout ROM; however, specific areas of the medial femoral condyle appear to confer higher degrees of isometry throughout ROM than others, as evidenced by the white elliptical region on the heat map. This relationship was consistent for all 6 cadaveric specimens.

Upon measurement of length changes for each femoral tunnel location, the DB-PMB position demonstrated the smallest length change at each position on the tibia, with a maximum length change of 13% in relation to the AM tibial position. In contrast, the DB-ALB position demonstrated a maximum length change of 26% in relation to the AM tibial position. The SB position demonstrated a maximum change of 20%, also with respect to the AM tibial position (Table 1).

Factors Affecting Ligament Length

Factorial ANOVA with normalized PCL length as the dependent variable demonstrated that the following independent variables resulted in significant changes: femoral position ($F = 21.13$, $p < .001$); flexion angle ($F = 229.81$, $p < 0.001$); angle of fixation ($F = 629.93$, $p < .001$); interaction of femoral position and angle of flexion ($F = 28.14$, $p < .001$); and interaction of femoral position and fixation angle ($F = 105.70$, $p < .001$). Tibial position was not a significant factor in any case (all $p > .31$).

Table 1. Range of Normalized Lengths (%)

	DB-ALB	DB-PMB	SB
Tibial points			
Anteromedial	26	13	20
Center	25	13	21
Posterolateral	22	11	17

Note. Minimum length and maximum length through range of motion were used to normalize the depicted range of length changes.
DB-ALB, double-bundle anterolateral bundle; DB-PMB, double-bundle posteromedial bundle; SB, single bundle.

Factorial ANOVA to determine the factors that affected minimum normalized length, indicating a lax, nonfunctional ligament, showed significant variation based on the following independent variables: femoral position ($F = 20.48$, $p < .001$), angle of fixation ($F = 170.70$, $p < .001$), and the interaction of these 2 variables ($F = 27.83$, $p < .001$). Tibial position was not a significant factor, with all $p > .57$. For femoral location, post hoc pairwise comparisons with Tukey correction demonstrated significant differences between DB-PMB and DB-ALB (contrast 0.03, $p < .001$) and SB versus DB-PMB (contrast −0.02, $p < .001$); the difference between SB and DB-ALB was not significant (contrast 0.012, $p = .07$).

An identical factorial ANOVA test using maximum normalized length, indicating the possibility of ligament failure or overconstraint, as the dependent variable also demonstrated significant differences based on the same 3 independent variables: femoral position ($F = 21.52$, $p < .001$), angle of fixation ($F = 72.52$, $p < .001$), and the interaction between femoral position and fixation angle ($F = 12.35$, $p < .001$). Again, tibial position was not a significant factor, with all $p > .22$. For femoral location, post hoc pairwise comparisons with Tukey correction demonstrated significant differences between DB-PMB and DB-ALB (contrast −0.06, $p < .001$) and SB versus DB-PMB (contrast 0.04, $p < .001$); there was no significant difference between SB and DB-ALB (contrast −0.02, $p = .06$).

Effect of Graft Fixation Angle

The length-change patterns of each combination of femoral and tibial tunnels with graft fixation at 0°, 30°, and 90° flexion are displayed in Figure 4. At all 3 fixation angles, length-change patterns clustered by

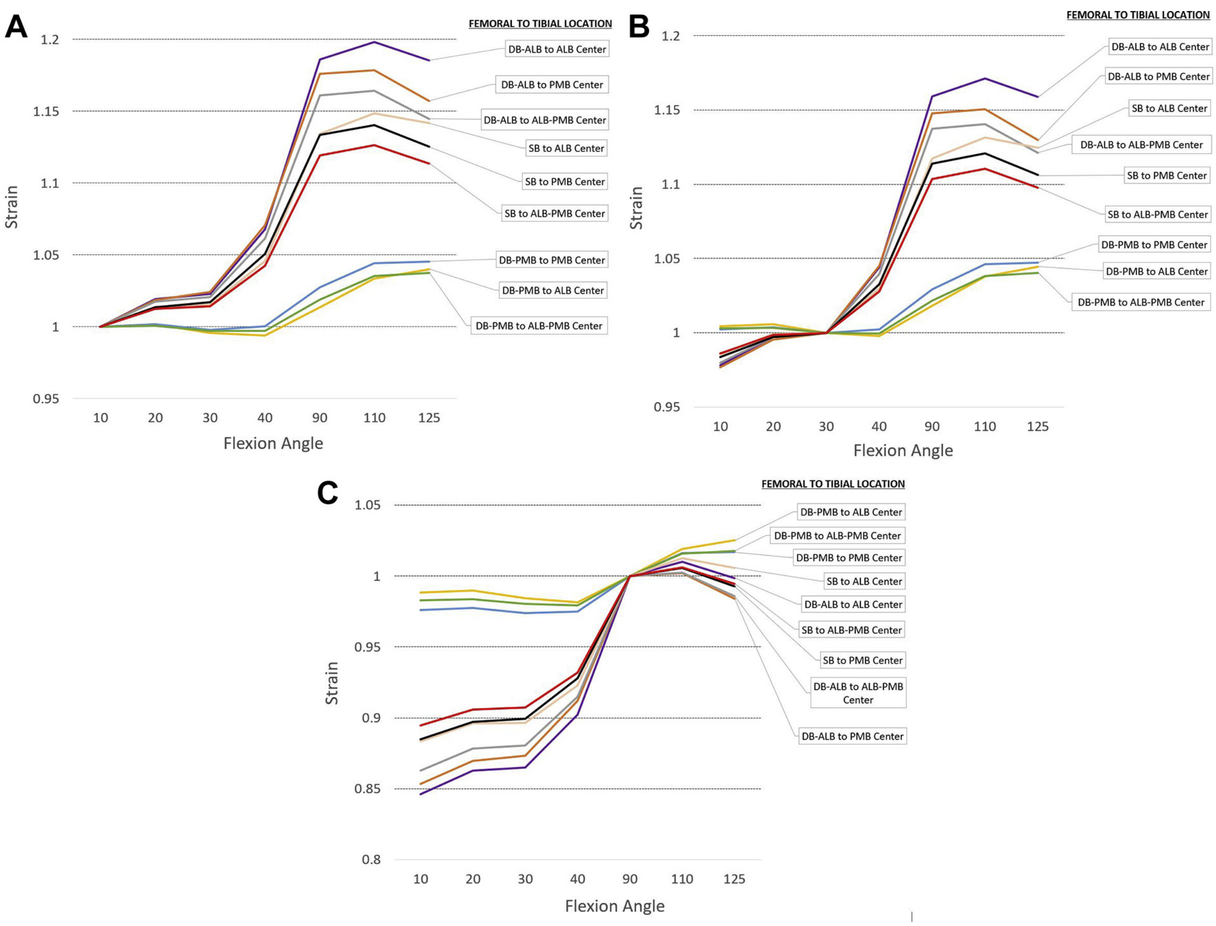

Figure 4. Normalized ligament length through range of motion for all combinations of femoral and tibial tunnel positions with the graft fixed at 0° (A), 30° (B), and 90° (C) of knee flexion. Graft strain is reported as incremental changes from the reference point of 0° of flexion. Strain of 1 indicates isometry, with greater values indicating overtensioning and lesser values indicating laxity.

Table 2. Comparisons of PCL Length Changes at Different Graft Fixation Angles Stratified by Femoral Tunnel Position

Tunnel Fixation Angle (°)	Contrast (mm)	*p* Value	95% Confidence Interval
DB-ALB			
30° versus 0°	−0.026	0.83	−0.080 to 0.028
90° versus 0°	−0.18	<.001*	−0.23 to −0.12
90° versus 30°	-0.15	<.001*	−0.20 to −0.092
DB-PMB			
30° versus 0°	0.0030	1.0	−0.051 to 0.057
90° versus 0°	−0.020	0.96	−0.074 to 0.033
90° versus 30°	−0.024	0.90	−0.077 to 0.030
SB			
30° versus 0°	−0.018	0.98	−0.071 to 0.036
90° versus 0°	−0.13	<.001*	−0.18 to −0.077
90° versus 30°	−0.11	<.001*	−0.17 to −0.059

Note. Contrast indicates difference in graft length between 2 fixation angles. If positive, contrast indicates that the graft length became shorter at the second fixation angle (right) compared with the first fixation angle (left); if negative, the graft length became longer at the second fixation angle compared with the first.

DB-ALB, double-bundle anterolateral bundle; DB-PMB, double-bundle posteromedial bundle; SB, single bundle.

*Statistically significant.

location of the femoral tunnel (all $p < .01$), regardless of tibial tunnel location ($p > .22$ all). Additionally, at all 3 fixation angles, the DB-PMB femoral position resulted in the highest degree of isometry throughout ROM relative to the other bundles, because the trendline consistently most closely approximated graft strain of 1.

Overall comparisons of different fixation angles for each femoral tunnel location are displayed in Table 2. For DB-ALB, fixation at 90° was significantly different than fixation at 0° or 30° (both $p < .001$), whereas fixation at 30° was not significantly different from fixation at 0° ($p = .83$). The same relationships were true for SB. With regard to DB-PMB, no significant differences were found when comparing any 2 fixation angles (all $p \geq .90$).

Figure 5 demonstrates the combinations of tunnels that most closely resemble SB and DB PCLR. With a femoral tunnel at SB and a tibial tunnel at ALB-PMB center, which most closely resembles SB PCLR, the graft demonstrated greater degrees of overconstraint when fixed at 0° or 30° compared with fixation at 90° ($p < .001$). With fixation at 90°, however, the SB femoral position resulted in laxity at lower ranges of knee flexion (Figure 5A). With a femoral tunnel at DB-ALB and a tibial tunnel at ALB center, representing the ALB portion of a DB PCLR, a similar relationship was observed with respect to the 3 fixation angles: fixation at 0° or at 30° resulted in greater overconstraint than fixation at 90° ($p < .001$) (Figure 5B). Finally, with a femoral tunnel at DB-PMB and a tibial tunnel at PMB center, representing the PMB portion of a DB PCLR, strain profiles were similar regardless of fixation angle ($p > .90$). This reflects the aforementioned superior isometry of the DB-PMB femoral position compared with the other bundles, with maximum strain of 1.047 when fixed at 30° and a flexion angle of 125°, and minimum strain of 0.974 when fixed at 90° and flexion angle of 30° (Figure 5C).

Discussion

This study revealed several clinically important findings. The most important finding was that ligament length was highly dependent on femoral tunnel position and angle of fixation, whereas tibial tunnel position had no significant impact. All PCL grafts demonstrated anisometry. For a DB PCLR, the PMB of the PCL demonstrated greater isometry than the ALB throughout the ROM, although no area of the lateral wall of the medial femoral condyle was truly isometric. Finally, the fixation angle did not significantly impact the PMB; however, the ALB should be fixed at 90°, because fixation in extension or at 30° of flexion resulted in significant overconstraint of the graft, which could predispose the surgical construct to failure.

This study demonstrated that femoral tunnel positioning was highly correlated with PCL graft length, whereas tibial tunnel position was not. Specifically, factorial ANOVA showed that that normalized ligament length, minimum normalized length, and maximum normalized length were highly dependent on femoral tunnel position, angle of fixation, and the interaction of these 2 variables. We investigated a region of points on the medial wall of the intercondylar notch of the lateral femoral condyle to reflect isometry of various tunnel positions rather than comparing single point combinations, which likely reflects a more anatomic tunnel topography and graft behavior during PCL reconstruction. Previous cadaveric biomechanical studies have also suggested that modifying tunnel location within the femoral footprint may influence graft length changes. Burns et al.[14] examined the effect of multiple femoral tunnel positions on graft tension in 7 cadaveric knees. They determined that repositioning the graft femoral tunnel position proximally or distally to an isometric tunnel location decreased and increased graft tension, respectively. Furthermore, distal femoral tunnel translocation resulted in a 8.5-mm greater posterior translation than a normal knee at 90° flexion. Although numerous studies have sought to define optimal tibial tunnel placement for PCL reconstruction techniques,[15-20] the 3-dimensional mapping analysis used in the current study suggests that tibial tunnel placement plays a limited role in mediating intra-articular graft length change. It is plausible that the native large area of insertion of the ALB and PMB (mean of 18 mm^2)[4,8,12] confers a lower threshold for length-change during knee flexion, while the convergence of these bundles at the tibial plateau allows for a smaller effect.

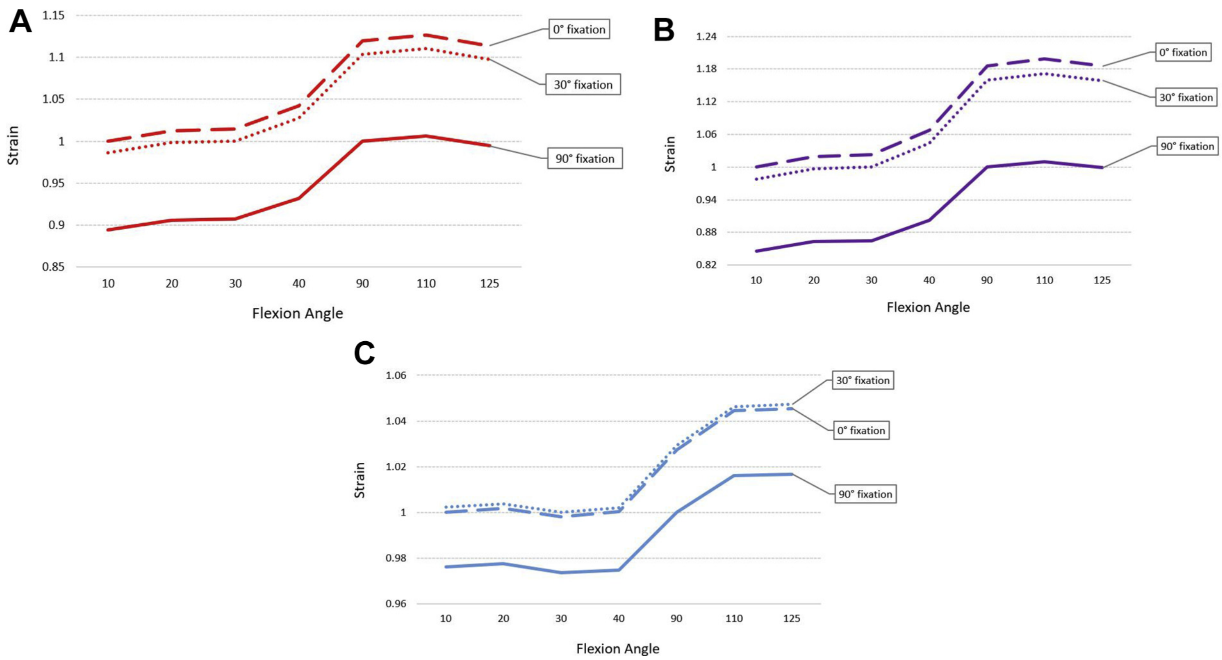

Figure 5. Normalized ligament length through range of motion for femoral and tibial tunnel combinations representing single-bundle (SB) and double-bundle (DB) posterior cruciate ligament reconstruction (PCLR). (A) Femoral position SB to tibial position anterolateral bundle (ALB)-posteromedial bundle (PMB) center, representing SB PCLR. (B) Femoral position DB-ALB to tibial position ALB center, representing the ALB portion of an anatomic DB PCLR. (C) Femoral position DB-PLB to tibial position PLB center, representing the PLB portion of an anatomic DB PCLR. Graft strain is reported as incremental changes from the reference point of 0° of flexion. Strain of 1 indicates isometry, with greater values indicating overtensioning and lesser values indicating laxity.

Interestingly, the PMB of the PCL consistently maintained a higher degree of isometry throughout knee flexion relative to both the ALB of the PCL and graft insertion into a tunnel representative of a single bundle reconstruction. The length changes of the PMB were only as high as 13% at any degree of flexion, compared with 26% for the ALB and 20% for a SB PCLR. In a comparison of the biomechanical properties of the ALB and PMB of the PCL in 22 cadaveric knees, Wright et al.[21] determined that both the ALB and PMB demonstrated largely equivalent biomechanical properties; however, the PMB demonstrated significantly more stress relaxation than the ALB throughout motion ($p = .004$) and showed a gradient of decreasing strength and alignment from anterior to posterior across the PMB. This suggests that distinct functions of the PCL bundles result primarily from anatomic location.[21] Although the findings of the present investigation suggest that no femoral tunnel location was uniformly isometric throughout range of motion at any angle of fixation, the more posterior insertion of the PMB on the lateral wall of the medial femoral condyle appears to be the optimal tunnel location for isometry. This positioning may minimize graft forces as much as possible in the long term. Notably, several authors have also described techniques for retaining remnant PCL tissue during reconstruction procedures.[7,22-24] Doing so and subsequently splinting the affected knee in extension postoperatively may help tighten the posterior capsule and contribute to scar formation of the remnant PMB, adding stability to the overall construct.

Although the PMB location appears to confer the most isometric properties during knee flexion, it is important to recognize the varying graft strains of the ALB if performing a DB PCLR. Indeed, our analyses demonstrated significant graft strain of the ALB above 40° of knee flexion when the fixation angle was at 0° or 30°. Moreover, these data suggest that the ALB must be fixed at 90° to avoid overconstraint of the knee during DB PCLR, because graft strain was high at 0° and 30° of fixation at this femoral tunnel position. A similar concept has been reported by a biomechanical analysis of PCLR kinematics by Kennedy et al.[25] In their investigation, the authors subjected 9 cadaveric specimens with DB PCLR fixation to various posterior tibial loads and internal, external, and valgus rotation torques. They found that fixation of the ALB at 75° resulted in significantly larger graft forces, compared with fixation at 90° or 105° during all load conditions. Ultimately, their results agreed with the findings of the present investigation, and they recommended ALB fixation at 90° or 105° to avoid graft attenuation or failure over time.

When the SB PCLR graft was fixed at 0° or 30°, considerable graft strain was observed when knees were flexed >40°. In contrast, considerable graft laxity was observed at lower degrees of flexion when the graft was fixed at 90°. Other cadaveric studies have also reported shortcomings of SB PCLR: Kennedy et al.[25] found that SB PCLR with fixation at 75°, 90°, or 105° was unable to reduce knee laxity to the baseline state during posterior tibial loading, internal rotation at flexion angles ≥60° flexion, and external rotation at ≥75° flexion.[2] These results, in conjunction with the findings of the present investigation, suggest that DB PCLR may be favorable versus SB PCLR to optimize isometry and functionality of the graft construct. LaPrade et al.[26] demonstrated the efficacy of DB PCLR at 3-year follow up, reporting significant increases in Tegner activity score from 2 to 5, Lysholm from 48 to 86, Western Ontario and McMaster Universities osteoarthritis index (WOMAC) from 25.5 to 5, and SF-12 physical component from 34 to 54.8 in a cohort of 100 patients (all $p < .001$). The complication rate was only 6%, and outcome scores were comparable to patients who underwent isolated ACL reconstruction (all $p > .64$).[26] Chahla et al.[6] compared DB and SB PCLR in a systematic review of 11 studies encompassing 441 patients and reported that although both techniques resulted in increases in patient-reported outcomes, DB PCLR produced significantly better objective posterior tibial translation stability in stress radiographs ($p = -0.58$, 95% confidence interval [CI] −106 to −0.10). However, postoperative Lysholm ($p = .60$, 95% CI −0.98 to 2.18) and Tegner scores ($p = .37$, 95% CI −0.19 to 0.92) were not significantly different between groups.[6] In a randomized controlled trial with 2-year follow-up, Li et al.[27] reported DB PCLR to be superior to SB PCLR with regard to postoperative IKDC grade (DB 71.6 ± 6.7 versus SB 65.5 ± 7.8, $p < .05$) and reduction in side-to side difference in posterior translation (DB 2.2 ± 1.3 versus SB 4.1 ± 1.3 mm, $p < .05$).[27] However, other authors have reported equivalent results after the 2 techniques,[28-30] including Fanelli et al.,[31] who found that both SB and DB techniques were effective in cases of multiple-ligament knee injury. As such, long-term randomized controlled trials investigating the issue of SB versus DB PCLR should be performed to further characterize the relationship between isometry and postoperative outcomes.

Limitations

The results of this investigation should be considered in the context of some limitations. The current study failed to perform an a priori power analysis and used a small sample size of 6 cadaveric knees to test isometry and other biomechanical parameters. However, the point-matrix methodology allows for the use of the same specimens for all measurements and maintenance of identical insertion points throughout the arc of knee flexion, and osseous landmarks were systematically used to minimize error. Furthermore, the computed distances of length-change do not account for ligament integrity and deformation throughout range of motion and may not emulate exact physiologic motion during testing. As such, the viscoelasticity and isometric or anisometric properties of the native PCL, which allows for a small degree of "normal" strain throughout ROM, was not accounted for in the current models. Moreover, because CT scan provides limited information on ligamentous anatomy, we were unable to verify that there was no prior ligamentous damage. However, these stipulations were given to the tissue bank from which the specimens were ordered. Another limitation is that the biomechanical properties of the PMB and ALB together as one construct were not considered, as the primary aims were to independently map length changes and quantify graft strain of individual bundles. Surgeons should consider the individual properties of each bundle when performing a DB-PCLR if applying findings from the current study. All knees were also flexed without rotational torque to maintain neutral alignment; depending on the inherent internal or external rotation of the specimen knee, this may have influenced computed lengths and ligament strain. Despite this possibility, careful inspection of the specimens and CT scanning were performed during all experiments, making the likelihood of this possibility low. Finally, all PCL graft bundles were compared against each other, and data regarding graft strain and length changes of a native PCL were not used for comparisons. It should be noted that in knee extension, the native PCL demonstrates some degree of laxity, similar to the SB reconstruction (Figure 4C). Therefore, definitions of relative isometry pertain to the graft reconstructions in this study and not to the native PCL.

Conclusion

PCL length was significantly dependent on femoral tunnel position and angle of fixation, whereas tibial tunnel position did not significantly contribute to observed differences. All PCL grafts demonstrated anisometry, with the anterolateral bundle being more anisometric than the posteromedial bundle. For DB PCLR, the posteromedial bundle demonstrated the highest degree of isometry throughout ROM, although no area of the LWMFC was truly isometric. The anterolateral bundle should be fixed at 90° to avoid overconstraint, and SB PCLR demonstrated significant laxity at lower ranges of flexion.

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