

Original Research Article

Morphometric analysis of posterior cruciate ligament: an Indian cadaveric study

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ABSTRACT

Background: Functionally, the posterior cruciate ligament (PCL) is divided into an anterolateral (AL) and a posteromedial (PM) bundle. Bundle-level morphometric data are needed to guide anatomically accurate PCL reconstruction.

Methods: The AL and PM bundles of the PCL were dissected and measured in 30 adult Indian cadaveric knees. Measurements of bundle length, midpoint width, and femoral and tibial attachment areas were recorded at knee flexion angles of 30°, 60°, and 90°.

Results: The AL bundle length increased from 34.5 mm at 30° flexion to 38.5 mm at 90° flexion, while its midpoint width decreased from 6.23 mm to 5.92 mm. In contrast, the PM bundle length decreased from 32.82 mm to 30.79 mm, whereas its midpoint width increased from 4.14 mm to 4.32 mm across the same range of flexion. Both bundles demonstrated larger femoral attachment areas compared to their corresponding tibial attachment areas. These findings indicate significant flexion-dependent changes in PCL bundle morphology.

Conclusions: Knee flexion produced significant, reciprocal changes in the dimensions of the two PCL bundles. These values provide population-specific anatomical reference data that may assist the planning of anatomical PCL reconstruction in Indian patients; their clinical relevance requires confirmation.

Keywords: Anterolateral bundle, Cadaver, Footprint area, Knee flexion angle, Morphometry, Posterior cruciate ligament, Posteromedial bundle, PCL reconstruction

INTRODUCTION

Acting together with the posterolateral corner, the posterior cruciate ligament (PCL) is the primary structure that resists backward displacement of the tibia on the femur.¹ It arises from the lateral surface of the medial femoral condyle within the intercondylar notch and inserts into a depression on the posterior aspect of the tibial intercondylar area. Accurate identification of its femoral attachment landmarks is important for anatomical tunnel placement during PCL reconstruction.² Its fibres are conventionally described as an anterolateral (AL) bundle

and a posteromedial (PM) bundle, although these components act together rather than functioning as entirely separate restraints.^{3,4}

The geometry of the PCL is not constant along its length or across knee positions. Cadaveric investigations have shown regional differences in ligament cross-sectional shape and have identified distinct bony footprints for the two bundles.⁵⁻⁷ Such anatomical information can inform the placement of graft tunnels and the attempt to reproduce the native orientation of ligament fibres.^{2,8} Biomechanical experiments also indicate that the relative contributions of

the bundles to posterior restraint change over the flexion arc.⁴

Indian cadaveric series have reported PCL length, width, insertional area and related cruciate ligament dimensions, but their measurement protocols and anatomical terminology differ.⁹⁻¹¹ Nayyar and Gupta, for example, report their bundle data using anteromedial and posterolateral nomenclature, which cannot be assumed to correspond directly to the AL and PM bundles described here.⁹

Bundle-specific dimensions recorded at several standardized flexion angles have not been widely reported in these cohorts. Such data would show how the measured geometry of each bundle varies across the flexion arc, although cadaveric measurements alone cannot predict graft behavior *in vivo*. Accordingly, the present study set out to quantify, in adult Indian cadaveric knees, how the length and mid-bundle width of the AL and PM bundles differ between 30°, 60° and 90° of knee flexion, and to determine the femoral and tibial footprint area of each bundle.

METHODS

This descriptive cadaveric study evaluated the morphometry of the posterior cruciate ligament (PCL) bundles and their bony attachments in an Indian population. Specimens were obtained through the body donation program of the M.S. Ramaiah Advanced Learning Centre and the Department of Anatomy, M.S.

Ramaiah Medical College and Hospitals, Bengaluru. Sample size was estimated from the tibial insertion data of Tajima et al., who reported a mean anterolateral insertion length of 7.8 mm (SD 1.5 mm).⁶ Assuming comparable values, a 5% significance level and an absolute precision of 0.6 mm, a minimum of 28 knees was required; 30 knees were therefore studied. Knees from donors of either sex aged 18–60 years were eligible if the PCL was intact and there was no macroscopic degenerative change or evidence of previous trauma; knees with a PCL tear, marked macroscopic degeneration or prior injury were excluded. Right and left knees were equally represented. Each specimen extended from the mid-thigh to the mid-tibia so that the joint could be exposed completely. Specimens were stored at –20 °C and thawed at room temperature for 24 h before dissection to facilitate tissue handling and accurate measurement.

All knees were dissected using the same protocol. Through a midline incision, the skin, patellar ligament, surrounding muscles and joint capsule were reflected to expose the joint from the front and back. To obtain an unobstructed view of the PCL, both menisci, the anterior cruciate ligament and the medial and lateral collateral ligaments were excised. The lateral femoral condyle was then removed with a saw, exposing the full course of the AL and PM bundles and allowing their footprints to be measured precisely. The two bundles were distinguished by the direction of their fibres and their sites of insertion, and were carefully separated so that each could be measured independently (Figures 1 and 2).



Figure 1 (A-C): Soft tissue dissection of knee with a midline incision.

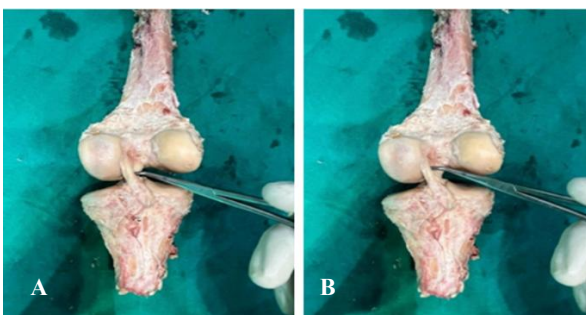


Figure 2 (A and B): PM bundle of PCL on the left and AL bundle on the right.

Linear dimensions were measured with a digital vernier caliper (resolution 0.01 mm), and a goniometer was used to set the knee at 30°, 60° and 90° of flexion. The caliper was calibrated before every measurement session. At each flexion angle, six parameters were recorded for each bundle: bundle length, mid-bundle width, and the length and width of its tibial and femoral footprints. Because bundle length changed with flexion, the mid-bundle point was defined as the point halfway along the length measured at that angle. Each parameter was measured three times, and the mean of the three readings was used for analysis (Figures 3 and 4).



Figure 3: (A) Knee with AL & PM Bundle at 30°, 60°, 90° flexion; (B) measuring the length and width of AL and PM bundle length at 30°, 60°, 90° flexion.



Figure 4: (A) Length and width of the AL bundle area of attachment at the femoral surface; (B) length and width of the PM bundle area of attachment at the femoral surface; (C) length and width of the AL bundle area of attachment at the tibial surface; and (D) length and width of the PM bundle area of attachment at the tibial surface. Abbreviations: AL=anterolateral; PM=posteromedial.

The study followed institutional guidelines for research on donated human bodies. Consent for research use had been obtained through the institutional body donation program. Ethical approval was granted by the Institutional Ethics Committee of M.S. Ramaiah Medical College & Hospitals (approval no MSRMC/EC/PG-147/07-2022; dated 22/07/2022), and the anonymity of donors was preserved throughout.

Data were recorded in a spreadsheet and expressed as mean $\pm$ standard deviation (SD). Statistical analyses were performed using Jamovi software. Measurements taken at different flexion angles in the same specimen were compared using paired t-tests, and right- and left-sided specimens were compared using independent-samples t-tests. Statistical significance was set at $p < 0.05$.

RESULTS

Four groups of measurements were obtained for each knee: AL and PM bundle lengths at 30°, 60° and 90° of flexion; the mid-bundle width of each bundle; the length and width of each bundle's tibial and femoral footprint; and the tibial

and femoral attachment area of each bundle. As flexion increased from 30° to 60° and then to 90°, mean AL bundle length rose from 34.5 ± 0.5 mm to 36.0 ± 0.5 mm and 38.5 ± 0.5 mm, whereas mean PM bundle length fell from 32.82 ± 0.2 mm to 31.81 ± 0.2 mm and 30.79 ± 0.2 mm. Mid-bundle widths showed inverse trends: AL narrowed ($6.23 \pm 0.03 \rightarrow 6.07 \pm 0.03 \rightarrow 5.92 \pm 0.03$ mm) and PM widened ($4.14 \pm 0.02 \rightarrow 4.23 \pm 0.02 \rightarrow 4.32 \pm 0.02$ mm). Paired comparisons between angles for both bundles were significant (all $p < 0.001$). Inter-specimen variability was minimal (length min–max span 2 mm at each angle; width ranges 0.06–0.08 mm).

Figure 5 illustrates these steady, opposing trends. Bundle lengths and mid-bundle widths at each flexion angle are listed in Table 1 (mean $\pm$ SD, minimum–maximum and range). Table 2 gives the tibial and femoral attachment area of each bundle, together with the combined PCL attachment area on each bone. Table 3 reports paired t-test comparisons of AL and PM bundle lengths across flexion angles (30° vs 60°, 60° vs 90° and 30° vs 90°). All comparisons were statistically significant ($p < 0.001$).

Table 1: Length and width of anterolateral (AL) and posteromedial (PM) bundles at 30°, 60°, and 90° of knee flexion.

Bundle type	Flexion angle (°)	Mean $\pm$ Std Dev (mm)	Min–Max (mm)	Range (mm)
AL length	30°	34.5 ± 0.5	33.5 – 35.5	2
	60°	36 ± 0.5	35 – 37	2
	90°	38.5 ± 0.5	37.5 – 39.5	2
PM length	30°	32.82 ± 0.2	31.5 – 33.5	2
	60°	31.81 ± 0.2	30.5 – 33	2
	90°	30.79 ± 0.2	29.5 – 32	2
PM width	30°	4.14 ± 0.02	4.10 – 4.18	0.08
	60°	4.23 ± 0.02	4.20 – 4.26	0.06
	90°	4.32 ± 0.02	4.28 – 4.35	0.07
AL width	30°	6.23 ± 0.03	6.18 – 6.26	0.08
	60°	6.07 ± 0.03	6.03 – 6.11	0.08
	90°	5.92 ± 0.03	5.88 – 5.96	0.08

Table 2: Tibial and femoral attachment areas of anterolateral (AL) and posteromedial (PM) bundles, including total attachment areas.

Bundle type	Location	Mean $\pm$ Std Dev (mm ²)	Min – Max (mm ²)	Range (mm ²)
AL	Tibial	66.13 ± 1.14	63.44 – 68.38	4.94
	Femoral	71.73 ± 1.18	69.93 – 73.60	3.67
PM	Tibial	47.88 ± 0.76	46.79 – 49.34	2.55
	Femoral	52.12 ± 0.60	51.24 – 52.92	1.68
Total	Tibial	114.45 ± 1.66	110.45 – 117.30	6.85
	Femoral	123.83 ± 1.42	121.57 – 126.24	4.67

Table 3: Comparing AL and PM bundle lengths at different degrees of knee flexion (Paired t-test).

Bundle type	Comparison	t-statistic	P value
AL	30° vs 60°	-38.47	<0.001

Continued.

Bundle type	Comparison	t-statistic	P value
PM	60° vs 90°	-40.98	<0.001
	30° vs 90°	-62.10	<0.001
	30° vs 60°	-105.28	<0.001
	60° vs 90°	-106.33	<0.001
	30° vs 90°	-177.63	<0.001

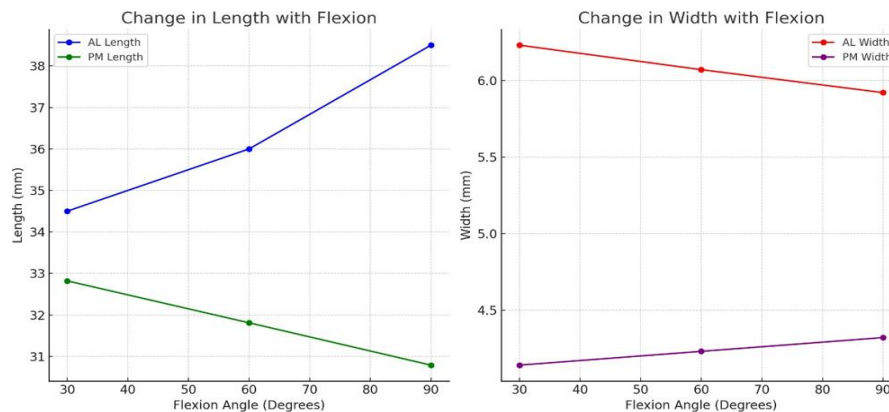


Figure 5: Line graph showing changes of AL and PM bundle length and width at 30°, 60° and 90°.

DISCUSSION

Across the 30 knees examined, the two PCL bundles changed in opposite directions as the knee was flexed from 30° to 90°. The AL bundle progressively lengthened from 34.5 mm at 30° to 38.5 mm at 90° and became narrower, whereas the PM bundle shortened from 32.82 mm to 30.79 mm and became wider. This pattern is consistent with the functional organization of the PCL, in which the AL bundle becomes taut with flexion and the PM bundle is relatively taut near extension.³ Harner et al likewise reported that knee flexion alters the cross-sectional shape of the PCL, although not its cross-sectional area.⁵

The reciprocal behavior of the two bundles supports the concept that the PCL functions as a coordinated multi-bundle structure rather than as a uniform ligament. Using a robotic testing system, Kennedy et al found that the AL and PM bundles share in resisting posterior tibial translation across the flexion range (a codominant relationship), with the balance between them shifting according to knee position.⁴

Earlier selective-sectioning work by Gollehon et al likewise established that the PCL, together with the posterolateral structures, is central to restraining posterior tibial displacement.¹ Because our data are anatomical rather than mechanical, they provide a structural background to these biomechanical findings but cannot be used to infer ligament tension or joint kinematics, neither of which was measured.

The AL bundle demonstrated a larger attachment area than the PM bundle on both femoral and tibial surfaces, and the

total femoral attachment area was greater than the total tibial attachment area. Prior anatomical studies describe distinct AL and PM insertional footprints, although measurement methods and reported areas differ.^{6,7} Radiographic landmarks have also been proposed to guide identification of these attachments during reconstruction.⁸

The present findings have potential implications for anatomical PCL reconstruction. Identifying the femoral origin using anatomical landmarks is important for tunnel positioning, as described by Morgan et al.² Detailed understanding of the tibial footprint may also inform tibial tunnel planning.⁶ The observed angle-dependent differences between the AL and PM bundles suggest that graft positioning and tensioning should account for their differing behavior throughout the flexion arc. Biomechanical studies comparing reconstruction techniques have shown that anatomical double-bundle reconstruction may reproduce native posterior and rotational knee stability more closely than single-bundle reconstruction at selected flexion angles.¹² However, the present study provides morphometric rather than clinical outcome data and therefore cannot establish the superiority of one reconstruction technique over another.

The measurements obtained in this Indian cadaveric cohort provide anatomical reference values that may inform graft selection and femoral and tibial tunnel planning. Indian cadaveric studies have described PCL dimensions and insertional anatomy, although methodological and terminological differences limit direct comparisons.⁹⁻¹¹ Population-based means should not be interpreted as fixed surgical thresholds; patient-specific anatomy and established landmarks remain important.

A strength of this study was the standardized assessment of both PCL bundles at three predefined flexion angles, with triplicate measurements used to improve measurement consistency. The principal limitations include the cadaveric design, absence of physiological loading and neuromuscular control, and inability to directly measure ligament tension or functional knee stability. Dissection and removal of surrounding structures may also alter the native mechanical environment of the PCL. Nevertheless, the consistent reciprocal changes observed in AL and PM bundle dimensions across flexion provide useful anatomical information regarding the dynamic morphology of the native PCL.

Overall, the study demonstrates that PCL bundle morphometry changes significantly with knee flexion, with the AL bundle lengthening and narrowing and the PM bundle shortening and widening. Together with their distinct femoral and tibial attachment areas, these findings reinforce the importance of bundle-specific anatomy during PCL reconstruction and provide morphometric reference data relevant to the Indian population.

CONCLUSION

In adult Indian cadaveric knees, the AL bundle lengthened and narrowed, whereas the PM bundle shortened and widened, as the knee was flexed from 30° to 90°; both bundles had larger femoral than tibial footprints. These population-specific reference values may help surgeons plan graft dimensions and tunnel placement for anatomical PCL reconstruction. Whether tailoring reconstruction to these measurements improves knee stability or clinical outcome requires confirmation in clinical studies.

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