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Kinematic Analysis of the Posterior Cruciate Ligament, Part 1

The Individual and Collective Function of the Anterolateral and Posteromedial Bundles

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Investigation performed at the Department of BioMedical Engineering of the Steadman Philippon Research Institute, Vail, Colorado

Background: The posterior cruciate ligament (PCL) is composed of 2 functional bundles and has an essential role in knee function and stability. There is, however, a limited understanding of the role of each individual bundle through the full range of knee flexion.

Hypothesis: Both bundles provide restraint to posterior tibial translation across a full range of knee flexion. At higher angles of knee flexion ($>90^\circ$), the intact PCL also imparts significant rotational stability.

Study Design: Controlled laboratory study.

Methods: Twenty matched-paired, human cadaveric knees (mean age, 55.2 years; range, 51-59 years; 6 male and 4 female pairs) were used to evaluate the kinematics of an intact, anterolateral bundle (ALB) sectioned, posteromedial bundle (PMB) sectioned, and complete PCL sectioned knee. A 6 degree of freedom robotic system was used to assess knee stability with an applied 134-N posterior tibial load, 5-N·m external and internal rotation torques, 10-N·m valgus and varus torques, and a coupled 100-N posterior tibial load and 5-N external rotation torque at 0° , 15° , 30° , 45° , 60° , 75° , 90° , 105° , and 120° .

Results: All sectioned states had significant increases compared with intact in posterior translation, internal rotation, and external rotation at all tested flexion angles, with the exception of the ALB sectioned state at 75° of flexion for external rotation. The significant increases (mean \pm standard deviation) in posterior translation during a 134-N posterior tibial load at 90° of flexion were 0.9 ± 0.6 mm, 2.6 ± 1.8 mm, and 11.7 ± 4.0 mm for the PMB, ALB, and complete PCL sectioned states, respectively, compared with the intact state. The largest significant increases in internal rotation were in the PMB and complete PCL sectioned states at 105° of flexion, $1.3^\circ \pm 1.0^\circ$ and $2.8^\circ \pm 2.1^\circ$, respectively.

Conclusion: Both the ALB and the PMB assume a significant role in resisting posterior tibial translation, at all flexion angles, suggesting a codominant relationship. The PCL provided a significant constraint to internal rotation beyond 90° of flexion.

Clinical Relevance: This information broadens the understanding of native knee kinematics and provides a template for the evaluation of single- and double-bundle PCL reconstructions.

Keywords: posterior cruciate ligament; posteromedial bundle; anterolateral bundle; knee kinematics

The posterior cruciate ligament (PCL) has gained scientific interest recently because of its role in knee function and stability. The overall size of the PCL, which is the largest and strongest intra-articular knee ligament and comprises 2 functional bundles, is a reason for its importance in overall knee stability and function.^{5,34} In comparison to acute isolated anterior cruciate ligament (ACL) tears, acute

isolated PCL tears have been reported to exhibit inferior knee function preoperatively as evaluated with the Knee Injury and Osteoarthritis Outcomes Score (KOOS).³

The 2 functional bundles composing the PCL are the anterolateral bundle (ALB) and the posteromedial bundle (PMB). The ALB has been reported to be both larger and stiffer compared with the PMB.^{5,8,29} It has also been widely shown that the PCL functions as the primary restraint to posterior tibial translation and as a secondary restraint to external tibial rotation.^{13,26,37} However, a limited number of studies have compared the biomechanical function of each individually isolated bundle of the PCL^{10,25} or

examined the primary role of the PCL in providing knee stability beyond 90° of flexion.

Markolf et al²⁵ previously characterized the effect of sectioning the PMB on anteroposterior laxity of the knee at 0°, 10°, 30°, 45°, 70°, and 90° of knee flexion. The study reported that cutting the PMB produced small yet statistically significant increases in mean posterior knee translation at 0° and 10° of flexion; mean laxities at 30°, 45°, 70°, and 90° were unchanged. The investigators concluded that the PMB plays only a minor role in restraining posterior tibial translation. Conversely, using stress radiographs after sequential sectioning of the ALB and PMB, Garavaglia et al¹⁰ demonstrated that posterior translation was increased after cutting both the ALB and the PMB at 30° and 80° of flexion. Their study reported that both the ALB and PMB have a role in posterior translational stability at these tested flexion angles. Notably, neither study compared the biomechanics of each bundle in isolation, and only a limited number of testing states were chosen; posterior translation beyond 90° of flexion, external/internal rotation, varus/valgus rotation, and coupled motions were not measured. Further, neither study removed the bundles in their entirety; instead, the bundles were sectioned only from their femoral origin. Thus, a degree of uncertainty remains regarding the specific function of the individual bundles of the PCL.

The purpose of this study was to determine the primary biomechanical function of the isolated posteromedial bundle, anterolateral bundle, and the intact PCL between 0° and 120° of knee flexion by using a comprehensive series of testing conditions. This information would lead to a clearer understanding of the individual and collective role of each bundle in providing stability to the knee. It was hypothesized that both bundles of the PCL would be important in resisting posterior tibial translation across a full range of motion and that the intact PCL would have a significant role in rotational stability at higher ranges of knee flexion (>90°).

MATERIALS AND METHODS

Specimen Preparation

Twenty matched-paired (6 male and 4 female pairs) fresh-frozen, human cadaveric knees (mean age, 55.2 years;

range, 51-59 years) without evidence of prior injury, abnormalities, or surgery were used in this study. Each specimen was thawed for 24 hours before use. All soft tissues were removed 12 cm from the joint line for the tibia, fibula, and femur, but all ligaments and musculature were left intact within that 12 cm, except where otherwise noted. Each end was then potted in polymethylmethacrylate (Fricke Dental, Streamwood, Illinois).

PCL Bundle Identification

Access to the PCL was achieved through an anterior lateral parapatellar arthrotomy and a posterior modified Berg approach.⁴ The incision on the anterolateral aspect of the knee started at the distal portion of the vastus lateralis and was continued distally, lateral to the patella, and finished 2 cm lateral to the tibial tubercle. To initialize the posterior approach, the fibular head was palpated, and a horizontal incision was made 2 cm superior to the fibular head. The incision, which traversed medially, parallel to the popliteal crease, was reflected inferiorly to expose the medial head of the gastrocnemius muscle. The medial head of the gastrocnemius was released from its proximal insertion on the posterior capsule at the posterior medial femoral condyle. The oblique popliteal ligament was exposed and partially incised at its distal midsubstance, and the posterior capsule was incised vertically to access the posterior aspect of the PCL.

The knee was taken through flexion and extension to visualize the differing tensioning patterns of the bundles. The posterior meniscofemoral ligament (ligament of Wrisberg) when present was left preserved. As previously reported, the most distinct separation between bundles was noted posteriorly, where the PMB began to fan out laterally and cover the posterior aspect of the ALB, approximately 10 mm proximal to the bundle ridge (Figure 1).² A mosquito hemostat was then introduced anterior to the PMB fibers to separate the bundles distally to the bundle ridge² at the tibial insertion according to a previously described technique.² A looped suture was then passed around the PMB for identification purposes.

The specimen was then rotated to view the PCL anteriorly (Figure 1). As previously reported, the medial arch point,^{2,21} a bony inflection point along the medial wall of

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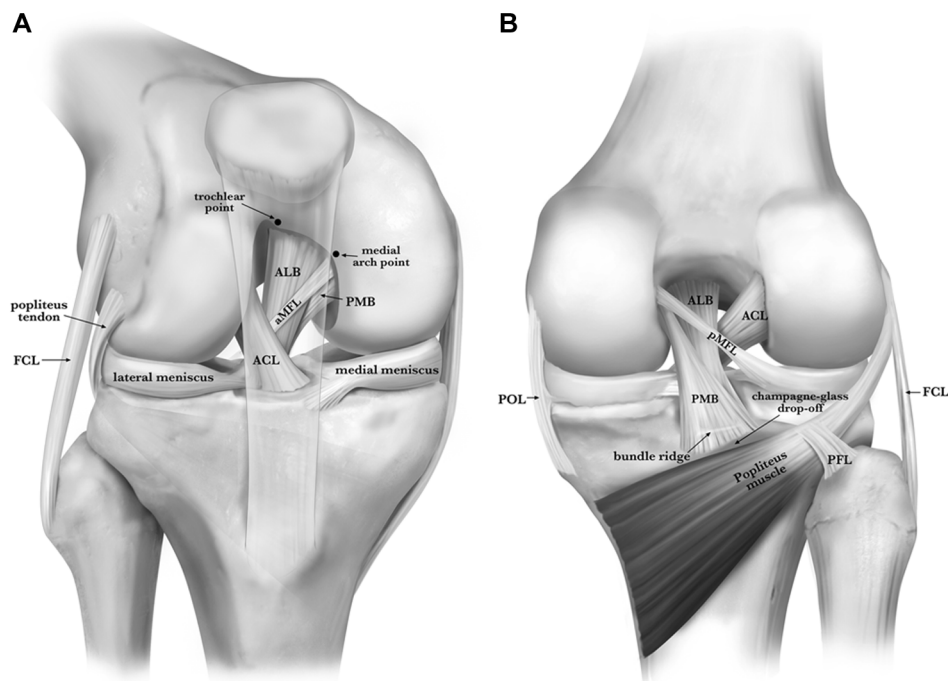


Figure 1. (A) Anterior and (B) posterior views of the native posterior cruciate ligament (PCL). Emphasized are the femoral and tibial attachments of the anterolateral bundle (ALB) and posteromedial bundle (PMB) of the PCL and the osseous landmarks: the trochlear point, the medial arch point, the bundle ridge, and the champagne-glass drop-off. ACL, anterior cruciate ligament; aMFL, anterior menisiofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior menisiofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament.

the intercondylar notch, was used to determine the separation between the 2 bundles at their femoral attachments.²¹ The separation of the 2 bundles was most clearly visualized approximately 1 cm proximal to the medial arch point. For identification purposes, a looped suture was passed through the bundle separation and, by use of the posterior incision, around the lateral edge of the ALB. The looped suture was then fed back to the anterior side, ensuring exclusion of PMB or ACL fibers. Two board-certified orthopaedic surgeons (A.A. and B.M.D.) dissected and separated bundles for each knee; the senior author (R.F.L.) additionally verified the accuracy of the bundle separation. Anterior and posterior incisions for individual bundle identification were closed before the initial testing of the native PCL.

Robotic System

Posterior cruciate ligament biomechanics were evaluated with a 6 degree of freedom (DOF) robotic system (KUKA KR 60-3, KUKA Robotics, Augsburg, Germany) (Figure 2).¹² With use of a custom tibial fixture, the potted tibia and fibula were mounted, in an inverted orientation, to a universal force-torque sensor (Delta F/T Transducer, ATI Industrial Automation, Apex, North Carolina) attached to the robotic end effector.¹²

With the knee mounted in full extension, palpable anatomic coordinates were selected with a coordinate

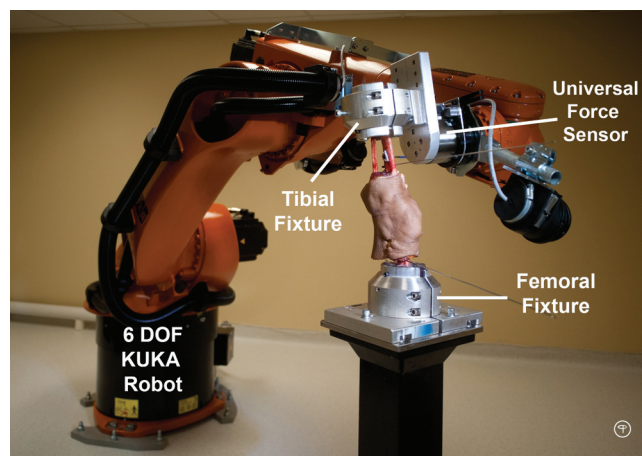


Figure 2. The robotic system setup during posterior cruciate ligament bundle testing with left knee mounted in a fixture attached to a universal force-torque sensor affixed to the end effector of a KUKA KR 60-3 six degree of freedom robot.

measuring machine (Microscribe MX, GoMeasure3D, Amherst, Virginia) to define a coordinate frame for the knee^{9,12,15}; tested accuracy for this system has been reported to be 0.113 mm.¹⁹ Eyelet pins were then drilled perpendicular to the tibia and femur. To establish a neutral alignment of the intact knee while mounting in the femoral

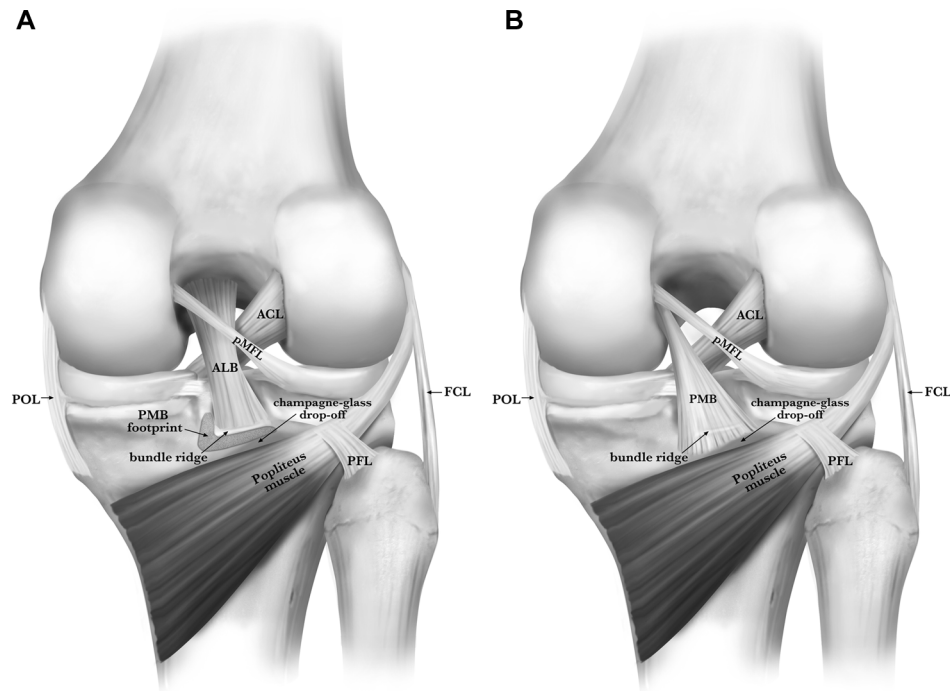


Figure 3. (A) Posterior view of the ALB (PMB sectioned) and (B) PMB (ALB sectioned) states. The bundle ridge is labeled in both figures. ACL, anterior cruciate ligament; ALB, anterolateral bundle; FCL, fibular collateral ligament; PFL, popliteofibular ligament; PMB, posteromedial bundle; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament.

fixture, a pointed-tip metallic weight was hung from the eyelet pin to ensure consistent orientation.

At 1° flexion angle increments, forces and torques in the remaining 5 DOF were minimized (<5 N and 0.5 N·m, respectively), while an axial force of 10 N was applied to ensure proper contact between the tibia and femoral condyles.¹² The passive flexion path was collected from 0° of flexion, or full extension, to 120° of flexion. Each specimen was preconditioned by moving it through the passive flexion path; passive path positions were used as starting points for laxity testing.

Biomechanical Testing

Intact Posterior Cruciate Ligament. A series of simulated clinical examinations were performed with the robotic system. During testing, a 10-N compressive force was used to ensure tibiofemoral contact, while forces at each specified flexion angle in the remaining 5 DOF were minimized with position and force control in conjunction with force feedback from the universal force-torque sensor. Internal system validation determined a point repeatability of 0.19 mm root mean square error and a system force repeatability of 0.02 N root mean square error.¹² Posterior laxity was tested with a 134-N posterior tibial force^{16,22,24,26,28} at 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120° of knee flexion. Additionally, intact knees were tested for rotational stability with 5-N·m external and internal rotation torques,^{14,25,26,37} 10-N·m valgus and varus rotation torques,²⁸ and a coupled 100-N posterior translation force and 5-N·m external rotation torque to simulate a clinical

posterolateral drawer test.²⁰ All tests were completed at each flexion angle, and the testing order was randomized. Intact knees (Figure 1) were first tested; individual bundle and complete PCL sectioned states were sequentially tested and compared with each knee's intact state.

PMB and ALB Deficient States. After intact state testing, either the PMB or ALB was chosen for initial sectioning, which was randomized between specimen pairs. The posterior incision was used to enter the tibiofemoral joint and section the PMB, while the anterolateral incision was used to section the ALB. A midsection incision of the PMB was performed where it had been tagged and separated from the ALB. The PMB was then reflected distally and carefully excised from its tibial attachment by following the bundle to its insertion at the bundle ridge (Figure 1). The anterior incision was used to separate the PMB from the ALB proximally to its femoral attachment. Starting at the medial arch point (Figure 1), the PMB was sharply dissected in an inferomedial direction until it was completely detached from its femoral attachment. Similar to the PMB sectioning, the ALB was incised where it had been tagged and was then reflected proximally toward its femoral insertion.² Again with the medial arch point as a starting point, the ALB was excised from its femoral attachment in a superolateral direction, toward the trochlear point² (Figure 1A). The remaining distal ALB fibers were excised after separation from the PMB at the bundle ridge^{2,18} (Figure 1). The skin incisions were closed and the robotic testing protocol was replicated for the sectioned specimens (Figure 3).

Complete PCL Sectioning. After testing of either the isolated ALB or PMB, sectioning of the remaining PCL bundle was performed. The remaining bundle was cut at its femoral and tibial attachments. The surgical incisions were again sutured and the robotic testing protocol was repeated.

Statistical Analysis

During the testing phase, statistical power calculations were made to estimate the necessary sample size to detect differences between the partial and complete PCL sectioned states. Statistical analysis was performed using a Student 1-sample *t* test to compare the sectioned, ALB sectioned, and PMB sectioned groups individually to the intact state. A 2-sample independent *t* test was used for comparison between the ALB, PMB, and complete PCL sectioned states. The Levene test was used to check for equality of variance, and the Welch *t* test was used when groups had significantly different variances. Differences were considered statistically significant when $P < .05$, and no adjustments were made for multiple comparisons.

RESULTS

The data for the intact, ALB sectioned, PMB sectioned, and complete PCL sectioned states collected from the robotic testing are compiled in Tables 1, 2, and 3. The most clinically pertinent significant findings are reported below as means and standard deviations.

Posterior Tibial Translation

During 134 N of posterior tibial loading, the ALB sectioned, PMB sectioned, and complete PCL sectioned states displayed significant increases in posterior tibial translation when compared with the intact state at all tested flexion angles (Figure 4 and Table 1). The largest increases in posterior tibial translation relative to intact were seen at 120° of flexion for the PMB sectioned state (1.5 ± 0.7 mm) ($P < .001$), at 75° for the ALB sectioned state (2.7 ± 2.0 mm) ($P = .002$), and at 105° for the complete PCL sectioned state (12.5 ± 4.5 mm) ($P < .001$). At 90° of flexion, the flexion angle at which the posterior drawer test is performed clinically, the increases in posterior translation were 0.9 ± 0.6 mm ($P = .001$), 2.6 ± 1.8 mm ($P = .001$), and 11.7 ± 4.0 mm ($P < .001$) for the PMB, ALB, and complete PCL sectioned states, respectively.

Both isolated bundle sectioned states displayed significantly less posterior tibial translation when compared with the complete PCL sectioned state at all flexion angles tested. Between the isolated bundle sectioned states, posterior translation for the ALB sectioned state was significantly greater than the PMB sectioned state for flexion angles between 15° and 90° (Figure 4 and Table 1). The largest difference found between the 2 isolated bundle sectioned states was at 30° of flexion, with the PMB sectioned state displaying 1.8 mm less posterior tibial translation ($P < .001$).

Coupled Posterior Translation and External Rotation

The ALB and complete PCL sectioned states displayed significant increases in posterior translation when compared with the intact state under a coupled 100-N posterior tibial load and 5-N·m external rotational torque at all tested flexion angles. The PMB sectioned state displayed significant increases in posterior translation when compared with the intact state at flexion angles of 30°, 60°, 75°, 105°, and 120°. At 90° of flexion, the position at which the posterolateral drawer test is performed clinically, the increases in posterior translation when compared with the intact state were 0.4 ± 0.5 mm ($P = .054$), 1.5 ± 0.9 mm ($P < .001$), and 3.5 ± 3.0 mm ($P < .001$) for the PMB, ALB, and complete PCL sectioned states, respectively (Table 1).

The PMB sectioned state had significantly less posterior translation when compared with the complete PCL sectioned state between 15° and 120° of flexion. The ALB sectioned state had significantly less posterior translation when compared with the complete PCL sectioned state at flexion angles greater than 30°. In comparisons between the bundle sectioned states, the ALB sectioned state had significantly larger posterior translations than the PMB sectioned state between 30° and 105° of flexion. The largest difference between the 2 individual bundle sectioned states was at 75° of flexion, with the ALB sectioned state displaying 1.3 mm ($P = .004$) more posterior translation.

Internal and External Rotation

All individual bundle and complete PCL sectioned states had significant increases in internal rotation when tested with 5 N·m of internal rotation torque compared with intact at all flexion angles (Figure 5 and Table 2). The largest increase in internal rotation for the complete PCL sectioned state when compared with the intact state was $2.8^\circ \pm 2.1^\circ$ ($P < .001$) at 105° of flexion. The largest increase in internal rotation for the PMB sectioned state when compared with the intact state was $1.3^\circ \pm 1.0^\circ$ ($P = .002$) at 105°. The largest increase in internal rotation for the ALB sectioned state when compared with the intact state was $0.9^\circ \pm 0.7^\circ$ ($P = .003$) at 75°. The PMB sectioned state had significantly less internal rotation compared with the complete PCL sectioned state at high flexion angles ($\geq 90^\circ$ of flexion). The ALB sectioned state had significantly less internal rotation than the complete PCL sectioned state at 0°, 90°, 105°, and 120° of flexion.

There were small but significant increases in external rotation for the PMB sectioned state and complete sectioned state when compared with the intact state for all tested flexion angles under a 5-N·m external rotation torque. The ALB sectioned state had significantly more external rotation than the intact state at all flexion angles except 75°. At 90° of flexion, all 3 states had significantly increased external rotation when compared with the intact state: $0.5^\circ \pm 0.4^\circ$ ($P = .004$), $0.8^\circ \pm 0.8^\circ$ ($P = .019$), and $0.9^\circ \pm 0.9^\circ$ ($P = .001$) for the PMB, ALB, and complete PCL sectioned states, respectively (Table 2). The PMB sectioned state had significantly less external rotation than

TABLE 1

Data Collected for Posterior Translation in Response to a 134-N Posterior Tibial Load and in Response to a Coupled 100-N Posterior Tibial Load and 5-N·m External Rotational Torque^a

Posterior Tibial Load				
Flexion Angle	Posterior Translation, mm		Change in Posterior Translation, mm	
	Intact (n = 20)	PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	10.5 ± 3.3	0.5 ± 0.4 ^{I,S}	0.7 ± 0.4 ^{I,S}	1.8 ± 1.1 ^I
15°	11.5 ± 3.6	0.6 ± 0.3 ^{I,S,B}	1.4 ± 0.8 ^{I,S,B}	3.5 ± 2.1 ^I
30°	10.8 ± 3.7	0.5 ± 0.4 ^{I,S,B}	2.3 ± 1.0 ^{I,S,B}	6.0 ± 2.3 ^I
45°	8.8 ± 3.4	0.7 ± 0.5 ^{I,S,B}	2.4 ± 1.2 ^{I,S,B}	8.1 ± 2.7 ^I
60°	7.3 ± 3.3	0.9 ± 0.6 ^{I,S,B}	2.2 ± 1.1 ^{I,S,B}	9.8 ± 3.1 ^I
75°	6.7 ± 2.9	0.9 ± 0.7 ^{I,S,B}	2.7 ± 2.0 ^{I,S,B}	11.0 ± 3.5 ^I
90°	7.0 ± 3.0	0.9 ± 0.6 ^{I,S,B}	2.6 ± 1.8 ^{I,S,B}	11.7 ± 4.0 ^I
105°	7.7 ± 3.1	1.3 ± 0.8 ^{I,S}	2.6 ± 2.3 ^{I,S}	12.5 ± 4.5 ^I
120°	8.8 ± 3.9	1.5 ± 0.7 ^{I,S}	1.5 ± 0.9 ^{I,S}	11.9 ± 4.3 ^I

Coupled Posterior Tibial Load and External Rotation				
Flexion Angle	Posterior Translation, mm		Change in Posterior Translation, mm	
	Intact (n = 20)	PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	6.5 ± 3.1	0.7 ± 1.5	0.3 ± 0.3 ^I	0.6 ± 0.7 ^I
15°	6.9 ± 3.6	0.2 ± 0.4 ^S	0.6 ± 0.5 ^I	1.1 ± 1.1 ^I
30°	6.9 ± 3.6	0.3 ± 0.4 ^{I,S,B}	0.9 ± 0.5 ^{I,B}	1.7 ± 1.8 ^I
45°	6.1 ± 3.1	0.5 ± 0.8 ^{S,B}	1.4 ± 0.7 ^{I,S,B}	2.6 ± 2.4 ^I
60°	5.7 ± 3.3	0.5 ± 0.6 ^{I,S,B}	1.4 ± 0.6 ^{I,S,B}	3.1 ± 2.6 ^I
75°	5.8 ± 3.1	0.3 ± 0.2 ^{I,S,B}	1.6 ± 1.0 ^{I,S,B}	3.3 ± 2.7 ^I
90°	6.3 ± 3.0	0.4 ± 0.5 ^{S,B}	1.5 ± 0.9 ^{I,S,B}	3.5 ± 3.0 ^I
105°	6.9 ± 3.3	0.5 ± 0.6 ^{I,S,B}	1.4 ± 0.8 ^{I,S,B}	3.5 ± 3.1 ^I
120°	7.8 ± 3.8	0.5 ± 0.4 ^{I,S}	0.8 ± 0.7 ^{I,S}	2.9 ± 3.0 ^I

Coupled Posterior Tibial Load and External Rotation				
Flexion Angle	External Rotation, deg		Change in External Rotation, deg	
	Intact (n = 20)	PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	10.2 ± 2.7	-1.0 ± 2.8	0.1 ± 0.3	-0.2 ± 0.6
15°	12.8 ± 5.0	0.0 ± 0.3	0.0 ± 0.6	-0.4 ± 1.2
30°	15.0 ± 7.2	0.0 ± 0.3 ^S	-0.4 ± 0.7	-1.0 ± 1.7 ^I
45°	15.4 ± 8.1	0.1 ± 0.3 ^S	-0.6 ± 0.9	-1.6 ± 2.3 ^I
60°	15.6 ± 8.0	0.3 ± 0.2 ^{I,S,B}	-0.4 ± 0.9 ^{S,B}	-1.7 ± 2.4 ^I
75°	16.5 ± 7.7	0.3 ± 0.4 ^{I,S}	-0.2 ± 1.1	-1.9 ± 2.5 ^I
90°	17.5 ± 7.8	0.4 ± 0.2 ^{I,S}	0.1 ± 0.9 ^S	-1.8 ± 2.7 ^I
105°	18.4 ± 8.4	0.2 ± 0.3 ^S	0.2 ± 0.7 ^S	-1.9 ± 3.1 ^I
120°	18.7 ± 9.3	0.1 ± 0.4 ^S	0.2 ± 0.4 ^S	-1.8 ± 3.1 ^I

^aValues are expressed as mean ± standard deviation. ALB, anterolateral bundle; PMB, posteromedial bundle.

^ISignificant difference ($P < .05$) from intact state.

^SSignificant difference ($P < .05$) from complete posterior cruciate ligament sectioned state.

^BSignificant difference ($P < .05$) between sectioned bundle states.

the complete PCL sectioned state at 30° and 60° of flexion. No significant differences were found when the individual bundle sectioned states were compared with each other.

Valgus and Varus Rotation

The complete PCL sectioned state had small but significant increases in valgus rotation compared with intact at 0°, 105°, and 120° under a 10-N·m valgus rotation torque

(Table 3). The largest increase in valgus rotation for the complete PCL sectioned state when compared with the intact state was $1.0° ± 1.2°$ ($P = .001$) at 105°. The PMB sectioned state had small but significantly increased valgus rotation compared with intact at 105° and 120°. The ALB sectioned state had significantly increased valgus rotation when compared with the intact state at 75° and 90°. The ALB sectioned state had significantly less valgus rotation than the complete PCL sectioned state at 105° of

TABLE 2
Data Collected for Internal and External Rotation in Response to 5-N·m Internal and External Rotation Torques^a

Flexion Angle	Internal Rotation, deg			
	Intact (n = 20)	Change in Internal Rotation		
		PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	10.4 ± 3.2	0.5 ± 0.6 ^I	0.2 ± 0.2 ^{I,S}	0.6 ± 0.6 ^I
15°	14.3 ± 6.2	0.3 ± 0.3 ^I	0.2 ± 0.2 ^I	0.4 ± 0.3 ^I
30°	17.2 ± 8.5	0.2 ± 0.2 ^I	0.2 ± 0.2 ^I	0.4 ± 0.3 ^I
45°	17.4 ± 8.5	0.3 ± 0.2 ^I	0.4 ± 0.2 ^I	0.6 ± 0.5 ^I
60°	16.8 ± 8.7	0.7 ± 0.7 ^I	0.7 ± 0.5 ^I	1.0 ± 1.0 ^I
75°	16.5 ± 8.5	0.8 ± 0.9 ^I	0.9 ± 0.7 ^I	1.7 ± 1.5 ^I
90°	16.5 ± 8.2	1.1 ± 1.1 ^{I,S}	0.9 ± 0.8 ^{I,S}	2.4 ± 1.8 ^I
105°	17.4 ± 8.7	1.3 ± 1.0 ^{I,S}	0.9 ± 0.8 ^{I,S}	2.8 ± 2.1 ^I
120°	18.3 ± 9.5	1.3 ± 1.0 ^{I,S}	0.7 ± 0.6 ^{I,S}	2.7 ± 2.0 ^I

Flexion Angle	External Rotation, deg			
	Intact (n = 20)	Change in External Rotation		
		PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	12.2 ± 3.2	0.3 ± 0.2 ^I	0.3 ± 0.4 ^I	0.6 ± 0.4 ^I
15°	15.7 ± 6.0	0.3 ± 0.2 ^I	0.5 ± 0.6 ^I	0.6 ± 0.5 ^I
30°	17.8 ± 8.0	0.3 ± 0.1 ^{I,S}	0.4 ± 0.4 ^I	0.5 ± 0.4 ^I
45°	17.4 ± 8.7	0.3 ± 0.4 ^I	0.4 ± 0.3 ^I	0.6 ± 0.5 ^I
60°	16.8 ± 8.5	0.4 ± 0.2 ^{I,S}	0.5 ± 0.5 ^I	0.8 ± 0.6 ^I
75°	17.1 ± 8.0	0.4 ± 0.4 ^I	0.7 ± 1.0	0.9 ± 1.1 ^I
90°	18.0 ± 8.0	0.5 ± 0.4 ^I	0.8 ± 0.8 ^I	0.9 ± 0.9 ^I
105°	18.9 ± 8.7	0.5 ± 0.5 ^I	0.7 ± 0.7 ^I	0.9 ± 0.9 ^I
120°	19.4 ± 9.7	0.3 ± 0.4 ^I	0.6 ± 0.4 ^I	0.8 ± 0.8 ^I

^aValues are expressed as mean ± standard deviation. ALB, anterolateral bundle; PMB, posteromedial bundle.

^ISignificant difference (*P* < .05) from intact state.

^SSignificant difference (*P* < .05) from complete posterior cruciate ligament sectioned state.

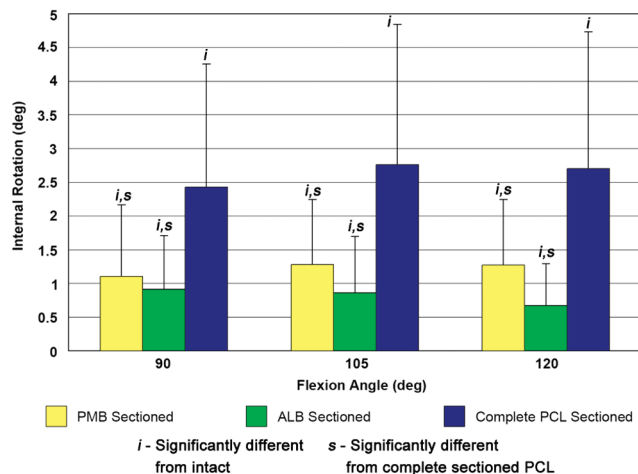
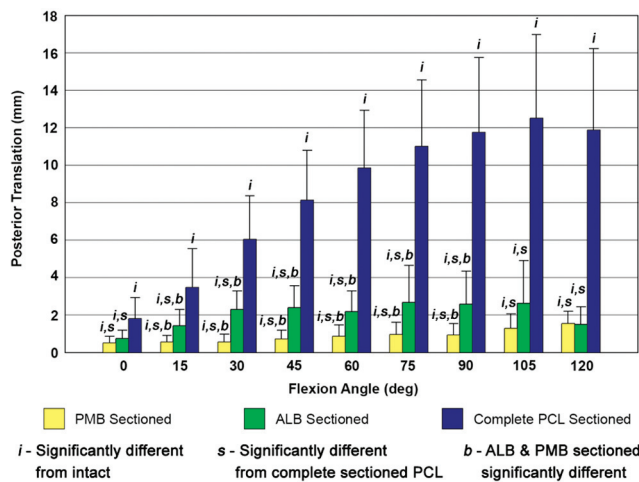


Figure 4. Changes in posterior translation after isolated sectioning of the anterolateral bundle (ALB), isolated sectioning of the posteromedial bundle (PMB), and complete sectioning of the posterior cruciate ligament (PCL). Data are reported as mean increases of posterior translation compared with the intact PCL knee in response to a 134-N posterior tibial force.

Figure 5. Changes in internal rotation after isolated sectioning of the anterolateral bundle (ALB), isolated sectioning of the posteromedial bundle (PMB), and complete sectioning of the posterior cruciate ligament (PCL). Data are reported as mean increases of internal rotation compared with the intact PCL knee in response to a 5-N·m internal rotation torque.

TABLE 3
Data Collected for Valgus and Varus Rotation in Response to 10-N·m Valgus and Varus Rotation Torques^a

Flexion Angle	Valgus Rotation, deg			
	Intact (n = 20)	Change in Valgus Rotation		
		PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	2.9 ± 0.7	0.1 ± 0.2	0.1 ± 0.1	0.1 ± 0.3 ^I
15°	3.9 ± 1.2	0.0 ± 0.3	0.1 ± 0.2	0.1 ± 0.4
30°	4.8 ± 2.0	0.1 ± 0.2	0.1 ± 0.3	0.1 ± 0.4
45°	5.2 ± 2.3	0.1 ± 0.3	0.3 ± 0.5	0.3 ± 0.6
60°	5.4 ± 2.5	0.2 ± 0.3	0.3 ± 0.5	0.0 ± 1.5
75°	5.9 ± 2.9	0.2 ± 0.3	0.4 ± 0.5 ^I	0.3 ± 1.6
90°	6.5 ± 3.2	0.2 ± 0.5	0.5 ± 0.4 ^I	0.4 ± 1.7
105°	7.1 ± 3.4	0.4 ± 0.4 ^I	0.3 ± 0.5 ^S	1.0 ± 1.2 ^I
120°	8.3 ± 3.8	0.4 ± 0.4 ^I	0.2 ± 0.8	0.9 ± 1.4 ^I

Flexion Angle	Varus Rotation, deg			
	Intact (n = 20)	Change in Varus Rotation		
		PMB Sectioned (n = 10)	ALB Sectioned (n = 10)	Complete Sectioned (n = 20)
0°	3.0 ± 0.9	0.1 ± 0.1	0.1 ± 0.1 ^I	0.1 ± 0.2 ^I
15°	3.9 ± 1.3	0.1 ± 0.2	0.1 ± 0.2	0.1 ± 0.3
30°	4.7 ± 1.7	0.1 ± 0.2	0.2 ± 0.3	0.2 ± 0.4 ^I
45°	5.0 ± 2.0	0.1 ± 0.2	0.1 ± 0.2	0.2 ± 0.4
60°	5.4 ± 2.3	0.0 ± 0.2	0.1 ± 0.3	0.1 ± 0.4
75°	5.9 ± 2.5	0.0 ± 0.3	0.2 ± 0.6	0.0 ± 0.8
90°	6.6 ± 2.8	0.1 ± 0.4	0.3 ± 0.8	0.1 ± 1.1
105°	7.4 ± 3.1	0.0 ± 0.3	0.6 ± 0.8	0.1 ± 1.3
120°	8.1 ± 3.6	-0.1 ± 0.4 ^B	0.5 ± 0.7 ^B	0.1 ± 1.2

^aValues are expressed as mean ± standard deviation. ALB, anterolateral bundle; PMB, posteromedial bundle.

^ISignificant difference ($P < .05$) from intact state.

^SSignificant difference ($P < .05$) from complete posterior cruciate ligament sectioned state.

^BSignificant difference ($P < .05$) between sectioned bundle states.

flexion. There were no significant differences between the individual sectioned states.

The complete PCL sectioned state had small but significantly more varus rotation than the intact state at 0° and 30° of flexion. The ALB sectioned had small but significant increases in varus rotation compared with the intact state at 0° of flexion under 10 N·m of varus rotation torque. There were no significant differences in varus rotation when comparing the individual bundle sectioned states to the complete PCL sectioned state. The ALB sectioned state had a small but significant increase in varus rotation at 120° of flexion compared with the PMB sectioned state.

DISCUSSION

The most important finding of this study was that both of the individual bundles of the PCL have a specific stabilizing function throughout the full range of knee flexion in the absence of the other bundle. By examining the effect of sequential sectioning of the individual bundles of the PCL on knee kinematics, this study has demonstrated that the ALB and PMB individually provide a significant restraint

to posterior translation in comparison with a deficient PCL. However, both provided significantly less posterior translational restraint than an intact PCL. The overall clinical relevance in regard to the amount of posterior tibial translation with an individual deficient bundle is not known. It would appear one would have to tear both bundles of the PCL to meet the posterior tibial translation necessary to constitute a grade 3 PCL tear. It was also found that in addition to having a role in restraining posterior translation, the PCL has a small but significant role in restricting tibial internal and external rotations, particularly beyond 90° of flexion. Our findings may be particularly relevant clinically when knee stability in the extremes of flexion (beyond 90°) is required, as occurs in specific competitive sports such as skiing, wrestling, and football.

Of note, there was no significant difference in posterior tibial translation between sectioning of the ALB and PMB at 0° and beyond 90° of flexion. However, as expected, an intact ALB offered slightly greater resistance to posterior translation between 15° and 90° of flexion. Although the ALB was the predominant restraint to posterior translation from 15° to 90°, the PMB also had a supplemental role at these angles.

The PCL restricted internal rotation at all ranges of flexion. The PMB specifically assumed a role in preventing internal rotation beyond 90° of flexion. Taken in isolation, external rotation was significantly increased when the PCL was deficient or either bundle was sectioned for most flexion angles. However, the increases in external rotation were small (<1° of external rotation) and may not be clinically relevant. Finally, complete sectioning of the PCL resulted in significant increases in valgus rotation at the extremes of flexion (105° and 120°). Given the small differences in valgus rotation measured (<1° of valgus rotation), the clinical significance of these valgus rotations is debatable.

A number of biomechanical studies have reported that the PCL is an integral component in preventing posterior tibial translation and provides resistance to external rotation.^{13,16,24-26,30,37} However, to date there are limited data characterizing the biomechanical effects of the PCL beyond 90° of flexion or when subjected to internal or varus/valgus rotation torques. Markolf et al²⁵ investigated the in situ forces on the PCL between 0° and 120° and reported that these forces increased with flexion angle during exposure to posterior tibial load or internal, external, varus, and valgus rotation torques; translations in response to these forces were not considered beyond 90° of flexion. The superficial medial collateral ligament, fibular collateral ligament, and anterior cruciate ligament have all been reported to be restraints to internal rotation; however, these structures have been reported to have a diminishing role in limiting internal rotation as flexion increases toward 90° of flexion.^{6,7,31,35}

The literature is also lacking comprehensive biomechanical analysis of the contributions of each individual PCL bundle.³⁸ While it has been generally accepted and reported that the 2 bundles tension reciprocally, there is less consensus on the distinct function of each bundle.^{11,23,25,29,36} It has been suggested that despite reciprocal tensioning, the 2 bundles exhibit a codominant relationship throughout the flexion range of motion.^{1,10,26,27} The data presented in this study, demonstrating few significant differences between different bundle sectioning states when subjected to a variety of simulated clinical tests, would further corroborate that the 2 bundles have a codominant role in overall PCL function. However, it is also important to consider that if an isolated ALB (sectioned PMB) leads to small but significant increases in posterior translation and external and internal rotation, then a single-bundle PCL graft reconstruction, aiming to replicate the native tensioning pattern and function of the ALB, may similarly result in residual knee instability. One could adjust for that instability by tightening the graft with excess load or with a different tensioning pattern; however, that could lead to overconstraint of the graft and possible graft failure.

The findings of this study also have clinical implications for the use and interpretation of PCL stress radiographs. In general, PCL stress radiographs are obtained at approximately 90° of knee flexion in a kneeling position.¹⁷ Yet, this study demonstrated that a greater degree of posterior translation due to a deficient PCL occurs at 105° rather than at

90° of flexion. This finding would imply that unless the degree of flexion is rigorously adhered to during stress radiographs, discrepancies, even in the same subject, are likely to exist. In light of this, the amount of knee flexion, and in particular the side-to-side comparison, should be taken into consideration when stress radiographs are being performed.

Our results reveal that an isolated PCL injury involving both bundles increased posterior translation by 11.7 mm at 90°, which was more than previously reported for an isolated PCL injury.^{16,32,33} Another clinically relevant finding was that a PCL-deficient knee did not result in increased external rotation in response to a coupled posterior drawer and external rotation torque at 90°. This finding demonstrates that one can be confident that a negative posterolateral drawer test at 90° would be consistent with an isolated PCL tear; however, a positive test would suggest secondary injury to the posterolateral corner of the knee.

The strengths of this study include the use of a highly accurate and repeatable 6 DOF robotic system. In addition, all dissections and bundle separations were performed by 2 orthopaedic surgeons and verified by a third orthopaedic surgeon with an extensive background in PCL anatomy. Fresh-frozen, match-paired specimens with a maximum age of 59 years were used. The skin was left intact and closed during all testing conditions. Furthermore, dissection was performed after testing to verify that the extensive testing protocol did not damage the surrounding ligamentous structures.

Nonetheless, we also recognize some limitations in this study. First, the current results only reflect time-zero knee stability in cadaver specimens. Second, the aim of this study was to assess knee laxity through the use of simulated clinical examinations at various flexion angles. Simulated clinical examinations do not explore the full range of loading that would be observed during dynamic in vivo loading, but clinical examinations are effective for assessing knee laxity. Third, some of the very small differences observed between groups should be interpreted with caution, since they may exceed our system's accuracy and repeatability. Nonetheless, the ability to discriminate small differences between groups represents an advantage of using a highly accurate and repeatable robotic testing platform. Fourth, it is possible that the lack of secondary muscle stabilization of the joint and the rigorous testing protocol could stretch out the primary and secondary knee stabilizers. However, posttesting knee dissection showed no signs of structural damage. Additionally, randomization of the flexion angle testing order likely reduced any incremental bias due to testing order. Fifth, ligament cutting studies are primarily applicable to scenarios in which the PCL is partially or completely absent. The function of the individual bundles when the PCL is partially sectioned may differ from the behavior of the bundles when the entire PCL is intact and unaltered.

CONCLUSION

This study provides a comprehensive understanding of the individual and collective role of the ALB and PMB through

a complete range of knee flexion after exposure to a series of simulated clinical examinations. Specifically, we have demonstrated that both the ALB and the PMB assume a significant role in resisting posterior translation at all flexion angles, thereby suggesting a codominant relationship. Likewise, both bundles assume a significant role in knee stability in the absence of the other bundle. Importantly, we have also identified that the PCL was a primary constraint to internal rotation beyond 90° of flexion. Additionally, the significant differences demonstrated between the sectioned and intact states for posterior translation and internal and external rotations indicate the importance of the PCL as a primary knee stabilizer throughout a full range of motion, especially beyond 90° of flexion. This information should serve as the foundation for re-creating the native knee kinematics with a PCL reconstruction.

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