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Kinematic Analysis of the Posterior Cruciate Ligament, Part 2

A Comparison of Anatomic Single- Versus Double-Bundle Reconstruction

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Background: A more thorough understanding of the posterior cruciate ligament (PCL) has led to an increase in awareness and treatment of complex PCL injuries. Controversy exists about whether PCL reconstruction (PCLR) using an anatomic single-bundle (aSB) or anatomic double-bundle (aDB) technique is the most effective.

Hypothesis: An aDB PCLR provides significantly better anterior-posterior and rotatory knee stability compared with an aSB PCLR and more closely recreates normal knee kinematics.

Study Design: Controlled laboratory study.

Methods: A total of 18 match-paired, cadaveric knees (mean age, 54.8 years; range, 51-59 years; 5 male and 4 female pairs) were used to evaluate the kinematics of an intact PCL, an aSB and aDB PCLR, and a complete sectioned PCL. A 6 degrees of freedom robotic system was used to assess knee stability with a 134-N applied posterior tibial load, 5-N·m external and internal rotation torques, 10-N·m valgus and varus rotation torques, and a coupled 100-N posterior tibial load and 5-N·m external rotation torque at 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120°.

Results: The aDB PCLR had significantly less posterior translation than the aSB PCLR at all flexion angles of 15° and greater. The largest difference in posterior translation was seen at 105° of flexion, where the aSB PCLR had 5.3 mm (P = .017) more posterior translation than the aDB PCLR. The aDB PCLR also had significantly less internal rotation than the aSB PCLR at all tested angles of 90° and greater. Neither reconstruction was able to fully restore native knee kinematics.

Conclusion: An aDB PCLR more closely approximated native knee kinematics when compared with an aSB PCLR. Specifically, the aDB PCLR demonstrated significantly more restraint to posterior translation at flexion angles between 15° and 120° and less internal rotational laxity at high flexion angles 90° to 120°.

Clinical Relevance: Comparison of the 2 reconstruction techniques illustrates the time-zero kinematic advantage imparted by the addition of the posteromedial bundle reconstruction. The benefit is most pertinent for resistance to posterior translation across a full range of flexion and rotational stability beyond 90° of knee flexion.

Keywords: anatomic single-bundle posterior cruciate ligament reconstruction; anatomic double-bundle posterior cruciate ligament reconstruction

Previously, studies have reported that isolated posterior cruciate ligament (PCL) tears could be treated nonoperatively with relative success.[9,27,31] However, recent long-term clinical studies have reported that nonoperative treatment often leads to early onset osteoarthritis of the medial and patellofemoral compartments and an overall decline in knee function.[1,5,7,8,14] Despite these reports, nonoperative treatment is frequently prescribed over operative treatment. Several reasons might explain the reluctance to proceed with operative intervention, but one of the most compelling facts is that an ideal, reproducible, and predictable reconstruction technique has yet to be demonstrated for grade 3 PCL tears.

Anatomic single-bundle (aSB) PCL reconstruction (PCLR) is the most commonly performed PCLR method. This technique focuses on reconstructing the larger of the 2 bundles, the anterolateral bundle (ALB), by centering the femoral and tibial tunnels on the native ALB footprint. This procedure was originally performed with an isometric PCL graft and tunnel location.[29] However, later studies

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reported that anatomic positioning of the tunnels and graft, as opposed to isometric positioning, led to improved clinical results and posterior translational stability, particularly at higher degrees of flexion.[10,26,29] Notwithstanding this improvement, aSB PCLRs have achieved mixed subjective and objective results.[4,11,16,17,19,30,34] The ability of this procedure to restore the knee's resistance to posterior translation, equal to that of the native knee, has been disputed.[21] Consequently, alternative methods of PCLR have been explored.

To more closely recreate the native PCL footprint, an anatomic double-bundle (aDB) PCLR has been proposed.[13] The aDB PCLR is based on the fact that the PCL is made up of 2 bundles that behave synergistically, the ALB and the posteromedial bundle (PMB).[13,23,25,29] The individual bundles have been reported to display different tensioning at varying degrees of flexion; the PMB is taut in extension, whereas the ALB is taut in flexion.[12,22,24,28,33] This difference in tensioning, combined with kinematic findings from part 1[15] of our 2-part study, which showed increased laxity with 1 bundle sectioned when compared with an intact PCL, indicates that both bundles may need to be reconstructed and tensioned individually to adequately restore the native biomechanics of the knee.[13]

Controversy exists as to which is the best PCLR method. Some studies suggest that the single-bundle (SB) reconstruction techniques yield satisfactory clinical results and are as effective as, if not superior to, double-bundle (DB) reconstructions.[4,16,19,30] However, other clinical studies have reported that patients who underwent SB PCLR failed to regain normal knee kinematics.[11,17,34] Clinical studies have reported promising outcomes for DB PCLRs, and it has been suggested that native kinematics are more closely reestablished with this technique.[6,32] In addition, kinematic investigations have reported that DB reconstructions result in decreased posterior laxity compared with SB PCLRs across a large range of motion in the knee.[29] However, because of the disparity of the current literature, neither technique has conclusively been determined to be superior.

Nevertheless, one of the drawbacks of the currently available literature is that the cohort of patients studied generally contains a mixture of both isolated PCL and combined, multiligament injuries. Therefore, it is difficult to analyze the isolated effect of the PCLR in clinical studies without considering the influence of the damage to the other knee structures. In addition, it has been postulated that the reason for varied findings in many biomechanical studies and the difficulty in determining the superiority of either method relates to inconsistency of experimental setup, fixation angles, tunnel placement, and graft choice, among other factors.[18] To date, there is limited research available regarding how SB or DB PCLRs function kinematically in deep flexion beyond 90°. This information regarding kinematic function in deep flexion may have significant implications for return-to-play outcomes in athletes with PCL injuries who participate in sports in which the functional range of motion involves the extremes of flexion.

The purpose of this study was to investigate the kinematic differences between aSB and aDB PCLRs at the time of surgery compared with the native and complete PCL sectioned states. These results were also compared with selectively sectioned knees, for isolated PCL bundle function, at 0° to 120° of flexion, as reported in part 1 of this 2-part series. Having demonstrated the individual and collective function of each bundle, we hypothesized that an aDB PCLR would more closely restore native knee kinematics compared with an aSB PCLR throughout knee flexion, particularly beyond 90° of flexion. It was anticipated that this information would help to determine whether an aSB or aDB PCLR technique would be most effective in restoring native knee kinematics.

MATERIALS AND METHODS

Specimens

Eighteen match-paired, fresh-frozen, human cadaveric knees (mean age, 54.8 years; range, 51-59 years; 5 male and 4 female pairs) without evidence of prior injury, abnormality, or surgery, from part 1 of this 2-part series, were used in part 2 of this study to analyze 2 different PCLR techniques. These specimens were concurrently used in part 1 of this study to determine the isolated primary function of the PCL bundles with respect to native knee

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kinematics. Knees in each bilateral pair were randomly assigned to the aDB or aSB PCLR group. Soft tissues were removed 12 cm from the joint line for the tibia and femur and potted in polymethylmethacrylate (Fricke Dental, Streamwood, Illinois). Knees were mounted in an inverted orientation in a custom fixture to a universal force-torque sensor (Delta F/T Transducer, ATI Industrial Automation, Apex, North Carolina) attached to the robotic end effector of a 6 degrees of freedom (DOF) robotic system (KUKA KR 60-3, KUKA Robotics, Augsburg, Germany). For each knee, the passive flexion path, from 0°, or full extension, to 120° of flexion, was collected in 1° flexion angle increments. Forces and torques were minimized (<5 N and 0.5 N·m, respectively) in the remaining 5 DOF, and a 10-N axial force was applied to ensure contact between the tibia and femur. Passive path positions were used as starting points for laxity testing.

Biomechanical Testing. At 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120° of knee flexion, all knees were subjected to 6 load conditions: a 134-N posterior tibial load, 5-N·m external and internal rotation torques, 10 N·m valgus and varus rotation torques, and a coupled 100-N posterior tibial load and 5-N·m external rotation torque to simulate a clinical posterolateral drawer test. At each specified flexion angle during testing, a 10-N compressive force was used to ensure tibiofemoral contact, while forces 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. All tests were completed at each flexion angle, and the testing order was randomized. After intact and sectioned state testing, knees were randomized between the aSB and aDB PCLR groups, and testing was repeated for the reconstructed states.

Surgical Technique

Graft Preparation. An Achilles allograft (AlloSource, Centennial, Colorado) was used for the ALB graft for both the aSB and aDB PCLR techniques. The graft was prepared to be 11 mm in diameter and had a 25-mm-long calcaneal bone plug. The grafts were sized to 11 mm in diameter with a graft sizing block. If diameters exceeded 11 mm at any point along the length of the graft, the graft was sharply trimmed to 11 mm to ensure consistency between specimens.

The soft tissues at the distal end of the graft were trimmed and made tubular with the use of a nonabsorbable No. 5 suture, similar to previously reported clinical use.[32] The most distal 20 mm of each graft was tubularized to fit through a 7- to 8-mm tunnel by use of the graft sizing block. This allowed for easy passage of the graft through the tibial tunnel and out the anterior aspect of the tibia. A tibialis anterior allograft (AlloSource) was sized to 7 mm in diameter, also with a graft sizing block, and was used for the PMB graft during the aDB PCLR reconstruction.[32] All grafts were prepared by a single orthopaedic surgeon (A.A.) using the same supplies and graft source.

Anatomic SB PCLR Technique. An anterolateral arthrotomy was made to visualize the femoral attachment of the ALB. The aSB PCLR was performed placing the closed socket femoral tunnel in the visualized footprint of the ALB.[2] A scalpel with a No. 15 blade and a rongeur were used to debride the footprint. An 11-mm acorn-tipped cannulated reamer (Arthrex, Naples, Florida) was used as a guide and was centered over the ALB footprint on the lateral wall of the medial femoral condyle. After this, an eyelet pin was drilled through the center of the drill bit.[32] The position of the eyelet pin was confirmed and a tunnel depth of 25 mm was reamed with the 11-mm reamer. The Achilles bone block, with the tendinous insertion facing anteriorly, was passed into the tunnel and fixed with a 7 × 25-mm titanium screw (Arthrex) superiorly and proximally in the tunnel (Figure 1). After removal of the tibial footprint of both bundles, we identified the bundle ridge,[2] an arthroscopic surgical landmark, which was located approximately 6 to 7 mm proximal to the champagne-glass drop-off.[2] The ligament of Wrisberg was preserved if present. An eyelet pin was drilled through the bundle ridge,[2] while ensuring that it exited 1 cm medial to the tibial tuberosity and 6 cm distal to the joint line. Once the guide pin positioning was confirmed, an 11-mm acorn-tipped reamer was used to drill the tibial tunnel from posterior to anterior directions. A tunnel smoother (Gore Smoother, Smith & Nephew, Andover, Massachusetts) rounded the aperture, exiting from the proximal end of the tibial tunnel. The knee was positioned at 90° of flexion to allow the smoother to pass through the tibial tunnel and between the femoral condyles to exit anteriorly. The smoother was then pulled back and forth 3 to 5 times to remove any bony debris at the tunnel aperture that could damage the graft. The sutures of the ALB were passed through the looped end of the smoother. The smoother was then pulled distally and out of the tibial tunnel, so that the sutures as well as the Achilles graft were pulled through the tunnel. Before distal fixation was performed, the knee was robotically cycled through a full range of motion 5 times with manual distal tension on the graft. The graft was manually tensioned to 88 N at the distal end and in line with the tunnel by use of a graft tensioning device (Arthrex) during fixation.[13,25] The graft was fixed to the anterior aspect of the tibia at 90° of flexion with a bicortical 6.5 × 40-mm cancellous screw and an 18-mm spiked washer (Arthrex) while the robot applied a 134-N anterior tibial load to simulate the anterior drawer reported in clinical studies (Figure 1).[13,25]

Anatomic DB PCLR Technique. Similar to the aSB PCLR technique, the aDB PCLR technique was performed by positioning the femoral and tibial tunnels anatomically. The knee was flexed to 90° to facilitate visualization of the femoral footprints of the ALB and PMB on the lateral wall and roof of the medial femoral condyle. An 11-mm acorn-tipped cannulated reamer was used as a guide for the ALB tunnel, as described for the aSB technique, and a 7-mm reamer was used as a guide for the PMB tunnel, which was centered approximately 8 to 9 mm posterior to the edge of the articular cartilage on the femoral condyle.[2] After confirmation of the position of the eyelet pin, which was inserted into the cannulated reamer before reaming,

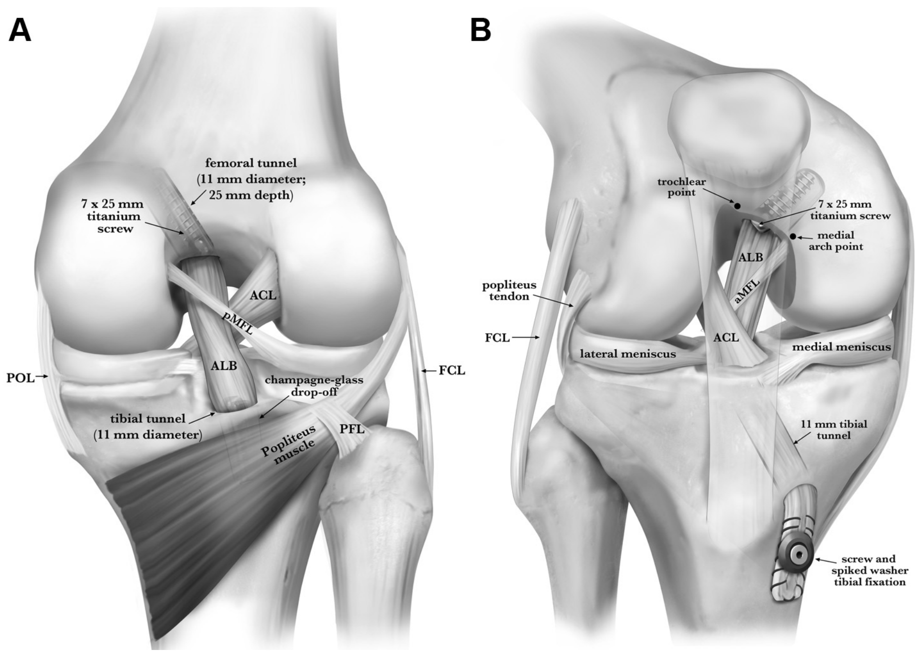

Figure 1. (A) Posterior and (B) anterior views of the anatomic single-bundle (aSB) posterior cruciate ligament reconstruction (PCLR). Reconstructed anterolateral bundle (ALB) shows the location, size, and shape of the femoral and tibial tunnels. The champagne-glass drop-off is the anatomic landmark for drilling of the tibial tunnel. ACL, anterior cruciate ligament; aMFL, anterior meniscofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament.

both tunnels were drilled to a depth of 25 mm to create closed socket anatomic tunnels. The PMB graft was pulled into the tunnel and fixed with a 7 × 23-mm biocomposite screw (Arthrex) inferior to the graft in the tunnel. The ALB bone plug was then pulled into the ALB femoral tunnel and fixed with a 7 × 25-mm titanium screw as described for the aSB PCLR (Figure 2).

Next, the knee was positioned in full extension to allow access to the tibial attachments. Because of the close proximity of the bundle attachments on the tibia and the compact overall PCL tibial footprint, it was not possible to ream separate bundle tunnels on the tibia. Similar to the aSB tibial tunnel preparation, an eyelet pin was drilled at a 55° angle through the bundle ridge on the posterior tibia and exited 6 cm distal to the joint line and 1 cm medial to the tibial tuberosity.[2,20] A 12-mm reamer was used to drill the tibial tunnel for the aDB technique, which covered the majority of the PCL tibial attachment.

The knee was returned to 90° of flexion, and as previously described, a smoother was used to round the aperture of the tibial tunnel and then to pull both grafts through the tibial tunnel. The knee was robotically cycled 5 times with manual tension on the grafts before distal tibial fixation was performed. A 134-N anterior tibial load was robotically applied for fixation of the ALB. A graft tensioning device (Arthrex) was also used to manually tension the ALB graft with an 88-N traction force before fixation.[13,25] An 18-mm spiked washer was then used to fix the ALB graft to the tibia with a 6.5-mm cancellous screw.

The PMB was then fixed to the tibia on the medial side of the ALB insertion at full extension with a 67-N tension force applied to the graft at the distal end in line with the tunnel with a graft tensioning device (Arthrex).[13,25] The same size screw and washer were used for the PMB fixation (Figure 2). Knee posterior and anterolateral incisions were then sutured closed. All knees were taken through the range of flexion before robotic testing was initiated.

Posttesting Examination

A manual examination of each knee was carried out immediately after testing to assess for anteroposterior laxity and rotational stability and to confirm the integrity of the secondary structures. All knees were dissected and the position of the reconstruction grafts was evaluated by inspection by 2 orthopaedic surgeons (A.A. and R.F.L.). The fibular collateral ligament was also dissected free, and normal tension was verified after testing. Tibial tunnel placement was reviewed in each specimen to document that an intended anatomic placement of the tunnels was obtained, with reference to postsurgical anatomic landmarks.

Statistical Analysis

During the testing phase, statistical power calculations were made to estimate the necessary sample size to detect differences between the sectioned and reconstructed

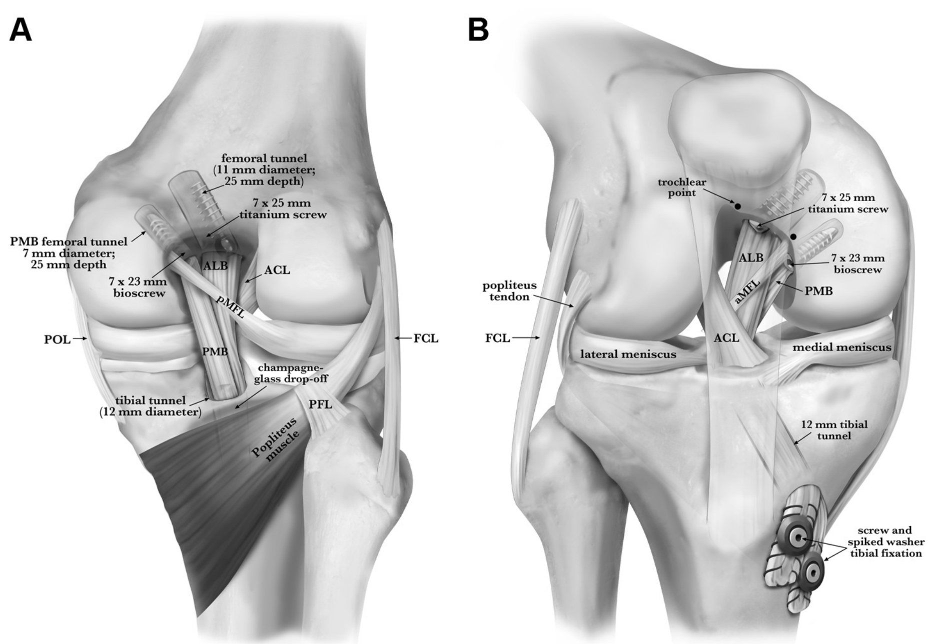

Figure 2. (A) Posterior and (B) anterior views of the anatomic double-bundle (aDB) PCLR. The reconstructed anterolateral bundle (ALB) and posteromedial bundle (PMB) are shown, as well as the size, shape, and location of their femoral and tibial tunnels. The PMB enters the tibial tunnel posteromedial to the ALB. The PMB is posterior in the transtibial tunnel and exits deep to the ALB and then is fixed medially and distally to the ALB. Femoral fixations of both bundles and the champagne-glass drop-off, the anatomic landmark for transtibial tunnel drilling, are also displayed. ACL, anterior cruciate ligament; aMFL, anterior meniscofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament.

states. Statistical analysis was performed with Student 1-sample t test to compare the sectioned PCL, aSB reconstruction, and aDB reconstruction states individually to the intact state. A 2-sample independent t test was used for comparison between the sectioned PCL and reconstruction 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

Posterior Tibial Translation

While tested under a 134-N posterior tibial load, the aSB PCLR state had significantly less posterior translation compared with the complete PCL sectioned state at 30°, 45°, 60°, 75°, 90°, 105°, and 120° of flexion. The aDB PCLR state had significantly less posterior translation compared with the complete PCL sectioned state at all flexion angles tested.

When the 2 reconstruction techniques were compared, the aDB PCLR had significantly less posterior translation than the aSB PCLR at all flexion angles tested except for 0° of flexion. The largest difference in posterior translation between the 2 surgical techniques was at 105° of flexion, where the aSB PCLR had 5.3 mm ($P = .017$) more posterior translation than the aDB PCLR (Figure 3 and Table 1).

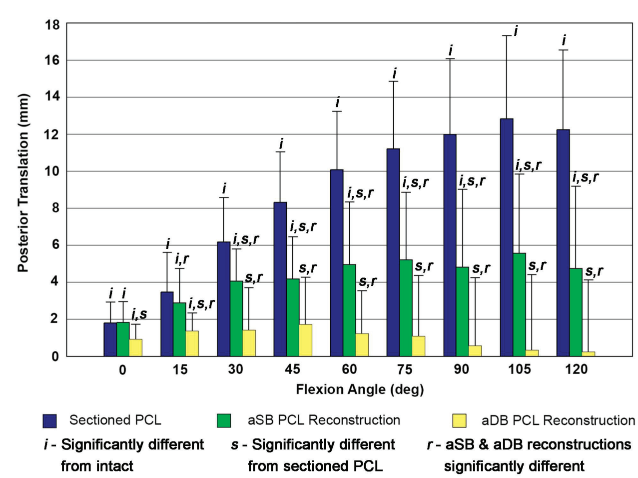

Figure 3. Changes in posterior translation after complete posterior cruciate ligament (PCL) sectioning, anatomic single-bundle (aSB) PCL reconstruction, and anatomic double-bundle (aDB) PCL reconstruction. Data are reported as average increases of posterior translation compared with the intact PCL knee in response to a 134-N posterior tibial force.

TABLE 1
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 Rotation Torque[a]

	Posterior Tibial Load			
	Posterior Translation, mm	Change in Posterior Translation, mm		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	10.6 ± 3.5	1.8 ± 1.1[I]	1.8 ± 1.1[I]	0.9 ± 0.8[I,S]
15°	11.5 ± 3.8	3.5 ± 2.1[I]	2.9 ± 1.8[I,R]	1.4 ± 1.0[I,S,R]
30°	10.8 ± 3.9	6.2 ± 2.4[I]	4.0 ± 1.7[I,S,R]	1.4 ± 2.3[S,R]
45°	8.9 ± 3.5	8.3 ± 2.7[I]	4.2 ± 2.3[I,S,R]	1.7 ± 2.6[S,R]
60°	7.4 ± 3.5	10.1 ± 3.1[I]	5.0 ± 3.4[I,S,R]	1.2 ± 2.3[S,R]
75°	6.8 ± 3.0	11.2 ± 3.6[I]	5.2 ± 3.6[I,S,R]	1.1 ± 3.3[S,R]
90°	7.0 ± 3.1	12.0 ± 4.1[I]	4.8 ± 4.2[I,S,R]	0.6 ± 3.7[S,R]
105°	7.7 ± 3.3	12.8 ± 4.5[I]	5.6 ± 4.3[I,S,R]	0.3 ± 4.1[S,R]
120°	8.9 ± 4.0	12.2 ± 4.3[I]	4.7 ± 4.4[I,S,R]	0.2 ± 3.9[S,R]
	Coupled Posterior Tibial Load and External Rotation			
	Posterior Translation, mm	Change in Posterior Translation, mm		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	6.6 ± 3.2	0.6 ± 0.7[I]	0.8 ± 1.1	0.5 ± 0.6[I]
15°	7.0 ± 3.7	1.0 ± 1.2[I]	1.2 ± 1.6	0.8 ± 0.9[I]
30°	7.2 ± 3.8	1.6 ± 1.8[I]	1.5 ± 1.9[I]	0.8 ± 1.2
45°	6.5 ± 3.3	2.5 ± 2.6[I]	2.2 ± 2.3[I]	1.6 ± 1.6[I]
60°	6.2 ± 3.7	3.0 ± 2.7[I]	2.6 ± 2.2[I]	1.5 ± 1.1[I]
75°	6.4 ± 3.4	3.2 ± 2.8[I]	2.9 ± 2.3[I]	1.3 ± 1.9[S]
90°	6.9 ± 3.3	3.5 ± 3.1[I]	2.8 ± 2.7[I]	1.3 ± 2.1
105°	7.6 ± 3.6	3.5 ± 3.3[I]	2.9 ± 2.8[I]	1.3 ± 2.0
120°	8.4 ± 4.1	2.9 ± 3.1[I]	2.4 ± 2.5[I]	0.9 ± 1.7
	Coupled Posterior Tibial Load and External Rotation			
	External Rotation, deg	Change in External Rotation, deg		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	10.0 ± 2.7	–0.1 ± 0.6	–0.4 ± 0.9	0.0 ± 0.7
15°	12.6 ± 5.1	–0.3 ± 1.2	–0.5 ± 1.7	–0.1 ± 1.0
30°	14.8 ± 7.5	–0.8 ± 1.8	–0.7 ± 1.7	0.2 ± 0.8
45°	15.3 ± 8.5	–1.4 ± 2.3[I]	–0.6 ± 1.3	0.3 ± 1.3
60°	15.6 ± 8.5	–1.5 ± 2.4[I]	–0.2 ± 1.7	0.8 ± 0.8[I,S]
75°	16.5 ± 8.2	–1.7 ± 2.6[I]	–0.1 ± 1.9	0.7 ± 1.2[S]
90°	17.5 ± 8.2	–1.8 ± 2.9[I]	0.1 ± 1.8	1.0 ± 1.2[I,S]
105°	18.3 ± 8.8	–1.8 ± 3.2[I]	–0.1 ± 1.6	1.1 ± 1.4[I,S]
120°	18.7 ± 9.8	–1.7 ± 3.2[I]	–0.1 ± 1.5	0.6 ± 0.9[S]

[a]Values are expressed as mean ± standard deviation. aSB, anatomic single-bundle; aDB, anatomic double-bundle.
[I]Significant difference ($P < .05$) from intact state.
[S]Significant difference ($P < .05$) from complete posterior cruciate ligament sectioned state.
[R]Significant difference ($P < .05$) between the reconstructed states.

The aSB PCLR state had significantly increased average posterior translation when compared with the intact state at all flexion angles tested (Figure 3 and Table 1). The aDB PCLR had significantly increased posterior translation when compared with the intact state at 0° and 15° of flexion. The increases in posterior translation at 90° flexion, where a posterior drawer test is performed clinically, when compared with the intact state were 4.8 ± 4.2 mm (P = .009) and 0.6 ± 3.7 mm (P = .667) for the aSB and aDB PCLRs, respectively.

Coupled Posterior Translation and External Rotation

The aDB PCLR state had significantly less posterior translation when compared with the sectioned state under

TABLE 2
Internal and External Rotation in Response to 5-N·m Internal and External Rotation Torques[a]

	Internal Rotation	Change in Internal Rotation, deg		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	10.7 ± 3.1	0.6 ± 0.6[I]	0.9 ± 0.8[I]	0.4 ± 0.4[I]
15°	15.0 ± 6.0	0.4 ± 0.3[I]	0.6 ± 0.5[I]	0.3 ± 0.3[I]
30°	18.2 ± 8.3	0.4 ± 0.3[I]	0.6 ± 0.4[I]	0.3 ± 0.3[I]
45°	18.4 ± 8.4	0.6 ± 0.6[I]	0.8 ± 0.4[I]	0.6 ± 0.5[I]
60°	17.8 ± 8.6	1.0 ± 1.0[I]	0.9 ± 1.0[I]	0.9 ± 0.7[I]
75°	17.5 ± 8.4	1.7 ± 1.6[I]	1.7 ± 1.7[I]	0.1 ± 1.7[S]
90°	17.5 ± 8.1	2.4 ± 1.9[I]	1.7 ± 1.8[I,R]	–0.6 ± 2.6[S,R]
105°	18.3 ± 8.6	2.9 ± 2.1[I]	2.3 ± 1.8[I,R]	–1.2 ± 3.5[S,R]
120°	19.4 ± 9.4	2.8 ± 2.1[I]	2.1 ± 1.6[I,R]	–0.3 ± 2.1[S,R]

	External Rotation	Change in External Rotation, deg		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	11.8 ± 2.8	0.5 ± 0.4[I]	0.5 ± 0.3[I]	0.6 ± 0.4[I]
15°	15.2 ± 6.0	0.6 ± 0.5[I]	0.7 ± 0.6[I]	0.7 ± 0.5[I]
30°	17.4 ± 8.3	0.6 ± 0.4[I]	0.7 ± 0.4[I]	0.5 ± 0.5[I]
45°	17.3 ± 9.1	0.7 ± 0.5[I]	0.9 ± 0.6[I]	0.7 ± 0.7[I]
60°	16.7 ± 8.9	0.9 ± 0.6[I]	1.4 ± 1.1[I]	0.5 ± 0.7
75°	17.0 ± 8.4	0.9 ± 1.1[I]	1.6 ± 1.7[I]	0.4 ± 1.5
90°	17.9 ± 8.4	0.9 ± 1.0[I]	1.6 ± 1.3[I]	0.4 ± 1.6
105°	18.7 ± 9.1	0.8 ± 0.9[I]	1.2 ± 1.1[I]	0.4 ± 2.1
120°	19.2 ± 10.1	0.7 ± 0.8[I]	1.1 ± 0.9[I]	–0.2 ± 1.8

[a]Values are expressed as mean ± standard deviation. aSB, anatomic single-bundle; aDB, anatomic double-bundle.
[I]Significant difference ($P < .05$) from intact state.
[S]Significant difference ($P < .05$) from complete posterior cruciate ligament sectioned state.
[R]Significant difference ($P < .05$) between the reconstructed states.

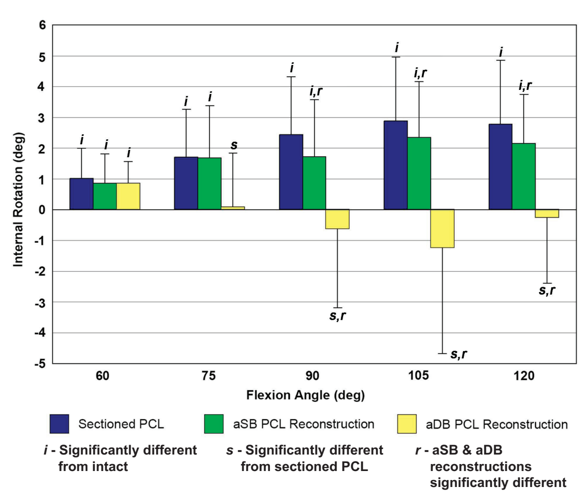

Figure 4. Changes in internal rotation after complete posterior cruciate ligament (PCL) sectioning, anatomic single-bundle (aSB) PCL reconstruction, and anatomic double-bundle (aDB) PCL reconstruction. Data are reported as average increases of internal rotation compared with the intact PCL knee in response to a 5-N·m internal rotation torque.

a coupled 100-N posterior tibial load and 5-N·m external rotation torque at 75° of flexion. The aDB PCLR displayed significant increases in posterior translation when compared with the intact state at 0°, 15°, 45°, and 60° of flexion (Table 1). The aSB PCLR displayed significant increases in posterior translation when compared with the intact state between 30° and 120°. The increases in posterior translation when compared with the intact state at 90° of flexion were 2.8 ± 2.7 mm ($P = .015$) and 1.3 ± 2.1 mm ($P = .093$) for the aSB and aDB PCLRs, respectively.

Internal and External Rotation

The aDB PCLR had significantly less internal rotation when compared with the complete PCL sectioned state between 75° and 120° of flexion under a 5-N·m internal rotation torque (Table 2, Figure 4). The aDB PCLR also had significantly less internal rotation when compared with the aSB PCLR between 90° and 120° of flexion.

The aSB PCLR had significant increases in internal rotation when compared with the intact state at all flexion angles tested under a 5-N·m internal rotation torque. The aDB PCLR state had significantly increased internal rotation when compared with intact between 0° and 60° of flexion.

There were no significant differences in external rotation between the 2 PCLR states or between the PCLR states and

TABLE 3
Valgus and Varus Rotation in Degrees in Response to 10-N·m Valgus and Varus Rotation Torques[a]

	Valgus Rotation	Change in Valgus Rotation, deg		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	2.9 ± 0.7	0.2 ± 0.3[I]	0.2 ± 0.3	0.2 ± 0.4
15°	4.0 ± 1.2	0.1 ± 0.4	0.2 ± 0.2[I]	0.0 ± 0.7
30°	5.0 ± 2.0	0.1 ± 0.4	0.2 ± 0.2[I]	0.1 ± 0.7
45°	5.4 ± 2.3	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.8
60°	5.6 ± 2.5	0.0 ± 1.6	0.4 ± 0.7	0.5 ± 1.2
75°	6.1 ± 3.0	0.3 ± 1.7	0.6 ± 0.8	0.7 ± 1.6
90°	6.7 ± 3.3	0.4 ± 1.8	0.5 ± 1.1	0.5 ± 1.5
105°	7.3 ± 3.6	1.1 ± 1.2[I]	1.1 ± 0.7[I]	0.1 ± 1.5
120°	8.5 ± 4.0	0.9 ± 1.4[I]	0.9 ± 0.8[I,R]	–0.1 ± 0.9[R]

	Varus Rotation	Change in Varus Rotation, deg		
Flexion Angle	Intact (n = 18)	Complete Sectioned (n = 18)	aSB Reconstruction (n = 9)	aDB Reconstruction (n = 9)
0°	3.0 ± 1.0	0.1 ± 0.2[I]	0.2 ± 0.2[I]	0.1 ± 0.4
15°	4.0 ± 1.3	0.2 ± 0.3[I]	0.2 ± 0.3	0.2 ± 0.6
30°	4.8 ± 1.7	0.2 ± 0.4[I]	0.3 ± 0.3[I]	0.2 ± 0.6
45°	5.2 ± 2.0	0.2 ± 0.4	0.3 ± 0.4	0.1 ± 0.7
60°	5.7 ± 2.4	0.1 ± 0.5	0.3 ± 0.5	–0.1 ± 1.2
75°	6.2 ± 2.6	0.0 ± 0.8	0.4 ± 1.0	–0.3 ± 1.5
90°	6.8 ± 2.8	0.1 ± 1.2	0.7 ± 1.3	0.0 ± 1.5
105°	7.7 ± 3.1	0.0 ± 1.4	0.5 ± 1.3	0.3 ± 1.6
120°	8.3 ± 3.7	0.1 ± 1.3	0.4 ± 1.1	0.4 ± 1.5

[a]Values are expressed as mean ± standard deviation. aSB, anatomic single-bundle; aDB, anatomic double-bundle.
[I]Significant difference ($P < .05$) from intact state.
[R]Significant difference ($P < .05$) between the reconstructed states.

the complete PCL sectioned state under a 5-N·m external rotation torque (Table 2). The aSB PCLR had significant increases in external rotation when compared with the intact state at all flexion angles tested. The aDB PCLR had significant increases in external rotation when compared with the intact state at 0° to 45° of flexion.

Valgus and Varus Rotation

The reconstructions showed no significant differences in valgus rotation compared with the complete PCL sectioned state under a 10-N·m valgus rotational torque. The aSB PCLR had significantly more valgus rotation than the aDB PCLR at 120° of flexion. The aSB PCLR had significantly increased valgus rotation compared with the intact state at 15°, 30°, 105°, and 120°. The greatest increase in valgus rotation was seen at 105° and was 1.1° ± 0.7° (P = .003) for the aSB PCLR state (Table 3). There were no significant differences for valgus rotation between the aDB PCLR and the intact state at any flexion angle tested (Table 3).

The aSB PCLR state had significant increases in varus rotation at 0° and 30° of knee flexion when compared with the intact state under a 10-N·m varus rotational torque. No other significant differences were found for other comparisons with the reconstructions.

DISCUSSION

The most important finding of this study was that an aDB PCLR more closely approximates native knee kinematics, particularly beyond 90°. Specifically, we demonstrated that an aDB PCLR provided significantly more restraint to posterior translation than an aSB PCLR at all angles tested, apart from full extension. In addition, no significant differences were detected between the aDB PCLR and the intact knee in resisting posterior translation beyond 15° of flexion, thereby indicating its capacity to closely approximate the native kinematics of the knee. Finally, with regard to rotational laxity, it was observed that there were no significant differences between the aDB PCLR and the intact state for external and internal rotation beyond 45° and 60° of knee flexion, respectively.

Comparison of the 2 PCLR techniques illustrates the clinical advantage imparted by the addition of the PMB graft. As we hypothesized, the addition of the PMB graft increased anteroposterior stability at ≥15° of flexion but also provided a greater restraint to internal rotation beyond 90°. Interestingly, although the PMB was fixed at full extension, no appreciable superiority in resisting posterior translation was detected at this position. The greatest difference in posterior translation between the 2 surgical techniques occurred at 105° of flexion, which is the same angle at which the complete PCL sectioned state experienced the greatest increase in posterior tibial translation when compared with the intact state.

Although biomechanical studies have been undertaken comparing SB and DB PCLR techniques, a general consensus has still not been reached on a superior technique. Considerable disparity exists between reports; some groups contend that a DB PCLR more fully restores normal knee kinematics across a full range of motion, whereas others argue that the SB PCLR is equally effective, if not more so, at restoring normal anteroposterior stability.[3,13,24,29,35,36] Although each of these studies has validity, they have limitations in 2 key areas. First, they fail to characterize the isolated and combined function of each of the native bundles across a complete range of motion (0°-120°); second, PCLR techniques have not been subjected to a complete set of simulated clinical examinations through this same range of motion, including internal and external rotational torques and varus and valgus rotational torques.

Part 1 of this study[15] provided a template of the native kinematics of the intact, isolated ALB and PMB, and deficient PCL knee and illustrated the individual and collective role of each bundle. Specifically, we have demonstrated that the ALB and PMB have a codominant relationship in resisting posterior translation, and the PMB is a significant constraint to internal rotation beyond 90° of flexion. Results of part 1 suggest that even a perfectly recreated aSB PCLR of the ALB may not be sufficient to restore native knee kinematics. This fact was further corroborated by the result of the aSB PCLR in this study, which demonstrated that the stability conferred by this construct not only was inferior to the aDB PCLR but also was inferior to the isolated ALB, as determined by the sectioning study. In regard to posterior tibial translation, at 90° of flexion the aSB PCLR state had more than 3 mm of increased posterior translation when compared with the ALB isolated (PMB sectioned) state. The greatest difference seen between the aSB PCLR and the isolated ALB intact state in part 1 of this study was 4.3 mm at 105° of flexion. These findings further emphasize the deficit that remains in terms of anteroposterior and rotational stability when an aSB PCLR is performed in isolation. While an aDB PCLR generally resulted in improved knee kinematics when compared with an aSB PCLR, neither reconstruction fully restored native knee kinematics.

The strengths of this study include the use of a highly accurate and repeatable 6 DOF robotic system. All instruments, hardware, and graft tissue were identical to those used in clinical practice during PCLRs, including Achilles and tibialis anterior allografts from a certified graft distributor. In addition, all surgeries were performed together by 2 experienced orthopaedic surgeons (A.A., B.M.D.). Fresh-frozen, match-paired specimens with a maximum age of 59 years were used. Further, posttesting clinical examinations and dissections were performed, and consequently, a pair of specimens was excluded when a surgical error was identified.

The authors acknowledge that limitations existed within this study. The rigorous testing protocol, which included numerous simulated clinical examinations, may have deteriorated the primary and secondary knee stabilizers. However, randomization of the surgical technique and flexion testing order was used to reduce any bias that could potentially be introduced. Additionally, the integrity of secondary stabilizers was verified after testing with additional manual examinations. It is important to emphasize that the current results only reflect the time-zero knee stability in cadaver specimens. The effects of in vivo tissue remodeling, the effects of different rehabilitation protocols on graft healing, and other biological issues after the reconstruction are beyond the scope of this study. Furthermore, the significant differences seen between an aSB and an aDB PCLR pertain to aSB reconstructions with Achilles allografts fixed at 90° of knee flexion with an 88-N traction force and aDB reconstructions with Achilles allografts for the ALB fixed at 90° with an 88-N traction force and anterior tibialis allografts for the PMB fixed at 0° with a 67-N traction force. Our results may only be applicable to the reconstruction grafts and fixation techniques used for these anatomically based reconstructions.

CONCLUSION

This study demonstrates that an aDB PCLR more closely approximated native knee kinematics when compared with an aSB PCLR. Specifically, the aDB PCLR had significantly less posterior translation, during a simulated posterior drawer, compared with an aSB reconstruction for all angles of knee flexion beyond full extension. The aDB PCLR restored posterior translation to within 0.6 mm of the intact state at flexion angles greater than 90° and within 2 mm at all degrees of knee flexion. In contrast, an aSB PCLR allowed more than 4 mm of posterior translation at all flexion angles greater than 15°. The aDB also restored both internal and external rotation to within 2° of the intact state. Equally, the aSB PCLR had significantly more internal and external rotation than the intact state and had significantly more internal rotation than the aDB PCLR from 90° to 120° of flexion.

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