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Posterior Cruciate Ligament Graft Fixation Angles, Part 2

Biomechanical Evaluation for Anatomic Double-Bundle Reconstruction

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Background: Prior studies have suggested that anatomic double-bundle (DB) posterior cruciate ligament reconstruction (PCLR) reduces residual laxity compared with the intact state better than single-bundle PCLR. Although the anterolateral bundle (ALB) and posteromedial bundle (PMB) reportedly act codominantly, few studies have compared commonly used graft fixation angles and the influence that graft fixation angles have on overall graft forces and knee laxity.

Hypothesis: Graft fixation angle combinations of 0°/75° (PMB/ALB), 0°/90°, 0°/105°, 15°/75°, 15°/90°, and 15°/105° would significantly reduce knee laxity from the sectioned PCL state while preventing in vitro graft forces from being overloaded between any of the graft fixation angles.

Study Design: Controlled laboratory study.

Methods: Nine cadaveric knees were evaluated for the kinematics of the intact, PCL-sectioned, and DB PCLR techniques. The DB technique was varied by fixing the PMB and ALB grafts at the following 6 randomly ordered fixation angle combinations: 0°/75° (PMB/ALB), 0°/90°, 0°/105°, 15°/75°, 15°/90°, and 15°/105°. A 6 degrees of freedom robotic testing system subjected each specimen to an applied 134-N posterior tibial load at 0° to 120° of flexion and 5-N·m external, 5-N·m internal, and 10-N·m valgus rotation torques applied at 60°, 75°, 90°, 105°, and 120° of flexion. The ALB and PMB grafts were fixed to load cells that concurrently measured graft forces throughout kinematic testing. *t* tests compared the kinematics between groups, and 2-factor models assessed the contribution of ALB and PMB grafts after DB PCLR ($P < .05$).

Results: Consistently, DB PCLR significantly reduced posterior translation compared with the sectioned PCL and was comparable with the intact state during applied posterior tibial loads at flexion angles of greater than 90°; a mean residual laxity of 1.5 mm remained compared with the intact state during applied posterior tibial loads. Additionally, fixing the PMB graft at 15° resulted in significantly larger PMB graft forces compared with fixation at 0° during applied posterior loading, internal rotation, external rotation, and valgus rotation. Similarly, fixing the ALB graft at 75° resulted in significantly larger ALB graft forces compared with fixation of the ALB graft at 90° or 105° during all loading conditions.

Conclusion: Fixation of the PMB graft at 0° to 15° and the ALB graft at 75° to 105° during DB PCLR were successful in significantly reducing knee laxity from the sectioned state. However, fixation of the PMB graft at 15° versus 0° resulted in significantly increased loads through the PMB graft, and fixation of the ALB graft at 75° versus 90° or 105° resulted in significantly increased loads through the ALB graft.

Clinical Relevance: This study found that all 6 fixation angle combinations significantly improved knee kinematics compared with the sectioned state at time zero; however, it is recommended that fixation of the PMB graft be performed at 0° because of the significant increases in PMB graft loading that occur with fixation at 15° and that fixation of the ALB graft be performed at 90° or 105° rather than 75° to minimize ALB graft forces, which could lead to graft attenuation or failure over time.

Keywords: posterior cruciate ligament (PCL); PCL reconstruction; double bundle; knee kinematics; graft forces; posteromedial bundle (PMB); anterolateral bundle (ALB); graft fixation angles

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Several studies have reported that double-bundle (DB) posterior cruciate ligament reconstruction (PCLR) better reduces residual knee laxity compared with single-bundle

(SB) PCLR.[7,12,21] However, DB PCLR remains unable to fully restore knee kinematics to the intact state, which may be caused by increased graft forces that predispose the graft to permanent elongation over time because of less than ideal bundle fixation angles.[12] Residual laxity in DB PCLR could be influenced by less than ideal fixation of the anterolateral bundle (ALB) and posteromedial bundle (PMB) grafts. Historically, the ALB and PMB were believed to function independently in a reciprocal nature, with the primary function of the ALB in deep flexion and the PMB in extension.[4,6,19] Recently, a more synergistic and codominant relationship between the 2 bundles has been reported,[1,10,15,16] with both bundles demonstrating a significant resistance to posterior tibial translation throughout a full range of knee motion.

Because the codominance of the 2 PCL bundles has only recently been confirmed,[1,10] the ideal graft fixation angles for the ALB and PMB, which best restore native joint kinematics, have yet to be determined. Currently, multiple combinations of graft fixation angles are used clinically. While most DB PCLR procedures secure the PMB graft at 0° and the ALB graft at 90°,[4,6,18] other reported fixation angles are also utilized, such as 10° to 15° for the PMB graft and 70° for the ALB graft.[11,15,20] There are currently few biomechanical studies demonstrating the resultant effects of fixing the ALB graft in the range of 75° to 105° and the PMB graft in the range of 0° to 15° on graft forces and knee kinematics. Aside from fixation of the ALB graft at 90°, to the authors' knowledge, no biomechanical investigations exist for alternate graft fixation angles within the 60° to 90° range or at higher ALB graft fixation angles. While a biomechanical study has reported that fixation of the PMB graft at 30° resulted in elevated forces within the PMB graft and overconstrained the knee,[13] fixation of the PMB graft at 15° has yet to be biomechanically evaluated. With recent biomechanical studies reporting the ALB to be most resistant to posterior tibial translation between 70° and 105° and the PMB most resistant to posterior tibial translation between 0° and 15°,[10,12] alternative graft fixation angles within these ranges must be further investigated before an ideal DB graft fixation angle can be determined.

Thus, we aimed to evaluate several clinically relevant combinations of DB PCL graft fixation angles to determine both graft loads and restoration of joint kinematics to the intact state. The purpose of this study was to determine the optimal combination of DB PCL graft fixation angles for restoring intact knee joint kinematics while limiting forces on the grafts during applied loads. We hypothesized that all graft fixation angle combinations would significantly reduce knee laxity from the sectioned PCL state while preventing in vitro graft forces from overloading the grafts for any of the tested graft fixation angles.

MATERIALS AND METHODS

Specimen Preparation

A total of 9 match-paired, fresh-frozen human cadaveric knees (mean age, 52.3 years; range, 29-63 years; mean body mass index, 23.0 kg/m^2; 6 male and 3 female; 5 right and 4 left) were used in this study. Before inclusion, all knees were inspected for evidence of a prior injury, abnormality, prior surgery, or disease. The contralateral knees were used previously in part 1 of this study[9] for a total of 18 knees, 9 matched pairs, between the 2 parts of the study. Right and left knees of each pair were randomized between part 1 and part 2 of this study. Specimen preparation and robotic setup on the 6 degrees of freedom robotic system (Figure 1) are additionally outlined in part 1 of this 2-part study.

Graft Preparation

Nine Achilles tendon and 9 anterior tibialis allografts (AlloSource) were used to reconstruct the ALB and PMB of the PCL, respectively. Grafts were prepared in accordance with previously reported biomechanical and clinical studies.[18,21] The tendinous ends of the Achilles grafts were trimmed and tubularized using braided polyblend No. 5 sutures (FiberWire, Arthrex Inc) to a diameter of 11 mm. Similarly, the calcaneal bone plug was prepared to be 11 mm in diameter with a length of 25 mm. The anterior tibialis grafts were prepared to a diameter of 7 mm with each end tubularized with a braided polyblend No. 5 suture.

DB PCLR Technique

All surgeries were performed by a single orthopaedic surgeon (S.F.C.) with the knee in an inverted orientation while it remained in the robot. The DB PCLR technique was similar to the procedure reported by Spiridonov et al[18] and reported on biomechanically by Wijdicks et al.[21] The knee was positioned at 0° of flexion, and a posteromedial incision was used to visualize the tibial footprint of the PCL and transect both bundles of the PCL at the tibial insertion site. The tibial tunnel was centered on the bundle ridge.[2] A guide pin was drilled through the bundle

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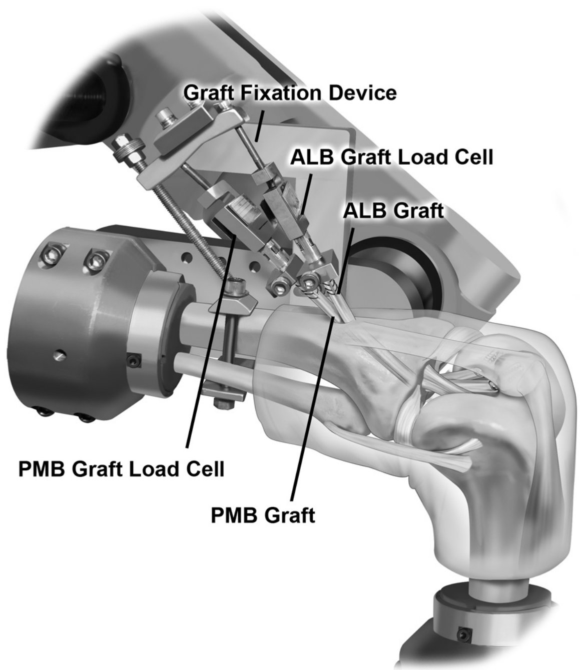

Figure 1. A left knee is shown mounted within the robotic system in an inverted orientation. The femur is fixed to a stationary pedestal, and the tibia and fibula are attached to a universal force-torque sensor affixed to the end effector of a 6 degrees of freedom robotic system (KR 60-3, KUKA). The anterolateral bundle (ALB) and posteromedial bundle (PMB) are clamped within external load cells at the distal tibial exit for concurrent acquisition of graft force measurements.

ridge and exited the anterior side of the tibia approximately 6 cm distal to the joint line and 1 cm medial to the tibial tuberosity. A 12-mm acorn-tipped reamer (Arthrex Inc) was used to ream a transtibial tunnel from posterior to anterior.

Next, the knee was positioned at 90° of flexion, and an anterolateral incision was used to visualize the native femoral footprints of the ALB and PMB. After the native bundles had been dissected away from their femoral attachments, a cannulated 11-mm acorn reamer (Arthrex Inc) was used as a guide to overlay the native ALB footprint on the femur. An eyelet pin was then drilled through the cannulated reamer. The same reamer was used to ream the closed-socket ALB femoral tunnel to a depth of 25 mm. Next, a 7-mm acorn-tipped reamer was centered on the footprint of the native PMB and used as a guide to drill an eyelet pin out of the anteromedial distal femur. A 7-mm reamer was then used to ream the closed-socket PMB femoral tunnel to a depth of 25 mm. The calcaneal bone plug of the Achilles graft was fixed in the ALB femoral tunnel with a 7 × 25–mm titanium screw (Cannulated Interference Screw, Arthrex Inc). One end of the anterior tibialis graft was then fixed in the PMB femoral tunnel with a 7 × 23–mm biocomposite interference screw (Bio-Interference Screw; Arthrex Inc).

After femoral fixation, the proximal end of a tunnel smoother (9.5-mm Gore Smoother; Smith & Nephew) was pulled into the joint space and cycled through the transtibial tunnel to remove bony debris and smooth the proximal aperture of the tibial tunnel. The smoother was also used to deliver the passing sutures of the Achilles and anterior tibialis grafts distally through the tibial tunnel. The grafts were then secured in the custom graft fixation device as outlined below. The arthrotomy was closed separately, and the anterior and posterior incisions were sutured closed.

Custom Graft Fixation Device and Graft Force Data Acquisition

To determine the tension on the ALB and PMB grafts throughout biomechanical testing, the soft tissue ends of the PCLR grafts that exited the tibia were each inserted into custom graft clamps, which were attached to load cells (Model 60050-100; Vishay Precision Group) rigidly mounted to a custom graft fixation device attached to the end effector of the robot. The load cells were calibrated to within 0.25% accuracy using a calibrated tensile testing machine (ElectroPuls E10000, Instron) before biomechanical testing. The graft fixation device, which rigidly attached the graft load cells to the robot end effector, allowed unlimited positional adjustability of the load cells and grafts to ensure axial alignment with the distal tibial tunnel exit. Once the load cells were aligned, the graft fixation device was locked in place.

Before distal graft fixation within the custom graft clamps, the grafts were manually loaded to approximately 250 N 10 times to ensure proper passage of both grafts through the tibial tunnel, minimize creep effects, and remove any potential for initial graft slippage. Next, the knees were robotically cycled through the full range of flexion angles 5 times before distal graft fixation to the load cells was performed. Finally, the grafts were fixed in place, while a 134-N anterior tibial load was robotically applied to the knee.[8] During graft fixation, the ALB graft was tensioned to 88 N, and the PMB graft was tensioned to 67 N, and each was individually secured to the custom graft clamps attached to the load cells.[7] All grafts were secured in the custom graft clamps at the distal end of the graft within 3 cm of exiting the tunnel and aligned with the tibial tunnel. Load data for each graft were acquired during testing with a data acquisition conditioner (Model D4; Micro-Measurements). Graft loads were recorded at maximum tibiofemoral displacement for each test condition after the applied experimental loads were achieved.

Biomechanical Testing

For biomechanical testing, robotic force control was used to simulate clinical examinations throughout the full range of flexion-extension. Intact, reconstructed, and sectioned PCL knees were subjected to a 134-N posterior tibial load at 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, and 120° of flexion, and 5-N·m external rotation, 5-N·m internal rotation, and 10-N·m valgus torques were each applied at 60°, 75°, 90°, 105°, and 120° of flexion based on previous data demonstrating that these knee flexion angles had significant increases in laxity for the sectioned PCL state during

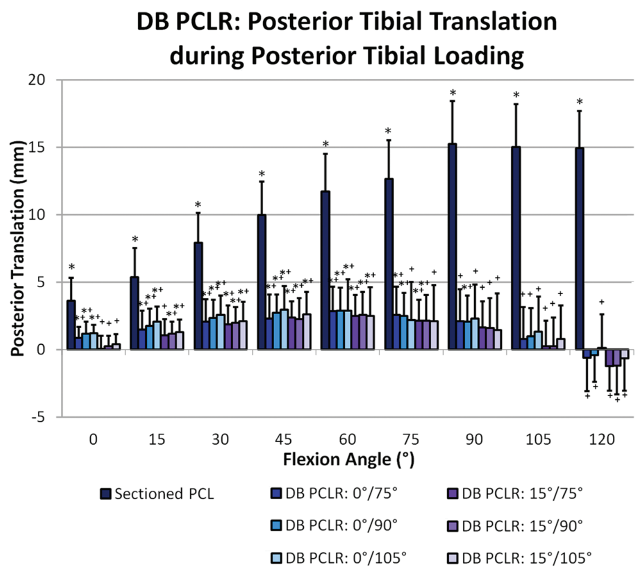

Figure 2. Changes in posterior tibial translation after sectioning of the posterior cruciate ligament (PCL) and double-bundle (DB) PCL reconstruction. Data are presented as mean ± SD increases in posterior translation compared with the intact knee in response to an applied 134-N posterior tibial load. *Significantly different from the intact state. +Significantly different from the sectioned state. $P < .05$.

applied loads.[10,21] Combinations of graft fixation angles investigated for DB PCLR included 0°/75° (PMB graft/ALB graft), 0°/90°, 0°/105°, 15°/75°, 15°/90°, and 15°/105° with a randomized order of fixation angle testing across specimens. Additionally, the order of flexion angles for biomechanical testing was randomized to minimize any incremental testing bias that might result. In between testing of each combination of graft fixation angles, both grafts were loosened and retensioned to the aforementioned loads before fixation at the new angles. After testing of the intact and reconstructed states, the sectioned PCL state was tested after the removal of all grafts and hardware.

Statistical Analysis

Student *t* tests analyzed kinematic differences between the PCLR states and the intact and sectioned states after each applied loading condition (posterior tibial load, external rotation, internal rotation, and valgus rotation). All kinematic results are reported as the difference from each knee's respective intact state. One-sample *t* tests compared the kinematics of the sectioned PCL and DB PCLR groups individually to the intact state. Two-sample *t* tests were used for kinematic comparison between the DB PCLR and sectioned PCL states. Bonferroni corrections were performed individually within each flexion angle for the intact and sectioned comparisons. In all cases, the Levene test was used to check for the equality of variance, and the Welch *t* test was used when groups had significantly different variances. The PCLR states were analyzed with a 2-factor repeated-measures model using the MIXED command in SPSS (SPSS Statistics for Windows version 20.0, IBM Corp) to evaluate the influence that the fixation angle of each bundle had on posterior translation during applied posterior loads. The factors included the ALB and PMB graft fixation angles, and main effects were interpreted only after checking for significant interactions. A similar 2-factor model with repeated measures (PMB and ALB graft fixation angle) was used to analyze the graft force data after an applied posterior tibial load and internal, external, and valgus rotation torques. The least significant difference method was used for pairwise comparisons among ALB graft fixation angles. All statistical analyses were performed using the SPSS statistical package. For all comparisons, significance was declared for $P < .05$, with Bonferroni-corrected *P* values used when appropriate.

RESULTS

Biomechanical Response to Posterior Tibial Load

For the PCL-sectioned state, there was a significant increase in posterior tibial translation at all flexion angles compared with the intact state ($P < .05$) (Figure 2 and Table 1). Double-bundle PCL-reconstructed knees had significantly reduced translation during posterior tibial loads compared with the sectioned PCL state at all flexion angles ($P < .05$). Combinations of graft fixation angles with the PMB graft fixed at 0° had significantly increased translation compared with the intact state at 0° to 60° ($P < .05$). Combinations with the PMB graft fixed at 15° had significantly increased posterior tibial translation compared with the intact state at 15° to 75° of flexion ($P < .05$), except for 15°/75° at 15° of flexion and 15°/105° at 75° of flexion. At 120° of flexion, insignificant joint overconstraint was observed for all graft fixation combinations, except for fixation at 0°/105°. At 0° of flexion, the measured posterior translation was significantly affected by the fixation angle of the PMB graft with fixation at 15°, resulting in significantly reduced translation compared with fixation at 0° ($P < .05$). In contrast, the ALB graft fixation angle had no significant effect on posterior translation at any flexion angle. The combinations of 0°/75°, 0°/90°, 0°/105°, 15°/75°, 15°/90°, and 15°/105° graft fixation angles had increases in mean posterior tibial translation of 2.1 ± 2.3 mm ($P = .055$), 2.1 ± 1.9 mm ($P < .03$), 2.3 ± 2.5 mm ($P = .053$), 1.6 ± 1.9 mm ($P = .068$), 1.6 ± 2.2 ($P = .122$), and 1.4 ± 2.7 ($P = .298$), respectively, compared with the intact state at 90° of flexion.

During an applied 134-N posterior tibial load, increasing the ALB graft fixation angle caused significant decreases in ALB graft force for all flexion angles when pooling across the 2 PMB graft fixation angles (all *P* values <.02), except at 0° of knee flexion in which 90° was not significantly different from 105° ($P = .124$). Additionally, increases in ALB graft fixation angles caused increases in PMB graft forces. For PMB graft fixation angles, fixation at 15° versus 0° caused a significant increase in PMB graft forces when pooling across the 3 ALB graft fixation angles (all *P* values <.01). Additionally, fixation of the PMB graft at 15° caused

TABLE 1
DB Posterior Tibial Translation and PMB and ALB Graft Forces During Applied 134-N Posterior Tibial Loads[a]

Flexion Angle, deg	Posterior Translation, mm	Change in Posterior Translation From Intact, mm	DB PCLR[b]					
	Intact (n = 9)	Sectioned (n = 9)	0°/75° (n = 9)	0°/90° (n = 9)	0°/105° (n = 9)	15°/75° (n = 9)	15°/90° (n = 9)	15°/105° (n = 9)
0	6.8 ± 1.2	3.6 ± 1.7[c]	0.8 ± 0.8[c,d]	1.2 ± 0.9[c,d]	1.2 ± 0.6[c,d]	0.0 ± 1.0[d]	0.2 ± 0.8[d]	0.4 ± 0.7[d]
15	7.5 ± 1.1	5.4 ± 2.2[c]	1.5 ± 1.4[c,d]	1.7 ± 1.3[c,d]	2.0 ± 1.1[c,d]	1.1 ± 1.2[d]	1.2 ± 0.9[c,d]	1.3 ± 0.9[c,d]
30	7.4 ± 1.4	7.9 ± 2.2[c]	2.1 ± 1.6[c,d]	2.3 ± 1.4[c,d]	2.6 ± 1.4[c,d]	1.9 ± 1.4[c,d]	2.0 ± 1.2[c,d]	2.1 ± 1.4[c,d]
45	6.0 ± 1.2	10.0 ± 2.5[c]	2.3 ± 1.8[c,d]	2.7 ± 1.4[c,d]	2.9 ± 1.8[c,d]	2.4 ± 1.2[c,d]	2.2 ± 1.6[c,d]	2.6 ± 1.6[c,d]
60	5.1 ± 1.3	11.7 ± 2.8[c]	2.8 ± 1.8[c,d]	2.9 ± 1.7[c,d]	2.9 ± 2.3[c,d]	2.5 ± 1.6[c,d]	2.6 ± 1.7[c,d]	2.5 ± 2.2[c,d]
75	4.7 ± 1.4	12.7 ± 2.9[c]	2.6 ± 2.1[c,d]	2.5 ± 1.7[c,d]	2.2 ± 2.8[d]	2.1 ± 1.6[c,d]	2.2 ± 1.9[c,d]	2.1 ± 2.7[d]
90	4.8 ± 1.5	15.2 ± 3.2[c]	2.1 ± 2.3[d]	2.1 ± 1.9[c,d]	2.3 ± 2.5[d]	1.6 ± 1.9[d]	1.6 ± 2.2[d]	1.4 ± 2.7[d]
105	5.5 ± 1.7	15.0 ± 3.2[c]	0.8 ± 2.4[d]	1.0 ± 2.1[d]	1.3 ± 2.6[d]	0.2 ± 1.9[d]	0.2 ± 2.1[d]	0.8 ± 2.5[d]
120	6.6 ± 1.7	14.9 ± 2.8[c]	–0.6 ± 2.5[d]	–0.4 ± 2.0[d]	0.1 ± 2.5[d]	–1.2 ± 1.8[d]	–1.2 ± 2.1[d]	–0.7 ± 2.4[d]

Flexion Angle, deg	General Influencers of Graft Force[e]: PMB Graft Force, PMB Fixation Angle	PMB Graft Force, ALB Fixation Angle	ALB Graft Force, PMB Fixation Angle	ALB Graft Force, ALB Fixation Angle	Specific Graft Forces, N, DB PCLR: 0°/75° PMB	0°/75° ALB	0°/90° PMB	0°/90° ALB	0°/105° PMB	0°/105° ALB	15°/75° PMB	15°/75° ALB	15°/90° PMB	15°/90° ALB	15°/105° PMB	15°/105° ALB
0	●	-	-	●	68 ± 12	60 ± 30	60 ± 13	47 ± 27	66 ± 12	43 ± 31	105 ± 41	54 ± 28	124 ± 41	46 ± 28	115 ± 39	38 ± 24
15	●	-	○	●	44 ± 18	81 ± 25	42 ± 15	68 ± 22	47 ± 19	62 ± 29	64 ± 17	73 ± 21	76 ± 21	63 ± 24	72 ± 25	49 ± 17
30	●	○	○	●	38 ± 17	98 ± 19	37 ± 13	85 ± 16	46 ± 22	77 ± 22	49 ± 18	89 ± 19	60 ± 26	81 ± 18	61 ± 23	68 ± 18
45	●	○	○	●	38 ± 20	105 ± 13	38 ± 17	93 ± 13	49 ± 27	82 ± 20	51 ± 20	96 ± 19	62 ± 32	84 ± 17	64 ± 27	72 ± 17
60	●	○	○	●	43 ± 23	109 ± 15	43 ± 15	95 ± 17	58 ± 33	81 ± 22	55 ± 17	98 ± 23	67 ± 29	86 ± 18	73 ± 30	72 ± 20
75	●	○	○	●	54 ± 31	117 ± 23	54 ± 21	98 ± 20	69 ± 35	81 ± 22	69 ± 24	105 ± 30	87 ± 42	87 ± 23	95 ± 45	70 ± 21
90	●	○	○	●	66 ± 30	113 ± 28	65 ± 23	95 ± 27	83 ± 37	76 ± 24	79 ± 23	104 ± 39	102 ± 41	82 ± 29	110 ± 48	65 ± 25
105	●	○	-	●	96 ± 50	124 ± 62	90 ± 33	96 ± 40	120 ± 67	71 ± 25	113 ± 42	116 ± 66	140 ± 65	84 ± 39	147 ± 61	62 ± 24
120	●	○	-	●	124 ± 53	121 ± 74	117 ± 49	94 ± 53	138 ± 64	68 ± 33	136 ± 43	113 ± 72	172 ± 69	83 ± 50	171 ± 62	60 ± 33

[a]Data are presented as mean ± SD. ALB, anterolateral bundle; DB, double-bundle; PCLR, posterior cruciate ligament reconstruction; PMB, posteromedial bundle.
[b]Double-bundle PCLR with grafts independently fixed at the specified fixation angles (PMB graft fixation angle/ALB graft fixation angle).
[c]Significant difference ($P < .05$) from intact state.
[d]Significant difference ($P < .05$) from PCL-sectioned state.
[e]Results of a 2-factor model for the effect on graft forces of (1) PMB and (2) ALB graft fixation angles (pooled across opposite bundle fixation); significant influencers of graft force are indicated: ● $P < .001$; ○ $.001 < P < .05$; - $P > .5$.

a significant reduction in ALB graft forces between 15° to 90° (all P values <.04). The distribution of force between the 2 bundles (Figure 3) reflects the combined effects of both bundle fixation angles.

Biomechanical Response to Internal Rotation Torque

Sectioning of both PCL bundles resulted in significant increases in internal rotation at 60° to 90° of flexion (Table 2). All combinations of DB PCLR graft fixation had significantly less internal rotation compared with the sectioned state at all tested flexion angles ($P < .05$), except for the 0°/75° combination at 60° of flexion and 0°/105° at both 60° and 120° of flexion. Decreased internal rotation for PCLR indicated overconstraint compared with biomechanics of the intact state.

The ALB and PMB graft forces experienced during applied 5-N·m internal rotation torques are presented in Table 2. Increasing ALB graft fixation angles resulted in significantly decreased ALB graft forces (all P values <.02). Fixation of the PMB graft at 15° versus 0° resulted in significantly increased PMB graft forces (all P values <.05).

Biomechanical Response to External Rotation Torque

The PCL-sectioned state significantly increased in external rotation compared with the intact state for all tested flexion angles except 120° of flexion ($P < .05$) (Table 3). Additionally, no significant differences were observed between any of the combinations of graft fixation angles and the sectioned state. All combinations had significantly increased external rotation compared with the intact state at 60° and 75° of flexion, and additionally, PCLR fixed at 0°/105° and 15°/105° had significantly increased external rotation at 90° of knee flexion compared with the intact state ($P < .05$).

The mean graft forces measured during applied 5-N·m external rotation torques are reported in Table 3. Increasing ALB graft fixation angles resulted in significantly decreased ALB graft forces for all tested flexion angles (all P values <.02). Fixation of the PMB graft at 15° had significantly increased PMB graft forces compared with fixation at 0° between 75° to 120° (all P values <.02).

TABLE 2
DB Tibial Rotation and PMB and ALB Graft Forces During Applied 5-N·m Internal Torques[a]

	Internal Rotation, deg	Change in Internal Rotation From Intact, deg						
			DB PCLR[b]					
Flexion Angle, deg	Intact (n = 9)	Sectioned (n = 9)	0°/75° (n = 9)	0°/90° (n = 9)	0°/105° (n = 9)	15°/75° (n = 9)	15°/90° (n = 9)	15°/105° (n = 9)
60	20.2 ± 8.8	1.7 ± 1.3[c]	0.3 ± 1.1	0.4 ± 0.8[d]	0.2 ± 1.5	–0.1 ± 0.8[d]	0.0 ± 1.1[d]	0.2 ± 1.2[d]
75	19.2 ± 8.6	2.7 ± 1.8[c]	0.2 ± 2.0[d]	0.1 ± 1.8[d]	0.3 ± 2.0[c]	–0.6 ± 1.8[d]	–0.3 ± 1.7[d]	–0.2 ± 2.1[d]
90	19.2 ± 8.8	3.3 ± 2.6[c]	–0.7 ± 2.9[d]	–0.5 ± 2.7[d]	–0.3 ± 3.1[c]	–1.3 ± 2.8[d]	–1.2 ± 2.7[d]	–1.1 ± 3.1[d]
105	19.6 ± 9.4	3.4 ± 3.7	–2.0 ± 4.0[d]	–1.8 ± 4.3[d]	–1.4 ± 4.5[c]	–2.8 ± 3.8[d]	–2.7 ± 3.9[d]	–2.1 ± 4.2[d]
120	20.2 ± 9.8	3.2 ± 4.4	–3.1 ± 5.0[d]	–2.8 ± 5.1[d]	–2.2 ± 5.1	–3.8 ± 4.8[d]	–3.7 ± 4.8[d]	–3.0 ± 5.1[d]

	General Influencers of Graft Force[e]				Specific Graft Forces, N											
	PMB Graft Force		ALB Graft Force		DB PCLR											
					0°/75°		0°/90°		0°/105°		15°/75°		15°/90°		15°/105°	
Flexion Angle, deg	PMB Fixation Angle	ALB Fixation Angle	PMB Fixation Angle	ALB Fixation Angle	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB
60	○	-	-	●	31 ± 24	54 ± 17	27 ± 15	42 ± 14	43 ± 45	37 ± 14	37 ± 20	51 ± 19	48 ± 35	42 ± 13	50 ± 33	33 ± 16
75	○	-	-	●	42 ± 32	74 ± 15	40 ± 21	58 ± 12	53 ± 41	46 ± 14	52 ± 28	69 ± 22	68 ± 47	55 ± 15	68 ± 42	42 ± 19
90	○	-	-	●	51 ± 31	80 ± 20	47 ± 19	64 ± 16	62 ± 42	50 ± 15	59 ± 24	76 ± 29	80 ± 48	59 ± 19	81 ± 42	45 ± 19
105	○	-	-	●	75 ± 51	100 ± 54	67 ± 32	74 ± 36	92 ± 71	53 ± 17	85 ± 44	93 ± 52	111 ± 75	67 ± 29	111 ± 66	48 ± 22
120	○	-	-	●	90 ± 54	99 ± 58	83 ± 45	77 ± 45	99 ± 63	55 ± 26	99 ± 47	97 ± 60	133 ± 75	72 ± 41	120 ± 58	51 ± 27

[a]Data are presented as mean ± SD. ALB, anterolateral bundle; DB, double-bundle; PCLR, posterior cruciate ligament reconstruction; PMB, posteromedial bundle.
[b]Double-bundle PCLR with grafts independently fixed at the specified fixation angles (PMB graft fixation angle/ALB graft fixation angle).
[c]Significant difference ($P < .05$) from intact state.
[d]Significant difference ($P < .05$) from PCL-sectioned state.
[e]Results of a 2-factor model for the effect on graft forces of (1) PMB and (2) ALB graft fixation angles (pooled across opposite bundle fixation); significant influencers of graft force are indicated: ● $P < .001$; ○ $.001 < P < .05$; - $P > .5$.

Biomechanical Response to Valgus Rotation Torque

The DB PCL–sectioned state significantly increased ($P < .05$) in valgus rotation compared with the intact state at 60° to 90° of flexion (Table 4). Each combination of DB PCLR graft fixation had significantly decreased ($P < .05$) valgus rotation compared with the sectioned state at all flexion angles greater than 60° of flexion; however, the 15°/90° combination was additionally significantly decreased from the sectioned state at 60° of flexion ($P < .05$). Additionally, overconstraint, as indicated by decreased valgus rotation compared with the intact state, was observed for several of the DB PCLR combinations. The 15°/75° and 15°/90° graft fixation combinations were significantly decreased compared with the intact state at 105° ($P < .02$), and all reconstruction groups had significantly less valgus rotation than the intact state at 120° of flexion ($P < .05$), except for the 0°/105° and 15°/105° reconstruction groups ($P = .089$ and $P = .119$, respectively).

Graft forces during applied 10-N·m valgus rotation torques are located in Table 4. Increasing ALB graft fixation angles resulted in significantly decreased graft forces for all flexion angles (all P values <.02), except at 60° of flexion in which forces for ALB graft fixation at 90° and 105° did not significantly differ ($P = .091$). Fixation of the PMB graft at 15° resulted in significantly increased PMB graft forces compared with fixation at 0° for all angles of flexion (all P values <.05).

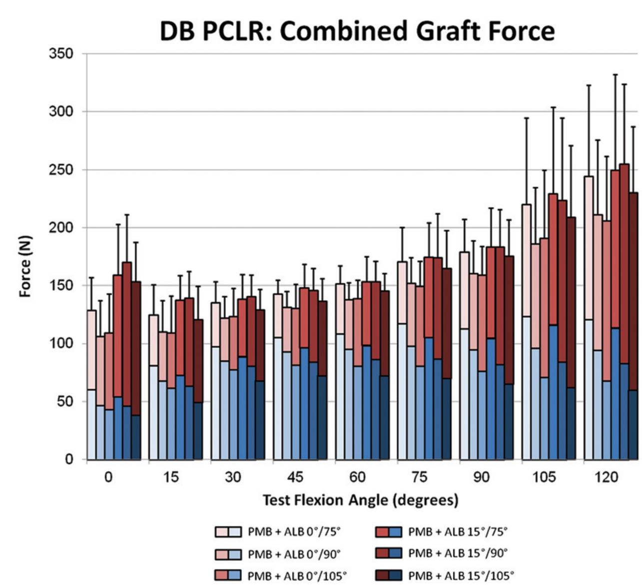

Figure 3. Double-bundle combined graft forces observed during an applied 134-N posterior tibial load. Data are presented as mean ± SD bars for combined graft forces. Each combined graft force is separated into the mean distribution of graft force between the anterolateral bundle (ALB) (bottom) and posteromedial bundle (PMB) (top).

TABLE 3
DB Tibial Rotation and PMB and ALB Graft Forces During Applied 5-N·m External Torques[a]

	External Rotation, deg	Change in External Rotation From Intact, deg						
			DB PCLR[b]					
Flexion Angle, deg	Intact (n = 9)	Sectioned (n = 9)	0°/75° (n = 9)	0°/90° (n = 9)	0°/105° (n = 9)	15°/75° (n = 9)	15°/90° (n = 9)	15°/105° (n = 9)
60	18.0 ± 5.8	2.9 ± 2.2[c]	2.2 ± 2.1[c]	1.9 ± 1.5[c]	1.9 ± 1.4[c]	2.2 ± 2.2[c]	1.9 ± 1.7[c]	1.8 ± 1.7[c]
75	17.8 ± 5.5	3.0 ± 2.1[c]	2.5 ± 2.5[c]	2.2 ± 1.7[c]	2.1 ± 1.8[c]	2.4 ± 2.5[c]	2.2 ± 2.2[c]	2.1 ± 1.9[c]
90	18.5 ± 4.9	3.1 ± 2.3[c]	2.2 ± 3.1	1.9 ± 2.3	1.8 ± 1.8[c]	2.0 ± 3.4	1.8 ± 2.9	2.0 ± 1.9[c]
105	19.4 ± 5.0	3.0 ± 3.2[c]	1.1 ± 4.5	0.8 ± 3.5	0.4 ± 3.2	0.7 ± 5.3	0.5 ± 4.7	0.3 ± 4.2
120	19.7 ± 5.2	3.2 ± 4.1	1.2 ± 5.7	0.8 ± 4.9	0.7 ± 4.3	0.9 ± 5.9	0.5 ± 5.5	1.0 ± 4.2

	General Influencers of Graft Force[d]				Specific Graft Forces, N											
	PMB Graft Force		ALB Graft Force		DB PCLR											
					0°/75°		0°/90°		0°/105°		15°/75°		15°/90°		15°/105°	
Flexion Angle, deg	PMB Fixation Angle	ALB Fixation Angle	PMB Fixation Angle	ALB Fixation Angle	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB
60	-	-	-	●	20 ± 20	48 ± 25	16 ± 12	38 ± 24	26 ± 32	34 ± 22	21 ± 15	46 ± 26	27 ± 29	42 ± 24	29 ± 24	35 ± 21
75	○	-	-	●	30 ± 33	79 ± 33	27 ± 18	62 ± 31	37 ± 41	50 ± 29	38 ± 23	78 ± 36	49 ± 48	64 ± 27	51 ± 47	50 ± 32
90	○	-	-	●	42 ± 38	100 ± 36	38 ± 29	82 ± 35	51 ± 53	63 ± 34	52 ± 33	97 ± 43	71 ± 58	79 ± 25	75 ± 56	61 ± 33
105	●	-	-	●	72 ± 66	132 ± 74	64 ± 48	103 ± 53	88 ± 90	70 ± 32	87 ± 61	125 ± 68	125 ± 87	103 ± 39	113 ± 91	66 ± 32
120	●	-	-	●	102 ± 73	141 ± 83	93 ± 62	114 ± 62	110 ± 90	80 ± 37	118 ± 67	141 ± 84	155 ± 98	109 ± 59	147 ± 92	76 ± 42

[a]Data are presented as mean ± SD. ALB, anterolateral bundle; DB, double-bundle; PCLR, posterior cruciate ligament reconstruction; PMB, posteromedial bundle.
[b]Double-bundle PCLR with grafts independently fixed at the specified fixation angles (PMB graft fixation angle/ALB graft fixation angle).
[c]Significant difference ($P < .05$) from intact state.
[d]Results of a 2-factor model for the effect on graft forces of (1) PMB and (2) ALB graft fixation angles (pooled across opposite bundle fixation); significant influencers of graft force are indicated: ● $P < .001$; ○ $.001 < P < .05$; - $P > .5$.

DISCUSSION

This study's primary finding was that PMB graft forces significantly increased in fixation of the PMB graft at 15° compared with 0° during applied posterior loads, internal rotation, external rotation, and valgus rotation. Additionally, fixation of the ALB graft at 75° versus 90° or 105° caused significant increases in ALB graft forces during applied posterior loads, internal rotation, external rotation, and valgus rotation. This disproved our hypothesis that different graft fixation angles would have no effect on graft loads. While DB PCLR significantly reduced posterior tibial translation compared with the sectioned state at all tested flexion angles, persistent laxity (mean, 1.5 mm) remained compared with the intact state, despite investigation into an optimal fixation angle combination. Because of the significant increases in PMB graft forces that occurred as a result of fixation of the PMB graft at 15°, we recommend fixation of the PMB graft at 0° of flexion to minimize PMB graft loading during applied posterior loads and internal, external, and valgus rotations. Additionally, because fixation of the ALB graft at 75° resulted in significantly increased ALB graft forces during applied loads, it is recommended that fixation of the ALB graft be performed at either 90° or 105° during DB PCLR to minimize ALB graft loads.

In the current study, we demonstrated that, when compared with the SB PCLR results from part 1 of this study, there were noticeable decreases in posterior tibial translation at higher flexion angles, regardless of the fixation angle combination. This finding corroborates a previous study that reported that DB PCLR, with the PMB and ALB fixed at 0° and 90°, respectively, better restored kinematics than SB PCLR with the ALB fixed at 90°.[21] Thus, inclusion of the PMB graft in DB PCLR may provide important additional resistance to posterior tibial translation. Similar to PCL kinematic sectioning studies,[10] both bundles had a substantial contribution, as highlighted by the load sharing or reciprocal influence of both bundles on graft forces, for restoring posterior tibial translation throughout the full range of tested knee motion during applied posterior loads. Interestingly, this reciprocal influence of both bundles was not fully observed during applied internal, external, or valgus rotations.

This study enhances the overall understanding of the effect of graft fixation angles on DB PCLR procedures by elucidating the increased graft loading that occurs with different combinations of graft fixation angles. Although the observed differences in graft forces from fixation angle selection remained substantially below values for screw fixation failure (400-600 N) and reported midsubstance graft failure (4617 N for Achilles tendons),[3,5,22] the maximum force differences of 50 N or more at 0°, 105°, and 120° of flexion during applied posterior loads between some of the different combinations could be compounded over time and lead to clinically relevant graft loosening. Additionally, knowledge of the increased graft forces at higher flexion angles could be used by clinicians for

TABLE 4
DB Tibial Rotation and PMB and ALB Graft Forces During Applied 10-N·m Valgus Torques[a]

	Valgus Rotation, deg	Change in Valgus Rotation From Intact, deg						
			DB PCLR[b]					
Flexion Angle, deg	Intact (n = 9)	Sectioned (n = 9)	0°/75° (n = 9)	0°/90° (n = 9)	0°/105° (n = 9)	15°/75° (n = 9)	15°/90° (n = 9)	15°/105° (n = 9)
60	7.0 ± 5.5	1.6 ± 1.5[c]	0.4 ± 0.8	0.5 ± 0.8	0.2 ± 0.7	0.3 ± 1.0	0.2 ± 0.9[d]	0.4 ± 1.1
75	7.2 ± 5.2	2.0 ± 1.8[c]	0.1 ± 0.8[d]	0.1 ± 0.6[d]	0.2 ± 0.6[d]	–0.2 ± 1.0[d]	–0.1 ± 0.9[d]	0.0 ± 1.3[d]
90	8.0 ± 4.9	1.8 ± 1.5[c]	–0.6 ± 1.2[d]	–0.2 ± 0.7[d]	–0.4 ± 1.3[d]	–0.6 ± 1.1[d]	–0.8 ± 1.6[d]	–0.6 ± 1.6[d]
105	8.9 ± 5.3	1.5 ± 1.6	–0.7 ± 1.3[d]	–0.7 ± 1.0[d]	–0.6 ± 1.3[d]	–1.3 ± 0.9[c,d]	–1.3 ± 1.1[c,d]	–0.8 ± 1.5[d]
120	9.9 ± 5.3	1.0 ± 1.9	–1.7 ± 1.7[c,d]	–1.7 ± 1.3[c,d]	–1.1 ± 1.4[d]	–2.3 ± 1.3[c,d]	–2.3 ± 1.2[c,d]	–1.3 ± 1.8[d]

	General Influencers of Graft Force[e]				Specific Graft Forces, N											
	PMB Graft Force		ALB Graft Force		DB PCLR											
					0°/75°		0°/90°		0°/105°		15°/75°		15°/90°		15°/105°	
Flexion Angle, deg	PMB Fixation Angle	ALB Fixation Angle	PMB Fixation Angle	ALB Fixation Angle	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB	PMB	ALB
60	○	-	-	●	21 ± 26	42 ± 22	18 ± 13	31 ± 15	29 ± 37	28 ± 16	24 ± 18	40 ± 19	33 ± 37	34 ± 13	33 ± 32	28 ± 18
75	○	-	-	●	31 ± 37	62 ± 22	26 ± 19	44 ± 19	37 ± 44	36 ± 18	36 ± 24	56 ± 24	50 ± 52	45 ± 17	51 ± 46	36 ± 20
90	○	-	-	●	39 ± 37	75 ± 23	32 ± 19	56 ± 21	44 ± 45	44 ± 19	46 ± 24	70 ± 29	65 ± 57	55 ± 19	65 ± 49	41 ± 19
105	○	-	-	●	64 ± 58	104 ± 67	54 ± 36	77 ± 48	76 ± 76	52 ± 22	77 ± 49	100 ± 59	102 ± 81	73 ± 37	97 ± 73	51 ± 25
120	○	-	-	●	85 ± 60	115 ± 73	78 ± 47	94 ± 66	90 ± 70	66 ± 39	98 ± 49	115 ± 70	130 ± 81	88 ± 60	117 ± 67	62 ± 41

[a]Data are presented as mean ± SD. ALB, anterolateral bundle; DB, double-bundle; PCLR, posterior cruciate ligament reconstruction; PMB, posteromedial bundle.
[b]Double-bundle PCLR with grafts independently fixed at the specified fixation angles (PMB graft fixation angle/ALB graft fixation angle).
[c]Significant difference ($P < .05$) from intact state.
[d]Significant difference ($P < .05$) from PCL-sectioned state.
[e]Results of a 2-factor model for the effect on graft forces of (1) PMB and (2) ALB graft fixation angles (pooled across opposite bundle fixation); significant influencers of graft force are indicated: ● $P < .001$; ○ $.001 < P < .05$; - $P > .5$.

selecting an appropriate postoperative rehabilitation protocol that minimizes the forces placed on the grafts. Regardless of either the PMB or ALB graft fixation angle, the PMB graft experienced a larger force than the ALB graft at 0° and 120° of flexion during applied posterior loads. Both the PMB and ALB graft forces had characteristic trends throughout flexion; the ALB graft force peaked at midflexion, whereas the PMB graft force fell at midflexion, with graft forces peaking at both full extension (0°) and deep flexion (120°). The selection of different PMB and ALB graft fixation angles influenced the distribution of force across each graft, which further reinforces the reciprocal roles that both bundle graft fixation angles play in influencing forces within each graft. As observed during applied posterior loading, this confirms a codominant relationship between the 2 DB PCLR grafts for both kinematics and graft forces, thus supporting the previously reported codominance observed for the native ALB and PMB.[10]

Prior work for determining the optimal DB PCLR by Carson et al[4] analyzed the effects of 3 drastically different fixation combinations: 90°/90°, 45°/45°, and 0°/90° (PMB/ALB). They reported that fixation at 0°/90° best reduced PMB graft loads.[4] After this study, it was our goal to determine whether 0°/90° was the ideal combination of DB PCLR graft fixation or if other graft fixation combinations could further improve knee kinematics without overloading the grafts. In this study, we found that fixing the PMB graft at 15° of flexion significantly increased PMB graft forces experienced during an applied posterior load but significantly reduced posterior tibial translation at 0° of flexion compared with the corresponding PMB graft fixation at 0°. However, because the PCL plays a less substantial role in resisting posterior tibial translation in full extension, we believe that the kinematic effects at 0° have little clinical significance. Because of the significant increase in PMB graft forces when fixed at 15° compared with 0° during an applied posterior load for flexion angles greater than 0°, we recommend fixing the PMB graft at 0° during DB PCLR.

Compared with the overall SB PCLR ALB graft force seen during posterior loading from part 1 of this study, the combined force of the ALB and PMB grafts was greater for all tested flexion angles. Harner et al[7] also reported similar findings; the combined PMB and ALB resultant graft force was larger than the force in a SB PCL graft.[13] In the Harner et al[7] study, they indirectly calculated the in situ forces seen in the native PCL bundles, which allowed the authors to compare the results of the SB and DB techniques to the intact state. However, recent findings suggesting PMB and ALB codominance decrease the validity of characterizing in situ graft forces in the individual PCL bundles because interaction between the bundles violates the superposition theorem's requirement that force vectors of the system remain independent of each other.[17] In this study in which graft forces were independently and directly measured for each bundle, we found that the PMB and ALB graft forces under an applied posterior load adhered to the same characteristic trend displayed by the native bundles in the study of Harner et al,[7] with the exception of the PMB graft at 0° of flexion.

The authors acknowledge the presence of limitations within this study. First, this is a time zero, cadaveric biomechanical study. The effects of in vivo tissue remodeling, the effects of different rehabilitation protocols on graft healing, and other biologically based issues after reconstruction are beyond the scope of this study. Second, this study aimed 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 are effective for assessing knee laxity. Third, the measurements of graft forces at the tibial tunnel could result in measurements that do not precisely match the graft forces seen intra-articularly because of the geometry of the knee and the tibial corner. Previous work[14] described a loss of force intra-articularly compared with forces at the tibial tunnel; the consistency of this force reduction suggests that increases or decreases in graft force at the tibial tunnel can be used as a surrogate for changes observed intra-articularly because of changes in the method of graft fixation. Fourth, the lack of secondary muscle stabilization of the joint during the extensive testing protocol could potentially stretch out the primary and secondary knee stabilizers. However, randomization of the flexion angle testing order and graft fixation order likely reduced any incremental bias due to testing order.

CONCLUSION

We found that PMB graft fixation angles in the range of 0° to 15° and ALB graft fixation angles in the range of 75° to 105° for DB PCLR were successful in significantly reducing knee laxity from the sectioned PCL state. However, fixation of the PMB graft at 15° versus 0° resulted in significantly increased loads through the PMB graft, and increasing ALB graft fixation angles resulted in significantly decreased loads through the ALB graft. While the results of this study suggest that all 6 combinations of DB PCLR graft fixation angles sufficiently restored knee joint kinematics, we recommend that PMB grafts be fixed at 0° because of the significant increase in PMB graft loads with fixation at 15° compared with PMB graft fixation at 0° and additionally recommend fixation of the ALB graft at 90° or 105° rather than 75° to minimize loads on the ALB graft.

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