Tibial Slope and Its Effect on Graft Force in Posterior Cruciate Ligament Reconstructions

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Background: A flattened posterior tibial slope may cause excessive unwanted stress on the posterior cruciate ligament (PCL) reconstruction graft and place patients at risk for PCL reconstruction graft failure. To date, there is a paucity of biomechanical studies evaluating the effect of posterior tibial slope on the loading properties of single-bundle (SB) and double-bundle (DB) PCL grafts.

Purpose/Hypothesis: The purpose of this study was to quantify the effect of sagittal plane tibial slope on PCL reconstruction graft force at varying slopes and knee flexion angles for SB and DB PCL reconstructions. The null hypothesis was that there would be no differences in SB or DB PCL graft forces with changes in posterior tibial slope or knee flexion angle.

Study Design: Controlled laboratory study.

Methods: Ten male fresh-frozen cadaveric knees had a proximal posterior tibial osteotomy performed and an external fixator placed for tibial slope adjustment. SB (anterolateral bundle [ALB] only) and DB PCL reconstruction procedures were performed and tested consecutively for each specimen. The ALB and posteromedial bundle graft forces were recorded before (unloaded force) and after (loaded force) compression with a 300-N axial load. Unloaded and loaded graft forces were tested at flexion angles of 45°, 60°, 75°, and 90°. Tibial slope was varied between $-2°$ and 16° of posterior slope at 2° increments under these test conditions.

Results: Modeling for unloaded testing revealed that tibial slope had an independently significant and linear decreasing effect on the force of all PCL grafts regardless of flexion angle (coefficient = -1.0, SE = 0.08, $P < .001$). Higher knee flexion angles were significantly associated with higher unloaded graft force for all PCL grafts ($P < .001$). After the graft was subjected to loading, tibial slope also had an independently significant and linear decreasing effect on the loaded force of all PCL grafts regardless of flexion angle (coefficient = -0.70, SE = 0.11, $P < .001$). The ALB graft of DB reconstructions had a significantly lower loaded graft force than the ALB graft of the SB PCL reconstruction (coefficient = 14.8, SE = 1.62, $P < .001$). The posteromedial bundle graft had a significantly lower loaded graft force than the ALB graft in both reconstruction states across all flexion angles (both $P < .001$). Higher knee flexion angles were also significantly associated with higher loaded graft force for all graft constructs ($P < .001$).

Conclusion: PCL graft forces increased as tibial slope decreased (flattened) in the loaded and unloaded states. An increased posterior tibial slope was protective of PCL reconstruction grafts. The findings of this study support the effect of tibial slope on PCL grafts that has been noted clinically, and a flat tibial slope should be considered a factor when evaluating the cause of failed PCL reconstructions.

Clinical Relevance: The authors validated that decreased tibial slope increased the loads on PCL reconstruction grafts. Patients with flat tibial slopes in chronic tears or revision PCL reconstruction cases should be evaluated closely for the possible need of a first-stage or concurrent slope-increasing tibial osteotomy.

Keywords: tibial slope; posterior cruciate ligament reconstruction; posterior tibial translation; PCL graft forces; osteotomy; double bundle

Recent advancements in understanding the anatomy and biomechanics of the posterior cruciate ligament (PCL) sought to resolve the challenges of restoring native knee kinematics after a PCL tear. Although the current literature has evolved to describe a variety of PCL reconstruction (PCLR) techniques that have led to improving patient outcomes,[4,13] residual postoperative posterior knee laxity remains problematic.[9] Further investigations regarding the bony geometry of the tibial plateau has also led to an increased awareness of the potential role of the native posterior tibial slope in PCL tears, and it is believed that decreased

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posterior tibial slope may be a risk factor for a PCL tear and persistent graft laxity after PCLR.[9]

The effects of posterior tibial slope on measured anterior tibial translation were described in the setting of anterior cruciate ligament (ACL) tears and treatment,[1,5,6,8,19,23] and clinical and biomechanical studies have since emerged to identify the effect of tibial slope on posterior knee stability.[7,16] While native posterior slope has been described to average 8°, it was reported that an increased posterior tibial slope may protect the PCL and further reduce posterior tibial translation in chronically injured PCL knees.[7,16] In contrast, a flatter tibial slope was reported to significantly correlate with increased residual posterior knee laxity after single-bundle (SB) PCLR.[9] Thus, it is theorized that bony correction of the native tibial slope by tibial osteotomy that increases the slope may be required in some cases, such as chronic PCL tears with flat tibial slopes or as a supplement to soft tissue reconstruction to minimize the risk of recurrent posterior knee laxity.[9] In addition, while an anatomic double-bundle (DB) PCLR was shown to more closely approximate native knee kinematics in comparison with SB PCLR,[12,22] the effects of tibial slope on a DB PCLR has not been evaluated.[22]

To date, the biomechanical effects of changes in tibial slope on SB or DB PCLR grafts when subjected to loading conditions at various knee flexion angles are not known. Therefore, the purpose of this study was to quantify the effect of sagittal plane tibial slope on PCLR graft force at varying slopes and knee flexion angles for SB and DB PCLRs. Our null hypothesis was that there would be no differences between SB or DB PCL grafts nor changes associated with changing posterior tibial slope or knee flexion angle with respect to observed graft forces.

METHODS

Specimen Preparation

Ten male fresh-frozen cadaveric knees with a mean age of 57.3 years (range, 44-65 years) and a mean body mass index of 23.7 kg/m^2 (range, 15.4-32.0 kg/m^2) were used in this study. After arthroscopy, specimens with prior surgery, evidence of cartilage damage, meniscal damage, ligament damage, or osteoarthritis were excluded from this study. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. Institutional review board approval was not required, because the use of cadaveric specimens is exempt at our institution.

The skin was removed, and all posterior subcutaneous tissues were dissected off the specimen >2 cm distal to the joint line. The posterior aspect of the knee was dissected of all muscle tissue down to the posterior capsule and popliteus muscle belly. The popliteus musculotendinous junction was then anchored to the posterior cortex of the tibia to maintain rotational stability of the knee. Anteriorly, a medial arthrotomy was performed for direct visualization into the joint. A small posterior window was also made in the capsule to ensure easy visualization of the PCL tibial footprint. The PCL was sharply resected off its femoral and tibial attachment sites with a No. 15 blade. All other ligamentous stabilizing structures were left intact, including the meniscofemoral ligaments. The femur, tibia, and fibula were cut 20 cm distal to the joint line, while the proximal portion of the interosseous membrane was left intact. The distal tibia and fibula were potted up to a point 11 cm distal to the tibial tubercle in a cylindrical mold with PMMA (polymethyl methacrylate; Fricke Dental International) with the tibial plateau oriented parallel to the base.

Surgical Technique

The PCL was reconstructed in 2 stages: (1) an anatomic SB technique replicating the anatomy of the anterolateral bundle (ALB) and (2) an anatomic DB technique as previously described.[4,20] The ALB and posteromedial bundle (PMB) femoral tunnels were drilled before SB PCLR testing. Tibial slope was then measured under fluoroscopy and defined as the angle between the medial tibial plateau and a line parallel to the middiaphysis of the tibia. The tibial middiaphyseal line was centered through the tibial shaft with 2 lines: one 5 cm distal to the joint line and one 15 cm distal to the joint line. The midpoint of these 2 lines represented the middiaphyseal line, and a line was drawn parallel to the tibial plateau. The angle between these lines was subtracted from 90° to give the resultant posterior tibial slope. We measured tibial slope off the medial tibial plateau because it was more reproducible than measuring it off the lateral tibial plateau while using fluoroscopy (Figure 1).[21]

Next, a posterior tibial osteotomy was performed 2.5 cm distal to the joint line and progressed parallel to the joint with a saw blade under live radiographic visualization, ensuring that the osteotomy did not break through the anterior cortex of the tibia while leaving a 5- to 6-mm anterior bone hinge. A posterior osteotomy was chosen to avoid the tibial tubercle and to allow opening and closing of the

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Figure 1. Lateral knee radiograph demonstrating the sagittal slope measurement technique. Posterior tibial slope (in degrees) is calculated by subtracting the tibial slope angle from 90°. The tibial slope angle is determined by the angle between the tibial middiaphyseal line and a line drawn parallel to the tibial plateau.[21]

wedge. A 15-mm wedge was resected to allow for adequate slope changes.

Medial and lateral external fixation pins (Synthes Medium External Fixator; Synthes USA) were placed in the proximal segment, and 1 pin was placed distal to the posterior aspect of the tibia to allow the tibial slope to be varied as desired and rigidly secured during testing. All specimens had 2 generic box nails placed along the most anterior aspect of the tibial plateau in a vertical fashion to ensure that no failure of the anterior hinge occurred while the slope was varied. Before testing, tibial slope states were verified under fluoroscopy in 2° increments from $-2°$ to 16° and individually marked on the lateral and medial external fixator bars to ensure reproduction of the desired slope during testing.

Graft Preparation and Fixation Protocol

For the SB PCLR testing arm of the study, an Achilles tendon allograft with an 11-mm-diameter and 20-mm-long calcaneal bone plug was prepared to reconstruct the ALB of the PCL. For the DB PCLR, a separate split Achilles tendon allograft was prepared as described to reconstruct the ALB, and a 7-mm-diameter and 20-mm-long calcaneal bone plug was also prepared to reconstruct the PCL PMB. Each tendon graft was trimmed and underwent tubularization of its end with No. 2 sutures (FiberWire; Arthrex).

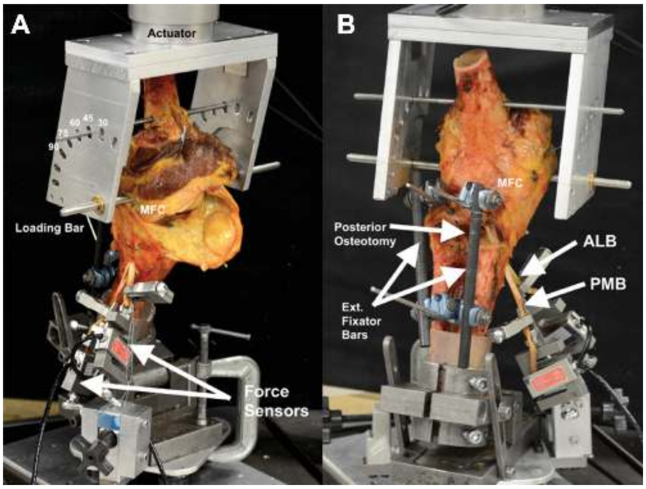

Figure 2. (A) Anteromedial and (B) posteromedial views of the biomechanical testing setup for posterior cruciate ligament grafts. ALB, anterolateral bundle; Ext, external; MFC, medial femoral condyle; PMB, posteromedial bundle.

Each graft was preconditioned with a constant force of 88 N for 10 minutes to ensure proper conditioning to minimize creep during testing.[11] After preconditioning, the ALB graft was fixed in the femoral tunnel with a 7 × 20–mm interference screw (Smith & Nephew). The PMB graft was also fixed in its respective femoral tunnel with a 7 × 20–mm interference screw. For SB PCLR testing, the PMB graft was not passed through the tibial tunnel, whereas the ALB graft was pulled through the tibial tunnel and clamped to a calibrated external load cell sensor (Sensortronics; Vishay Precision Group), which was calibrated and verified before testing to be within the manufacturer's reported accuracy (within 0.025 mm). For DB PCLR testing, a new ALB graft was fixated into its respective tunnel, and the ALB and PMB grafts were both pulled through the tibial tunnel to be clamped by 2 external load cell sensors (Figure 2). The same specimen sequentially underwent SB PCLR and DB PCLR testing.

Mechanical Testing Protocol

The potted tibia was rigidly secured in a custom fixture, which was clamped to a base that was allowed to freely translate on the testing table of the dynamic tensile testing machine (ElecroPuls E10000; Instron). The orientation of the tibia was modified by the custom fixture so that the middiaphyseal line was oriented at 30° with respect to the testing table. The femur was secured to a custom fixture that was rigidly mounted to the actuator, which was used to vary knee flexion by passing a 10-mm rod transversely through the femoral epicondyles.[15] The 10-mm rod acted as the load-bearing pivot axis. Next, a 7-mm rod was passed through the proximal femoral shaft to rigidly fix the femur in the desired flexion angle (Figure 2).

All specimens were tested by compressing the joint with a 300-N axial load, and the shear force of the femur on the tibia at randomized flexion angles at 45°, 60°, 75°, and 90° and the graft loads were recorded. This load was chosen after pilot testing revealed it to be sufficient to provide enough force to posteriorly translate the tibia on the testing table while maintaining the integrity of the tibial osteotomy without causing a fracture. Tibial slope was varied between −2° and 16° of posterior slope at 2° increments. The degree of tibial slope and flexion angle were randomized for all specimen tests. After each slope state, the knee was repositioned to 90° and the ALB graft retensioned to 88 N.[10,11] For DB PCLR testing states, the ALB graft was retensioned first to 88 N, and then the knee was positioned at full extension to retension the PLB graft to 67 N.[11] Throughout testing and preparation, the knees were sprayed with normal saline to prevent soft tissue desiccation.

Statistical Analysis

A 3-factor linear main-effect model was used to assess the effects of posterior tibial slope, knee flexion angle, and graft type (SB, DB anterolateral, and DB posteromedial) on graft force. Random intercepts were used to allow a different baseline force for each specimen and to account for the repeated-measures nature of the experimental design. Final model specification—including the decision to include an interaction effect and whether tibial slope required a polynomial relationship—was determined among candid models via the Akaike information criterion.[2] Residual diagnostics were performed to confirm model assumptions and model fit. The statistical computing software R with additional package lme4 was used for all analyses (access date, July 12, 2018; R Foundation for Statistical Computing).[17]

RESULTS

Results are reported in terms of the loaded and unloaded graft forces experienced by the PCL grafts before and after loading. Recorded unloaded and loaded graft forces for all testing states are summarized in Tables 1 and 2, respectively.

According to the Akaike information criterion, there was no requirement to assess a polynomial relationship for either state, and a 3-factor main-effects model was determined to be the best model to evaluate the linear interactions of posterior tibial slope, flexion angle, and graft type with graft force. All 3 experimental variables were interpreted independently for the unloaded and loaded testing states. Visual effect plots for each independent variable for unloaded and loaded states are shown in Figures 3 and 4, respectively.

Unloaded PCL Graft State

Modeling for unloaded testing revealed that tibial slope had an independently significant and linear decreasing effect on the force of all PCL grafts regardless of flexion angle (coefficient = −1.0, SE = 0.08, $P < .001$) (Figure 3). The ALB graft for DB reconstruction had significantly lower graft force than the ALB graft for SB reconstruction when unloaded (coefficient = −3.1, SE = 1.56, $P = .02$). Higher knee flexion angles were significantly associated with higher unloaded graft force for all grafts, with a statistically significant increase with each 15° increment (all $P < .001$).

TABLE 1
Unloaded Posterior Cruciate Ligament Graft Forces by Posterior Tibial Slope and Knee Flexion Angle[a]

Slope, deg	Flexion, deg	SB	DB ALB	DB PMB
–2	90	70.9 ± 8.2	66.7 ± 7.2	59.1 ± 11.3
–2	45	40.9 ± 5.7	40.1 ± 5.6	39.5 ± 6.1
–2	60	45.4 ± 6.2	51.5 ± 4.5	51.2 ± 7.8
–2	75	59.3 ± 6.6	58 ± 5.7	49.2 ± 8.6
0	90	73.5 ± 5.7	65.5 ± 4.9	60.9 ± 10.5
0	45	38.7 ± 5.2	39.4 ± 4.8	40.5 ± 5.7
0	60	51.5 ± 5.1	47.6 ± 4.6	44.5 ± 6.3
0	75	59 ± 3.7	59.1 ± 3.2	54.8 ± 8
2	90	68 ± 5.4	70.7 ± 4.5	57.9 ± 9.3
2	45	39.2 ± 5.7	43.2 ± 5.6	41.2 ± 5.1
2	60	46.7 ± 4.3	51.8 ± 4.6	46.5 ± 7.2
2	75	57.2 ± 5.6	58 ± 3.9	49.6 ± 7.8
4	90	66.9 ± 4.8	62 ± 6.5	53.6 ± 9.1
4	45	37.7 ± 4.5	38.2 ± 5.3	40.1 ± 4.9
4	60	42.2 ± 3.3	42.1 ± 5.2	37.2 ± 4.8
4	75	52.5 ± 4.2	51.2 ± 6.3	43.5 ± 6.3
6	90	56.1 ± 6.2	61.6 ± 5.8	49.4 ± 9.8
6	45	32.3 ± 5	34.7 ± 5.8	34.8 ± 5.7
6	60	38.1 ± 4.4	41.3 ± 6.2	35 ± 6.2
6	75	55.5 ± 3.7	47.2 ± 5.6	37.8 ± 7
8	90	58.5 ± 6	59.7 ± 4.7	47.4 ± 7.9
8	45	27.2 ± 3.1	39.4 ± 5.5	36.5 ± 5.4
8	60	31.7 ± 2.5	39.1 ± 4.9	31.9 ± 5.2
8	75	42.6 ± 4.4	51.1 ± 3.9	41.9 ± 6.6
10	90	52.4 ± 3.6	54.7 ± 7.1	42.5 ± 8
10	45	29.7 ± 3.7	29.4 ± 5.7	28.4 ± 6.6
10	60	35.8 ± 4	39.6 ± 6.1	31.9 ± 6.2
10	75	49.6 ± 5.3	45.1 ± 6.7	34 ± 7.3
12	90	52.1 ± 5.7	59 ± 4.3	44.6 ± 8.3
12	45	26.6 ± 3.6	33.4 ± 5.2	30.2 ± 4.5
12	60	29.8 ± 3.2	39.9 ± 3.6	34.5 ± 5.6
12	75	41.3 ± 4.1	49 ± 2.8	36.4 ± 6.2
14	90	50.4 ± 5.6	58.3 ± 4.7	40.2 ± 6.8
14	45	27.6 ± 4.9	33.6 ± 5.1	30.3 ± 5.2
14	60	33.8 ± 5.3	43.2 ± 5.9	34.6 ± 6.4
14	75	42.9 ± 4.8	48.9 ± 2.5	36.2 ± 5.9
16	90	51.1 ± 5.1	55.2 ± 5.5	39.2 ± 8.8
16	45	26.3 ± 4.2	27.9 ± 5.3	28.4 ± 6.6
16	60	29.8 ± 3.2	34.4 ± 3.4	28.6 ± 5.3
16	75	41.6 ± 4	41.4 ± 3.3	30.5 ± 6.3

[a]Data reported as N, mean ± SD, unless otherwise noted. ALB, anterolateral bundle; DB, double-bundle; PMB, posteromedial bundle; SB, single-bundle.

Loaded PCL Graft State

After the graft was subjected to loading, tibial slope had an independently significant and linear decreasing effect on

TABLE 2
Loaded Posterior Cruciate Ligament Graft Forces by Posterior Tibial Slope and Knee Flexion Angle[a]

Slope, deg	Flexion, deg	SB	DB ALB	DB PMB
–2	90	105.5 ± 7.9	79.2 ± 8.2	72.3 ± 11.7
–2	45	85.9 ± 7.5	69.9 ± 9.1	59.7 ± 6.9
–2	60	94.4 ± 7.6	79.9 ± 8.2	68.5 ± 8.2
–2	75	103.4 ± 8.5	79.4 ± 8.1	68.1 ± 9
0	90	112.1 ± 6.8	81.3 ± 6.2	73.3 ± 11.7
0	45	86.8 ± 7.1	74.8 ± 7.8	63.8 ± 7.7
0	60	101 ± 6.3	81.6 ± 7.3	65.7 ± 7.7
0	75	107.6 ± 6.6	83.8 ± 6	70.5 ± 8.7
2	90	112 ± 6.7	86.2 ± 9.2	69.9 ± 10.1
2	45	92.8 ± 10.2	79.5 ± 10.6	61.9 ± 7.3
2	60	105 ± 8.4	87.4 ± 9.2	67.2 ± 8.7
2	75	107.2 ± 9.5	88.2 ± 8.3	69.3 ± 9.4
4	90	114.6 ± 6.9	84.6 ± 11.2	69 ± 10.1
4	45	92.5 ± 9.9	76.3 ± 10.5	62.5 ± 6.8
4	60	101.6 ± 7.9	82.9 ± 10.6	62.1 ± 7
4	75	106.4 ± 7.8	82.5 ± 10.6	65.1 ± 8.1
6	90	97.8 ± 11.7	82.7 ± 11.3	66.2 ± 10.9
6	45	83.3 ± 7.6	67.8 ± 10.6	57.8 ± 7.8
6	60	95.7 ± 7.4	79.2 ± 10.9	59.9 ± 7.9
6	75	102.7 ± 7.7	81.7 ± 10.9	62.5 ± 8.7
8	90	99.7 ± 9.1	84.8 ± 11.1	62.1 ± 9.8
8	45	80.4 ± 9.9	80.2 ± 10.9	59.4 ± 7.4
8	60	87.4 ± 10.4	82.7 ± 10.7	56.6 ± 7.6
8	75	98.6 ± 8.3	87.5 ± 9.9	61.3 ± 8.4
10	90	105 ± 6.2	80 ± 11.8	55.3 ± 9.7
10	45	86.1 ± 11.4	63.5 ± 10.1	47.1 ± 8.6
10	60	100.3 ± 8.3	76.3 ± 11.8	51 ± 8.6
10	75	106.6 ± 7.3	76.6 ± 10.5	51 ± 9.1
12	90	92.4 ± 8.6	88.9 ± 8.3	62.1 ± 11.3
12	45	76.4 ± 11.8	74 ± 10.1	53.2 ± 8.4
12	60	90 ± 9.6	82.8 ± 9.3	56.3 ± 9.6
12	75	96.3 ± 9.1	88.4 ± 8.1	58 ± 9.4
14	90	99.2 ± 8.7	88.4 ± 8.5	55 ± 9.9
14	45	77.3 ± 14.1	71.5 ± 8.8	50.5 ± 8.2
14	60	88.9 ± 14.3	84.7 ± 9.9	52.1 ± 8.8
14	75	97.5 ± 10.7	87.4 ± 8.7	53.1 ± 8.9
16	90	92.3 ± 6	81.5 ± 8.4	55.6 ± 10.9
16	45	72.3 ± 11.6	59 ± 7.4	46.9 ± 8.9
16	60	84.6 ± 8.8	74.1 ± 7.7	48.9 ± 9.3
16	75	91.9 ± 7.2	78.7 ± 7.8	51.2 ± 9.6

[a] Data reported as N, mean ± SD, unless otherwise noted. ALB, anterolateral bundle; DB, double-bundle; PMB, posteromedial bundle; SB, single-bundle.

the loaded force of all PCL grafts regardless of flexion angle (coefficient = −0.70, SE = 0.11, $P < .001$) (Figure 4). The ALB graft for DB reconstruction had a significantly lower graft force than the ALB graft of the SB reconstruction (coefficient = 14.8, SE = 1.62, $P < .001$). The PMB graft had a significantly lower loaded graft force than the ALB graft in both reconstruction states (both $P < .001$) across all flexion angles. Regardless of graft type or tibial slope, a higher knee flexion angle was associated with a higher loaded graft force, with 45° having a significantly lower graft force than 60°, 75°, and 90° (all $P < .001$) and with 60° having a significantly lower graft force than 90° ($P = .023$).

DISCUSSION

The most important finding of this study was that we disproved our null hypothesis in that tibial slope had a significant and linear decreasing effect on PCLR graft force when loaded. Furthermore, the ALB and PMB grafts in the DB PCLR experienced significantly lower forces than the ALB graft of the SB PCLR loaded state. In both unloaded and loaded states, flexion angle was significantly associated with graft force with increased knee flexion (as anticipated).

Our study determined that a steeper posterior tibial slope decreased the force on PCLR grafts. Several studies have advocated for increased posterior tibial slope to protect PCL-deficient and PCL-reconstructed knees for patients with flat tibial slopes.[1,7,16] Although few clinical studies have investigated the effects of tibial slope and PCLR outcomes, decreased posterior tibial slope has been reported to be significantly correlated with increased posterior tibial translation and residual laxity after SB PCLR.[9] Therefore, in the case of addressing posterior knee instability, some authors suggested that soft tissue reconstruction may not be adequate to fully restore native knee biomechanics and that an osteotomy to increase tibial slope should be considered for PCL-deficient knees for patients with flatter tibial slopes.[9]

In comparison with prior biomechanical studies, our study evaluated the effect of posterior tibial slope and its effect on graft force for SB and DB PCLRs. Previous studies reported only on native PCL ligament strain or knee stability in PCL-deficient knees, or they examined the resting position of the tibia as a function of sagittal plane tibial slope. In a computer model, Shelburne et al[18] reported that a 1° increase in posterior tibial slope resulted in a 6-N decrease in native PCL force when subjected to physiologic loads during walking. Giffin et al[8] evaluated the effect of tibial slope on native ACL and PCL force when an axial load or simulated posterior drawer test was applied. The authors reported that tibial slope did not affect cruciate ligament forces when slope increased from 8.8° ± 1.8° to 13.2° ± 2.1°. However, they noted that increasing tibial slope caused an increase in anterior tibial translation, and they suggested that increasing tibial slope may reduce tibial sag in PCL-deficient knees. In a similar study, Martineau et al[14] reported that an anterior opening wedge osteotomy did not have an effect on the native PCL when subjected to compressive and anterior loading at 2 increased slope states.

Our study did note a significant decrease in the loaded graft force in the DB PCLR grafts as compared with the SB PCLR graft at all slopes and flexion angles. This corresponds with the findings of a previous systematic review that reported that a DB PCLR resulted in increased objective stability when compared with an SB PCLR,[3] and we theorize that our findings suggest a distribution of forces that may be protective to each graft of the DB PCLR. Biomechanical and clinical studies reported that performing a DB PCLR can significantly improve objective restoration of native knee kinematics and translate to positive patient outcomes at follow-up.[3] However, the effects of changes in sagittal plane tibial slope and its effects on SB and DB

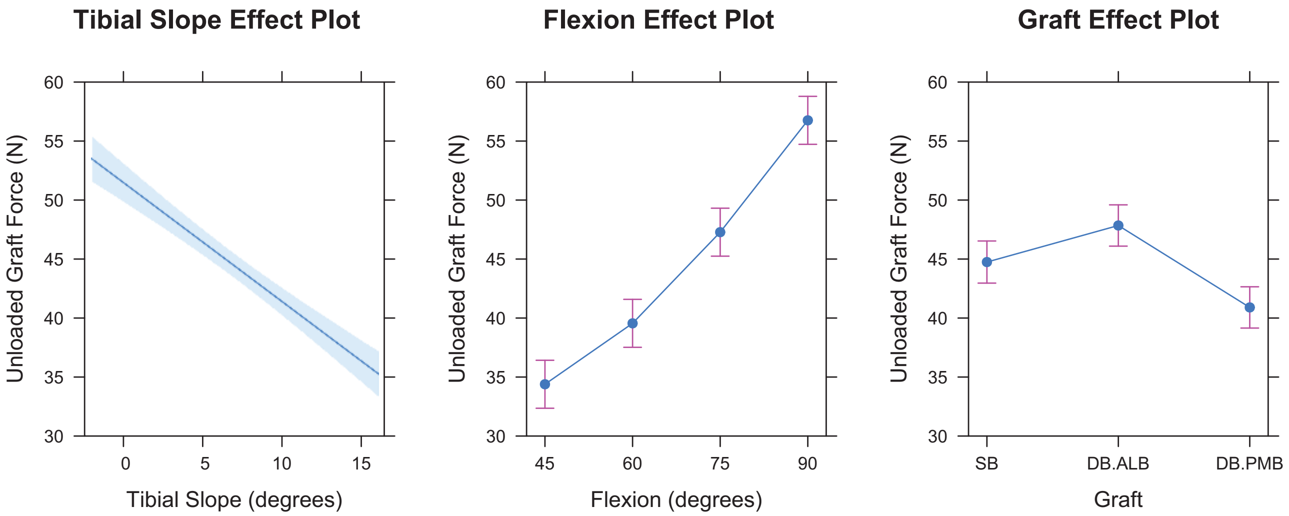

Figure 3. Modeled independent-effects plots for 3-factor linear mixed-effects models of posterior cruciate ligament graft force (N) in unloaded knees. Each panel demonstrates the effect of altering the variable on the horizontal axis while either holding the other 2 variables constant at their mean values (for continuous predictors) or presenting averaged effects across factor levels (for categorical variables). The shaded region and error bars represent the 95% confidence region for continuous predictors and 95% CIs for factor predictors, respectively. ALB, anterolateral bundle; DB, double bundle; PMB, posteromedial bundle; SB, single bundle.

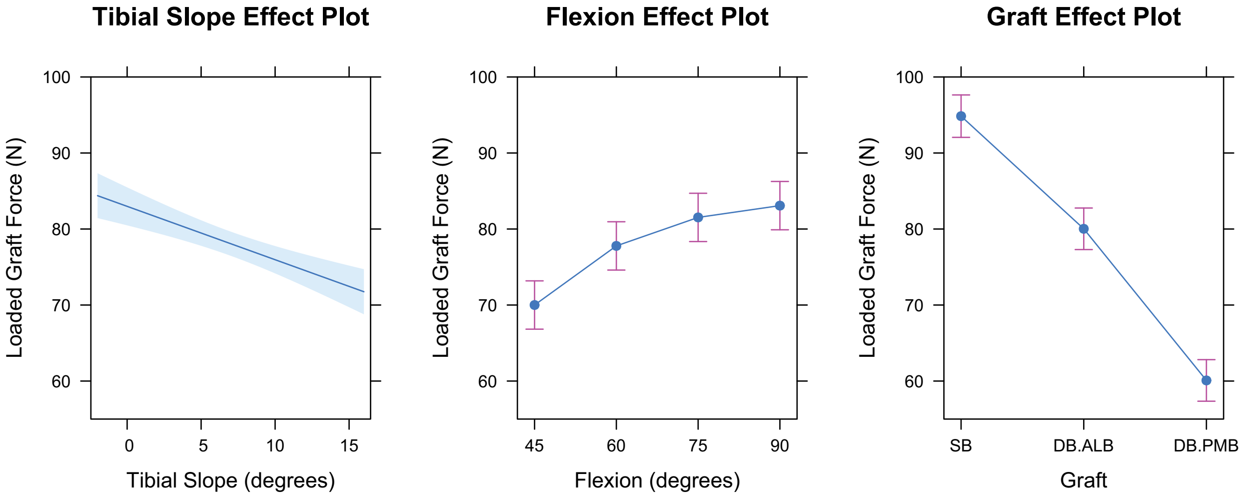

Figure 4. Modeled independent-effects plots for 3-factor linear mixed-effects models of posterior cruciate ligament graft force (N) in loaded knees. Each panel demonstrates the effect of altering the variable on the horizontal axis while either holding the other 2 variables constant at their mean values (for continuous predictors) or presenting averaged effects across factor levels (for categorical variables). The shaded region and error bars represent the 95% confidence region for continuous predictors and 95% CIs for factor predictors, respectively. ALB, anterolateral bundle; DB, double bundle; PMB, posteromedial bundle; SB, single bundle.

PCLR grafts have yet to be clarified. The results of our study indicate that performing a DB PCLR may reduce the effect of a decreased posterior slope. We theorize that patients with flattened native tibial slopes may benefit even more from a DB PCLR as compared with an SB PCLR because it would reduce the load on each PCLR graft, which potentially reduces the risk of residual posterior knee laxity and graft failure.

While a slope-increasing proximal tibial osteotomy may be protective of a PCLR and reduce graft force, there are potential risks inherent to surgical correction with an osteotomy procedure. These risks include overcorrection of tibial slope and risk of ACL injury, increase in contact mechanics of the knee joint, and change in overall knee kinematics with joint loading after an osteotomy. However, the current study was not designed to assess the clinical effects and/or potential complications of a proximal tibial osteotomy. Further research should be conducted to evaluate the potential changes in biomechanics involved with a slope-increasing proximal tibial osteotomy.

We acknowledge some limitations to this study. Innate to any cadaveric studies, biological healing effects cannot be replicated while testing at time zero. Multiple testing states may result in soft tissue laxity over time. However, we tried to limit the effects of soft tissue laxity by randomizing the testing order of knee flexion angles and degree of tibial slope. Furthermore, 300 N of compressive force is less than what is experienced in vivo; however, this was necessary to maintain the integrity of the osteotomy throughout all testing conditions. The PCLR grafts were also subjected to an axial load that produced a shearing force, so it could be possible that force values may differ when compressed with the tibia at different angles from the vertical. Additionally, the posterior aspect of the knee was dissected of all muscle tissue, including the posterior capsule and popliteus muscle belly, which may have affected knee rotation during testing. However, it was not possible to leave the entire muscle belly intact during biomechanical testing, and the popliteus musculotendinous junction was anchored to the posterior tibia to preserve rotational stability of the knee.

CONCLUSION

PCL graft forces increased as tibial slope decreased (flattened) in loaded and unloaded states. An increased posterior tibial slope was protective of PCLR grafts. The findings of our study support the effect of tibial slope on PCL grafts that has been noted clinically, and a flat tibial slope should be considered a factor when evaluating the cause of failed PCLRs.

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