Posterior Medial Meniscus Root Tears Potentiate the Effect of Increased Tibial Slope on Anterior Cruciate Ligament Graft Forces

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Background: Increased posterior tibial slope and posterior medial meniscus root tears increase the force experienced by the anterior cruciate ligament (ACL) and predispose patients to higher rates of primary ACL injury or ACL graft failure after an ACL reconstruction (ACLR). However, the interplay among sagittal plane tibial slope, medial meniscus root tears, and ACLR graft force remains inadequately defined.

Purpose/Hypothesis: The purpose was to quantify the effect of sagittal plane tibial slope on ACLR graft force at varying knee flexion angles with an intact medial meniscus, a posterior medial meniscus root tear, and a medial meniscus root repair. Our null hypothesis was that changes in slope and meniscal state would have no effect on the forces experienced by the ACLR graft.

Study Design: Controlled laboratory study.

Methods: Ten male fresh-frozen cadaveric human knees underwent a posteriorly based high tibial osteotomy. A spanning external fixator and wedges of varying sizes were used to stabilize the osteotomy and allow for accurate slope adjustment. After ACLR, specimens were compressed with a 1000-N axial load at flexion angles of 0° and 30° for each of the 3 meniscal states and at tibial slopes of 0° to 15° at 3° increments. Graft loads were recorded through a force transducer clamped to the graft.

Results: Increasing tibial slope led to a linear increase in ACLR graft force at 0° and 30° of knee flexion. Posterior medial meniscus root tear led to significant increases in ACLR graft forces over the intact state, while root repair restored the function of the medial meniscus as a secondary stabilizer. At 30° of knee flexion, the tibial slope effect on ACLR graft force was potentiated in the root tear state as compared with the intact and root repair states—test of interaction effect: $t(139) = 2.67$ ($P = .009$).

Conclusion: Increases in tibial slope lead to a linear increase in ACLR graft forces, and this effect is magnified in the setting of a posterior medial meniscus root tear. At slopes >12°, a slope-changing osteotomy could be considered in the setting of a revision ACLR with a concomitant medial meniscus root tear.

Clinical Relevance: Defining the relationship between tibial slope and varying states of meniscal insufficiency can help determine when it may be necessary to perform a slope-decreasing proximal tibial osteotomy before ACLR and meniscal repair.

Keywords: tibial slope; anterior cruciate ligament reconstruction; anterior tibial translation; meniscus root tear; root repair; ACL graft forces

Recent studies have demonstrated that increased sagittal plane posterior tibial slope (PTS)[‖] and medial meniscal insufficiency[31,34-37,42] increase anterior tibial translation (ATT) and, consequently, the forces experienced by the cruciate ligaments of the knee. As a result, greater PTS increases the likelihood of primary noncontact anterior cruciate ligament (ACL) injury[24,25,40,47] and the risk of graft rupture after ACL reconstruction (ACLR).[12,15,20,30,39,45] Likewise, posterior medial meniscus root (PMMR) tears have been shown to have deleterious effects on knee stability and kinematics in addition to the well-established changes in contact pressures within the knee.[3,21,32]

Bernhardson et al[7] recently described a linear relationship between PTS and the forces seen by ACLR grafts and suggested slope-decreasing proximal tibial osteotomy as an option to protect ACL grafts in the revision setting. Native

‖References 1, 2, 6, 7, 9, 12, 14, 16, 18, 22, 24, 25, 30, 33, 39, 40, 44-47.

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PTS has been described as a range from 0° to 18°, with an approximate mean of 8°.[17,18] While a few clinical studies[15,41] have demonstrated success with slope-changing osteotomy for slopes >12°, there is no consensus on which patients warrant this surgical treatment or what the goal for a corrected slope should be. Previous biomechanical studies have demonstrated the importance of the medial meniscus as a secondary stabilizer,[4,35,37,42] while other studies have highlighted the interdependence between the ACLR graft and the medial meniscus.[37,43]

The purpose of this study was to quantify the effect of PMMR tears on ACLR graft force at varying tibial slopes and knee flexion angles. Our null hypothesis was that changes in meniscal state and tibial slope would have no effect on the forces experienced by the ACLR graft.

METHODS

Specimen Preparation

Ten male fresh-frozen cadaveric human knees were used (6 nonpaired and 4 paired; mean age, 44 years; range, 26-64 years). Specimens were excluded if there was evidence of meniscal, cartilage, or ligamentous damage or osteoarthritis after diagnostic arthroscopy. The cadaveric specimens 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.

All knee specimens were dissected free of all skin and subcutaneous tissue, and all posterior musculature was removed down to the popliteus muscle belly, which was then reflected sharply off the posterior cortex of the tibia to provide exposure to the site of the posterior osteotomy. The popliteus tendon was anchored at the musculotendinous junction to the tibia to maintain rotational stability during testing. The ACL was then sharply resected off its femoral and tibial insertion sites, with all other ligamentous structures of the knee left intact. The femur, tibia, and fibula were cut 14 cm proximal and distal to the joint line. The distal tibia and fibula were fixated in anatomic position and potted in poly(methyl methacrylate) (Fricke Dental International).

Surgical Technique

The ACL was reconstructed by an anatomic single-bundle technique as previously described.[19] Similar to a prior study,[7] a posterior osteotomy was made 2.5 cm distal to the joint line with a sagittal saw under fluoroscopic guidance. The osteotomy was performed parallel to the joint line until approximately 5 to 6 mm from the anterior tibial cortex to maintain an anterior bone hinge. A wedge of 1.5 cm was then resected to allow adequate space for the tibial slope to be increased or decreased to the desired magnitude.

For the PMMR repair state, the root was repaired with an anatomic 2-tunnel transtibial pullout.[28] Tunnels were drilled anteriorly through the superior portion of the wedge to avoid altering the tension applied to sutures throughout various slopes in testing (Figure 1). The root was repaired by first passing 2 suture tapes (UltraTape; Smith & Nephew) with a suture passer (FirstPass Mini; Smith & Nephew). The sutures were then pulled through their respective tunnels and tied over a button on the anteromedial tibial cortex.[11]

A medial and lateral external fixation device (Medium External Fixator; Synthes USA) was secured to the knee to enable fixation throughout various degrees of tibial slope. Before testing, tibial slope was directly measured at 3°, 6°, 9°, 12°, and 15°, and these positions were marked on the external fixator device. PTS was measured on true lateral standard radiographs with a previously validated technique[7] and defined as the angle between the medial tibial plateau and a line parallel to the middiaphysis of the tibia. The resultant tibial slope was calculated by subtracting this measured angle from 90°.

Graft Preparation Protocol

Two semitendinosus tendons and 2 gracilis tendons were whipstitched at each end and together used as the ACL graft for each specimen. These tendons provided sufficient length to allow the ACL graft to extend from its femoral fixation through the tibial tunnel to the clamp of a calibrated external force transducer (Sensortronics; Vishay Precision Group). Grafts were preconditioned with a constant force of 89 N for 10 minutes, ensuring proper conditioning and minimizing creep during testing.[13] After preconditioning, the ACL graft was fixed in the femoral tunnel with an 8 × 20–mm interference screw (Smith & Nephew).

Mechanical Testing Protocol

The potted tibia was rigidly secured in a custom pivoting base that was allowed to freely translate in the transverse plane on the base of the dynamic testing machine (ElectroPuls E10000; Instron). The tibial orientation was adjusted as needed to ensure that the middiaphysis of the tibia was perpendicular to the testing table. The femur was secured to a custom fixture attached to the actuator of the dynamic

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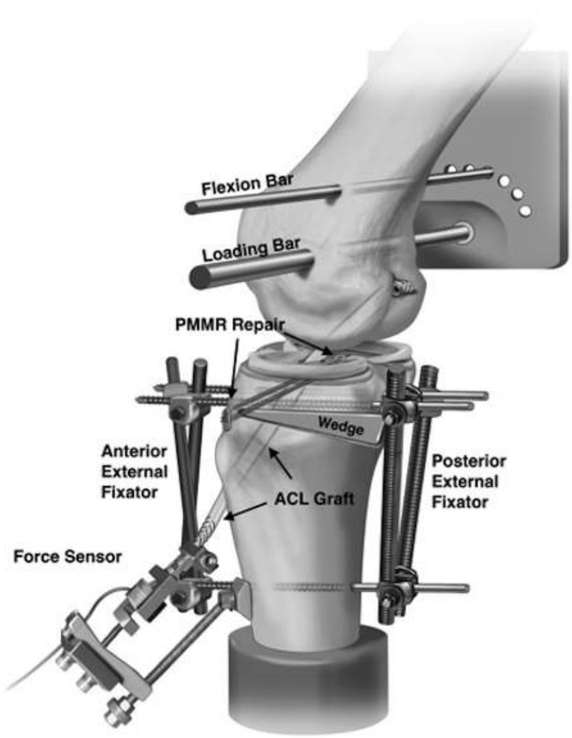

Figure 1. Schematic representation of the mechanical testing setup for a right knee. ACL, anterior cruciate ligament; PMMR, posterior medial meniscus root.

tensile machine with a 10-mm transepicondylar rod, which acted as the load-bearing axis during testing. Another 7-mm rod was passed proximally to serve as an adjustable fixation point for knee flexion angle (Figure 1).

Before testing, the grafts were further preconditioned by 6 cycles of knee joint compression to 1000 N at 30° of knee flexion and 15° of tibial slope. This preconditioning phase was added to further reduce graft creep, as repeatability pilot testing showed changes during the first 6 compressions with repeatable measurements thereafter. Furthermore, based on multiple osteotomy failures during pilot testing at 1000 N, 2 additional external fixator bars were attached anteriorly to the same fixator pins of the posterior external fixator device, and various sizes of press-fit wedges were created to insert into the osteotomy space to strengthen the osteotomy site; wedges were created with an open middle section to avoid interference with the ACL graft.

All specimens were loaded by compressing the knee joint with a 1000-N axial load at 0° and 30° of knee flexion. These angles were chosen per a previous study[7] that reported that knees in full extension experienced significantly higher graft forces when loaded as compared with knees in flexion, and the ACL has been reported to resist ATT primarily at 30° of flexion. Testing was performed at 3°, 6°, 9°, 12°, and 15° of PTS. The order of slope and flexion angle was randomized for all tests. At each change of slope, the ACL graft was retensioned to 88 N at full extension. Graft loads were recorded at 20 N (unloaded force) and 1000 N (loaded force) of axial compression in the testing machine for 20 seconds.

TABLE 1
Anterior Cruciate Ligament Loaded Graft Force by PTS, Knee Flexion Angle, and PMMR State[a]

	PMMR, N (Mean ± SD)		
Flexion: PTS	Intact	Tear	Repair
0°			
3°	69 ± 28.2	89.8 ± 40.1	79.6 ± 41.2
6°	88.4 ± 38.9	107.7 ± 63.6	90.9 ± 48.8
9°	103.5 ± 41.5	127.3 ± 52.7	100.4 ± 46.7
12°	110.2 ± 40	122.8 ± 48.4	128 ± 47.1
15°	121.9 ± 29.8	144.3 ± 52.4	123.7 ± 52.9
30°			
3°	29.2 ± 36.6	42.9 ± 50.5	59.1 ± 97.5
6°	72.9 ± 70.7	123.3 ± 107.8	104.9 ± 116.4
9°	100.3 ± 78	179.2 ± 95.8	96.9 ± 77.2
12°	111.5 ± 83.8	204.6 ± 76.2	140.9 ± 101.2
15°	151.4 ± 80.9	232 ± 83.7	185.9 ± 79.4

[a]PMMR, posterior medial meniscus root; PTS, posterior tibial slope.

All specimens were first tested in the ACLR state with intact menisci. The PMMR was then cut sharply 3 mm from the root attachment, and after randomization, the sequence of testing was varied: the root was either detached (cut state) or repaired (root repair state). Randomized sequences beginning with the repair state were preceded by removal of the meniscal repair sutures, yielding a torn meniscus root for the final testing state. To prevent soft tissue desiccation during preparation and testing, specimens were sprayed with normal saline.

Statistical Methodology

To address the hypotheses of this study, PTS and meniscus root state were assessed for their independent and/or joint effect on ACL graft force with linear mixed effects modeling.[5,26] 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. It was hypothesized a priori that the effect of tibial slope may depend on meniscus root condition, so interaction terms were assessed for inclusion in each model. Cubic polynomial relationships for tibial slope were considered in comparison with a linear relationship, and the Akaike information criterion was used to choose final model specification.[8] Residual diagnostics were performed to confirm model assumptions and model fit. The statistical computing software R was used for all analyses (v 3.5.2, lme4 and lmerTest packages; R Foundation for Statistical Computing).[38]

RESULTS

Loaded graft force represents the maximum force experienced by the graft under 1000-N compressive joint load. Table 1 presents means and standard deviations by PTS, knee flexion angle, and PMMR state.

Knee Flexion: 0°

Two-factor mixed effects modeling was utilized to assess the contributions of each experimental factor. The Akaike information criterion identified the linear main effects model as the best model at 0° of knee flexion. This indicates that in full extension, PMMR state and PTS were independently statistically significant contributors to loaded graft force (Figure 2). Thus, we interpret that the differences in maximum ACLR graft force among the PMMR intact, tear, and repair states did not meaningfully depend on the PTS with a nonsignificant interaction between the factors (F = 0.002; P = .998).

Higher PTS was associated with increased loaded graft force (beta = 4.17 N/deg; 95% CI, 3.28-5.07; $P < .001$). PMMR tear exhibited higher loaded graft force than the PMMR intact state (beta = 21.1 N; 95% CI, 9.8-32.4; $P < .001$). The PMMR repair state exhibited significantly lower loaded graft force than the PMMR tear state (beta = −13.8 N; 95% CI, −25.1 to −2.6; P = .011). PMMR intact and PMMR repair were not statistically different (beta = 7.3 N; 95% CI, −4.1 to 18.6; P = .288).

Flexion: 30°

Interestingly, at 30° of knee flexion, the PMMR state was found to significantly affect the influence of PTS on axially loaded graft force—interaction effect in linear mixed effects model: $F(2, 139)$ = 4.38 (P = .014); thus, the linear full interaction model was reported (Table 2). Specifically, the interaction between PTS and PMMR state indicated a significantly larger effect of PTS on loaded graft force for knees with a PMMR tear (beta = additional 6.3 N/deg of slope; 95% CI, 1.6-10.9; P = .009) (Figure 3).

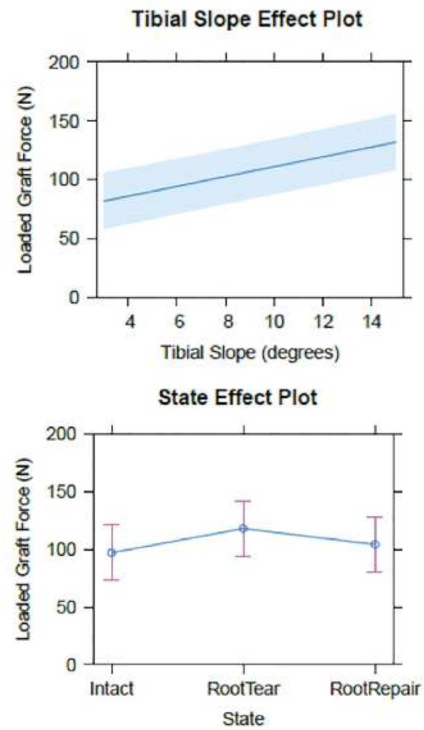

Figure 2. Independent effects of posterior tibial slope and posterior medial meniscus root state on loaded anterior cruciate ligament reconstruction graft force (N) at 0° of flexion. Effect estimates derived from a linear mixed effects model. In the top graph, the line represents estimated linear regression relationship, while the shaded area represents 95% confidence region. In the bottom plot, circles represent group effect estimates and error bars represent 95% confidence intervals.

DISCUSSION

The most important finding of the current study is the significant interaction between PTS and PMMR tear, where a PMMR tear was observed to potentiate the effect that increased PTS has on ACLR graft forces at 30° of knee flexion. A PMMR tear also led to a significant increase in ACLR graft force when compared with the intact state, whereas the meniscal repair state was not significantly different from the intact state.[3,21,32] Because the goal of the current study was to examine the interactions among PTS, PMMR status, and ACLR graft forces, our null hypothesis was disproven because increased PTS and changes in the PMMR state led to significant changes in the forces experienced by the ACLR graft. Our findings were also consistent with previous studies in which increasing PTS, as an independent variable, led to a linear increase in ACLR graft forces.[1,7,16,18,46]

While the effects of increased tibial slope or PMMR tear in isolation on ATT and ACL forces have been well-described, this is the first study to identify a significant

TABLE 2
Linear Mixed Effects Model With Slope × State Interaction Term for Loaded Anterior Cruciate Ligament Graft Force Tested at 30° of Knee Flexion[a]

	Beta	SE	*df*	*t*	*P* Value
(Intercept)	10.39	26.28	24.5	0.395	.696
Slope	9.06	1.68	139.0	5.402	<.001
State: root tear	8.16	23.18	139.0	0.352	.725
State: root repair	20.23	23.18	139.0	0.873	.384
Slope × state: root tear	6.25	2.35	139.0	2.665	.009
Slope × state: root repair	0.59	2.35	139.0	0.253	.801

[a]Tibial slope had a significantly larger effect on graft force when combined with a meniscus root tear, as compared with the intact and root repair states (P = .009).

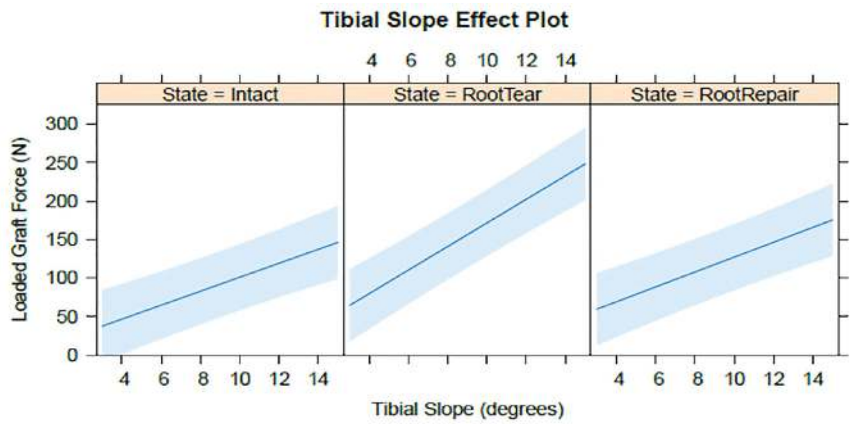

Figure 3. Unique effect of tibial slope on loaded anterior cruciate ligament graft force (N), for each meniscal state, tested at 30° of knee flexion. Effect estimates derived from a linear mixed effects model with a state × slope interaction term. Lines represent estimated linear regression relationships, while shaded areas represent 95% confidence regions.

interaction between these variables. Our findings indicate that a functional medial meniscus is biomechanically essential in patients with increased PTS. This finding corroborates and adds to the findings of previous studies[4,35,37,42] that highlighted the importance of the medial meniscus as a secondary stabilizer of the knee. Nearly 2 decades ago, Allen et al[4] documented increased ATT with medial meniscectomy in the ACL-deficient knee of between 2.2 and 5.8 mm depending on the knee flexion angle. In 2008, Allaire et al[3] reported that a PMMR tear is equivalent to a medial meniscectomy. It is likely this increased ATT that explains the majority of the increased graft forces seen in the current study, although internal rotation of the tibia during axial loading may also increase graft force. Prior studies have established differences in slopes between the lateral and medial aspects of the tibia,[23] which may lead to an increased tendency toward tibial internal rotation. Although tibial rotation was observed upon axial loading during testing, this study did not quantify and evaluate the degree of rotation and its effect on ACL graft force. Our model found that root tears amplify the deleterious effect that increased PTS has on ACLR graft forces, but it is likely that this finding applies to some extent to other medial meniscal pathology, such as ramp tears or a subtotal meniscectomy.

The observed interaction in this biomechanical study becomes clinically relevant in the setting of revision or re-revision ACL surgery because a subset of these patients will have the combination of increased PTS and medial meniscal pathology. Recent clinical studies demonstrated higher clinical failure rates after ACLR in patients with slopes >8.4° and 12°.[12,39] Increased rates of graft failure in these studies were as high as 11 times the control group.[39] Based on these clinical findings, the linear increase in ACLR graft force seen with increasing PTS,[7] the biomechanical consequences of a PMMR tear,[3,10,13,27-29] and the additive effect of concomitant increased PTS and PMMR tear seen in the current study, surgeons could consider a slope-reducing proximal tibial osteotomy before or concurrent with revision ACLR while addressing medial meniscal pathology in patients with PTS >12°.

We acknowledge some limitations inherent to the biomechanical design of the current study. First, it was a cadaveric study, and so the tests were all performed at time zero without replication of biological healing effects. Second, laxity or changes in the material properties of the soft tissues or grafts can occur with cyclic loading, and graft force measurement can additionally be influenced by frictional losses associated with changes in tibial slope. However, we tried to limit time variability by randomizing the order of testing. Last, a 1000-N axial load is less that that experienced with high-level activities in vivo.

CONCLUSION

Increases in tibial slope lead to a linear increase in ACLR graft forces, and this effect is magnified in the setting of a PMMR tear. At slopes >12°, a slope-changing osteotomy could be considered in the setting of a revision ACLR with a concomitant medial meniscus root tear.

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