Two Different Knee Rotational Instabilities Occur With Anterior Cruciate Ligament and Anterolateral Ligament Injuries: A Robotic Study on Anterior Cruciate Ligament and Extra-articular Reconstructions in Restoring Rotational Stability

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Purpose: To determine the effect of 2 extra-articular reconstructions on pivot-shift rotational stability and tibial internal rotation as a basis for clinical recommendations. **Methods:** A robotic simulator tested 15 cadaver knees. Group 1 (anterior cruciate ligament [ACL] cut) underwent ACL bone-patellar tendon-bone reconstruction followed by sectioning the anterolateral structures and an extra-articular, manual-tension iliotibial band (ITB) tenodesis. Group 2 (ACL intact) tested the rotational stabilizing effect of a low-tension ITB tenodesis before and after sectioning the anterolateral ligament/ITB structures. Lateral and medial tibiofemoral compartment translations and internal-external tibial rotations were measured under Lachman, 5N·m tibial rotation, and 2 pivot-shift simulations using 4-degree-of-freedom loading. Statistical equivalence was defined within 2 mm tibiofemoral compartment translation and 2° tibial rotation at $P < .05$. **Results:** The bone-patellar tendon-bone ACL reconstruction (group 1) restored pivot-shift lateral compartment translation within 0.7 mm (95% confidence interval [CI], -0.6 to 1.9; $P = .70$) of normal. The internal rotation limit was not affected by ACL sectioning or reconstruction. After anterolateral ligament/ITB sectioning there was no change in pivot-shift lateral compartment translation, however internal rotation increased 2.9° (95% CI, 0.6-5.2; $P = .99$) at 90° flexion. The manual-tension ITB tenodesis (fixated 13-22 N tension) decreased pivot-shift lateral compartment translation 4.8 mm (95% CI, 1.4-8.1; $P = .99$) and internal rotation by 21.9° (95% CI, 13.2-30.6; $P = .99$) at 90° flexion. The ACL forces decreased 45.8% in the pivot-shift test. In group 2 knees, with the ACL intact, the anterolateral ligament/ITB sectioning had no effect on pivot-shift translations; however, the internal rotation limit increased by 4.3° (95% CI, 1.9-6.8; $P = .99$) at 60° flexion. The low-tension ITB tenodesis (fixated 8.9 N tension) had no effect on pivot-shift translations and corrected internal tibial rotation with a mild overconstraint of 4.2° (95% CI, 1.9-6.8; $P = .99$) at 60° flexion. **Conclusions:** A low-tension ITB tenodesis, fixated at neutral tibial rotation to avoid constraining internal tibial rotation, has no effect in limiting abnormal pivot-shift subluxations. **Clinical Relevance:** A low-tension ITB tenodesis has limited clinical utilization as the pivot-shift subluxations are not affected, assuming appropriate tensioning to not overconstrain internal tibial rotation.

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Although some authors recommend an anterolateral ligament (ALL) reconstruction concurrent with anterior cruciate ligament (ACL) reconstruction, there is increasing evidence that the ALL is a secondary ligament restraint with an inability to resist anterior compartment subluxations in the pivot-shift

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The authors report the following potential conflicts of interest or sources of funding: L.H. received money from Arthrex to the institution to explore the kinematic function of the ALL. F.N. received a grant to the institution to explore the ALL, ITB, and their reconstruction. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Received January 18, 2018; accepted April 25, 2018.

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0749-8063/1872/$36.00

https://doi.org/10.1016/j.arthro.2018.04.023

phenomena.[1-3] Accordingly, the routine use of an ALL reconstruction has been questioned.[2,4] Instead, an ALL reconstruction or iliotibial band (ITB) tenodesis has been suggested for select revision or grossly unstable knees[5-9] or when a less robust ACL graft requires a backup procedure.[10]

Recent publications report the benefit of an ITB tenodesis, not as an anatomic substitute for the native anterolateral structures but as a femoral-tibial soft tissue restraint to resist pivot-shift anterior subluxations and abnormal increases in internal tibial rotation (Table 1). The recommendation for an ITB tenodesis applies particularly to knees with combined ACL and anterolateral injuries (ALL, ITB) with grossly positive grade 3 pivot-shift subluxations and abnormal increases in internal rotation.

Two rotational instabilities occur after ACL rupture with concurrent injury to the anterolateral structures that generate confusion in terms of the recommendation of surgical procedures to provide knee stability. The definition of instability refers to abnormal increases in joint motion limit or displacement, and not to the clinical symptom of patients' giving-way episodes.[20] The ACL provides varying contributions in resisting the 6 degrees of knee motion (3 rotations, 3 translations), either as a primary or secondary restraint.[1,21,22] The primary rotational ACL instability after ACL rupture is the pivot-shift anterior subluxation of the lateral and medial tibiofemoral compartments.[21] With an ACL injury and associated injury to the anterolateral structures, a grade 3 pivot-shift subluxation occurs, in contrast with a grade 2 pivot-shift, where the anterolateral structures still provide some resistance.[23-26] The second rotational instability with ACL and ALL/ITB injury represents an increase in internal tibial rotation, particularly at high flexion angles. Publications often do not discriminate between these 2 rotational instabilities in making recommendations for surgical procedures. Some authors recommend an extra-articular reconstruction for routine use in primary ACL reconstruction, particularly in athletes returning to cutting and pivoting activities.[11,15-17,19,27] Other authors reserve extra-articular procedures for select revision knees without stipulating which type of instability is being addressed.[6,8,9]

Some in vitro laboratory studies report that an ACL reconstruction does not restore normal knee kinematics with concurrent ALL/ITB sectioning.[14,28] In contrast, other in vitro studies have reported that a well-placed, well-tensioned ACL reconstruction restores pivot-shift compartment subluxations to normal even with concurrent injury to the ALL/ITB,[12,18] although there remains a slight increase in internal tibial rotation that is not believed to be clinically important.[2]

There is limited research on the effect of an ITB tenodesis on resisting pivot-shift subluxations using more modern robotic testing methodologies. This study uses a 4-degree-of-freedom simulated in vitro pivot-shift test with combined anterior translation, internal tibial rotation, and valgus loading during knee flexion-extension that produces major anterior subluxation of both the lateral and medial tibiofemoral compartments, correlating with the clinical pivot-shift examination.[21,29] These loading conditions were used in this study to determine the effect of an extra-articular procedure in limiting the pivot-shift subluxations of the lateral and medial tibiofemoral compartments. This process differs from other studies that simulate the pivot-shift test with internal rotation-valgus loading, which reduces the medial tibiofemoral compartment owing to an absence of anterior tibial loading.[21,29-31]

The purpose of this study was to determine the effect of 2 extra-articular reconstructions on pivot-shift rotational stability and tibial internal rotation as a basis for clinical recommendations. The first hypothesis of this study is that an ACL reconstruction restores abnormal tibiofemoral compartment translations in the pivot-shift to normal and an ITB tenodesis procedure is not required even with injury to the anterolateral structures. The second hypothesis is that a low-tension ITB tenodesis corrects the modest increase in internal tibial rotation with ACL and anterolateral injuries however will not decrease pivot-shift anterior subluxations.

Methods

Fifteen fresh frozen male cadaver knee specimens (RestoreLife USA, Elizabethton, Tennessee) were divided into 2 groups (Fig 1). The 7 group 1 specimens had a mean donor age of 57 ± 18 years (range 24-79 years) and the 8 group 2 specimens had a mean donor age of 51 ± 6 years (range 42-62 years). The decision was made to test group 2 specimens without cutting the ACL and performing a graft reconstruction to offset any variables introduced by an ACL reconstruction, and to entirely focus on the effects of an ITB tenodesis with injury to the ALL/ITB under the most ideal conditions. All specimens were assessed by the principal physicians (J.W., D.J.) to be free of disease, arthritis, and other abnormalities. Preparation and potting of specimens were performed as previously described.[2,21,22,24,32,33] After knee specimen potting, the anatomic tibial center relative to the robot's tibial rotation axis was located using a 3-dimensional coordinate digitizer (Microscribe G2, Revware, Raleigh, North Carolina) to determine and correct for misalignments between specimens and the robot rotation axis that could occur during potting. Medial and lateral compartment translation points were determined at 25% and 75% of the tibial width.[21,29]

A previously described 6-degree-of-freedom custom robot was used to apply joint motions and loads during testing.[21,22,33,34] Specimens were conditioned before

Table 1. Representative Clinical and Laboratory Studies From the Past 10 Years Involving ACL Reconstruction and Concurrent Lateral EA Reconstruction

Author	Type	Procedure	Graft (ACL/EA)	Flexion Angle of Fixation	Tension	Position (Femur)	Position (Tibia)	Result
Bignozzi et al., 2009[11]	Clinical	EA	STG/STG (both doubled)	?	?	ACL femoral over-the-top position	Gerdy's tubercle	Reduced lateral compartment translation only 1.6 mm and 1.0 mm at 30° and 90° flexion during AP test compared with single-bundle ACL reconstruction alone
Branch et al., 2015[5]	Clinical	EA	BTB/gracilis	30°, neutral rotation	?	Same as femoral ACL tunnel	Two free limbs secured on either side of Gerdy's tubercle	Compared with the contralateral healthy knee, the addition of the EAR limits IR by 11.4°
Butler et al., 2013[12]	Laboratory	Losee procedure	Rope/ITB (anterior 15 mm)	?	Maximum	Determined by isometric testing	—	Overconstraint of maximum 5.5° IR with ITB tenodesis at 90° flexion
Colombet, 2011[6]	Clinical	EA	STG (4-strand)/ STG (2-strand)	90°, neutral rotation	Manual	Same as femoral ACL tunnel	On Gerdy's tubercle	Decreased maximum IR by 7.5° compared with ACL reconstruction alone
Ibrahim et al., 2017[4]	Clinical	ALL reconstruction	Semitendinosus (doubled)/ gracilis (doubled)	30°, neutral rotation	Tensioned	Just proximal and anterior to the lateral collateral ligament origin	Midway between Gerdy's tubercle and the fibular head	At an average 27 months follow-up, no statistically significant difference in clinical assessments compared with ACL reconstruction alone
Imbert et al., 2015[13]	Clinical	ALL reconstruction	Semitendinosus (4-strand)/ gracilis (doubled)	90°, neutral rotation	?	1 cm proximal and posterior to the lateral epicondyle	At the posterior aspect of Gerdy's tubercle	Compared with the contralateral healthy knee, the addition of the ALL reconstruction overconstrained IR by 13° in high flexion
Inderhaug et al., 2017[14]	Laboratory	(1) ALL reconstruction (2) MacIntosh tenodesis (3) Lemaire tenodesis	(1) BTB/gracilis (2) BTB/ITB (central 15 mm) (3) BTB/ITB (central 15 mm)	20° (probable), neutral rotation	20 N (4.5 lbs) and 40 N (9.0 lbs)	(1) Proximal and posterior to lateral epicondyle (2) Insertion of lateral intermuscular septum (3) Proximal and posterior to lateral epicondyle	(1) Halfway between Gerdy's tubercle and fibular head (2) – (3) –	(1) Residual laxity in internal rotation after ALL injury and subsequent ALL reconstruction (2) Restored native internal rotation even after ALL injury (3) Restored native internal rotation after ALL injury when passed deep to LCL, overconstrained when passed superficial
Marcacci et al., 2009[15]	Clinical	EA	STG/STG (both doubled)	90°, external rotation and posterior drawer	?	ACL femoral over-the-top position	Gerdy's tubercle	The lateral EA procedure maintains stability with a 94% negative pivot-shift rate at 11 years follow-up
Monaco et al., 2007[16]	Clinical	Coker-Arnold	STG (doubled)/ ITB	90-100°, maximum external rotation	Under tension	—	Sutured to Gerdy's tubercle	Decreased internal rotation under manual maximum torque by 5.4°at 30° knee flexion

(continued)

Table 1. Continued

Author	Type	Procedure	Graft (ACL/EA)	Flexion Angle of Fixation	Tension	Position (Femur)	Position (Tibia)	Result
Nitri et al., 2016[17]	Laboratory	ALL reconstruction	BTB/semitendinosus	75°, unknown tibial position	88 N (19.8 lbs)	4.7 mm proximal and posterior to femoral attachment of the LCL	Midway between Gerdy's tubercle and the fibular head	The ALL reconstruction overconstrained IR by 2° at high flexion angles
Noyes et al., 2017[2]	Laboratory	ALL reconstruction	BTB/gracilis	60°, neutral rotation	8.9 N (2 lbs)	8 mm proximal and posterior to the lateral epicondyle	Midway between Gerdy's tubercle and the fibular head	The ALL reconstruction corrected the increase in internal rotation after ALL/ITB sectioning, but had no effect on pivot-shift subluxations
Schon et al., 2016[18]	Laboratory	ALL reconstruction	BTB/semitendinosus	0°, 15°, 30°, 45°, 60°, 75°, 90°; unknown tibial position	88 N (19.8 lbs)	4.7 mm proximal and posterior to femoral attachment of the LCL	Midway between Gerdy's tubercle and the fibular head	Overconstrained IR by no more than 5° at any fixation and testing angle
Sonnery-Cottet et al., 2015[19]	Clinical	ALL reconstruction	Semitendinosus (tripled)/gracilis	Extension, neutral rotation	?	Same as femoral ACL tunnel, determined by isometric testing	Above the superolateral corner of Gerdy's tubercle	91.6% negative pivot-shift at 2-year follow-up with the proposed procedure

ACL, anterior cruciate ligament; ALL, anterolateral ligament; BTB, bone-patellar tendon-bone; EA, extra-articular; EAR, extra-articular reconstruction; IR, internal rotation; ITB, iliotibial band; LCL, lateral collateral ligament; STG, soft tissue graft.

testing under a constant 135 N anterior load applied at 25° knee flexion for 10 minutes. The protocol for determining the zero-load reference path, which served as the starting position for each test as a function of flexion angle, and the motion limits under ±100 N anterior/posterior and ±5 N·m internal/external rotation has been previously described.[21,22,32]

Each group was tested under the same loading profile listed in Fig 1. The 2 pivot-shift tests vary only by the internal rotation torque applied (pivot-shift 1, 5N·m; pivot-shift 2, 1 N·m). These simulated clinical pivot-shift tests were based on actual clinical measurement of surgeons performing the pivot-shift test on an instrumented limb described elsewhere in detail.[29] Translation and rotation values for the pivot-shift tests were calculated at 25° flexion.

Surgical Technique

ACL reconstructions were performed as previously described[2,32] with a 10-mm bone-patellar tendon-bone (BPTB) graft placed in the central femoral and tibial native attachments. The graft was instrumented to determine ACL graft forces, as previously described.[32]

The ALL was sectioned based on its described anatomic location.[35-38] A limited anterolateral incision was made that included capsular tissues anterior to the popliteal tendon extending anterior to the anterior extent of Gerdy's tubercle. The capsulo-osseous portion of the ITB was sectioned by transecting all fibers that inserted onto the lateral tibial tubercle,[39,40] with care taken to preserve the ITB tibial attachment.

The manual-tension ITB tenodesis procedure was performed using a common surgical technique described in detail elsewhere.[41] The posterior or central one-third of the ITB (12 mm × 120 mm) was divided sharply, leaving the tibial attachment intact. The proximal attachment point on the femur was determined to be isometric with knee flexion (avoiding an anterior graft placement that would tighten excessively with flexion) using a guide-pin placed posterior and proximal to the lateral epicondyle and anterior to the gastrocnemius tubercle.[42] A 4.5-mm soft tissue screw and washer (Linvatec Corp, Largo, Florida) was placed at this point and the ITB strip was circled around the screw and secured by tightening the screw and washer combination. The ITB strip was folded back toward the tibial attachment and sutured to itself to provide supplementary fixation. The graft was fixated under modest manual tension (approximately 3-5 lbs tension, 13.3-22.2 N) at 10° knee flexion and neutral tibial rotation.

The low-tension ITB tenodesis is a modification of the above procedure that is less invasive, performed with a 3- to 4-cm incision and tensioned under minimal loads to have the least effect on restricting internal tibial rotation. The posterior one-third of the ITB (8 mm × 80 mm) was dissected leaving the distal tibial insertion

Testing Conditions		Loading Profile
GROUP 1	GROUP 2	1. Lachman test (100N anterior at 25° flexion)
Intact ↓ ACL sectioned ↓ ACL reconstructed ↓ ALL/ITB sectioned ↓ Manual-Tension ITB Tenodesis	Intact ↓ ALL/ITB sectioned ↓ Low-Tension ITB Tenodesis	2. Tibial rotation test (5N-m internal torque at 25°, 60°, 90°) 3. Pivot-Shift 1 test (100N ant, 5N-m IR, 7N-m val) 4. Pivot-Shift 2 test (100N ant, 1N-m IR, 7N-m val)

Fig 1. Testing conditions for groups 1 and 2 specimens, and the loading profile performed at every test condition. ACL, anterior cruciate ligament; ITB, iliotibial band; ALL, anterolateral ligament.

intact and was fixated into a femoral tunnel positioned at the approximate ALL femoral insertion at 8 mm proximal and 8 mm posterior to the lateral epicondyle (determined at full extension). This procedure is consistent with the isometric region defined by Kernkamp et al.[43] (Fig 2). A guide-pin was drilled at this location and the change in graft length was determined to be isometric with knee flexion-extension. An 8-mm tunnel was drilled (25-30 mm deep) and the sutured graft end was passed to the medial side. The knee was flexed to 30° at neutral rotation, and the graft secured with an 8-mm SwiveLock (Arthrex, Naples, Florida) while tensioned under a low load (2 lbs [8.9 N] measured with a digital scale). The interference screw was selected to provide secure fixation in the cadaveric knees. It should be noted that in the authors' clinical practice for younger patients the internal fixation is by a TightRope fixation (Arthrex).

The 2 ITB extra-articular procedures were chosen to simulate recommended surgical procedures. In the first technique, the procedure requires a long strip of ITB doubled on itself with screw fixation under a manual tensioning load at neutral tibial rotation. The second ITB procedure represents a modification of an ALL

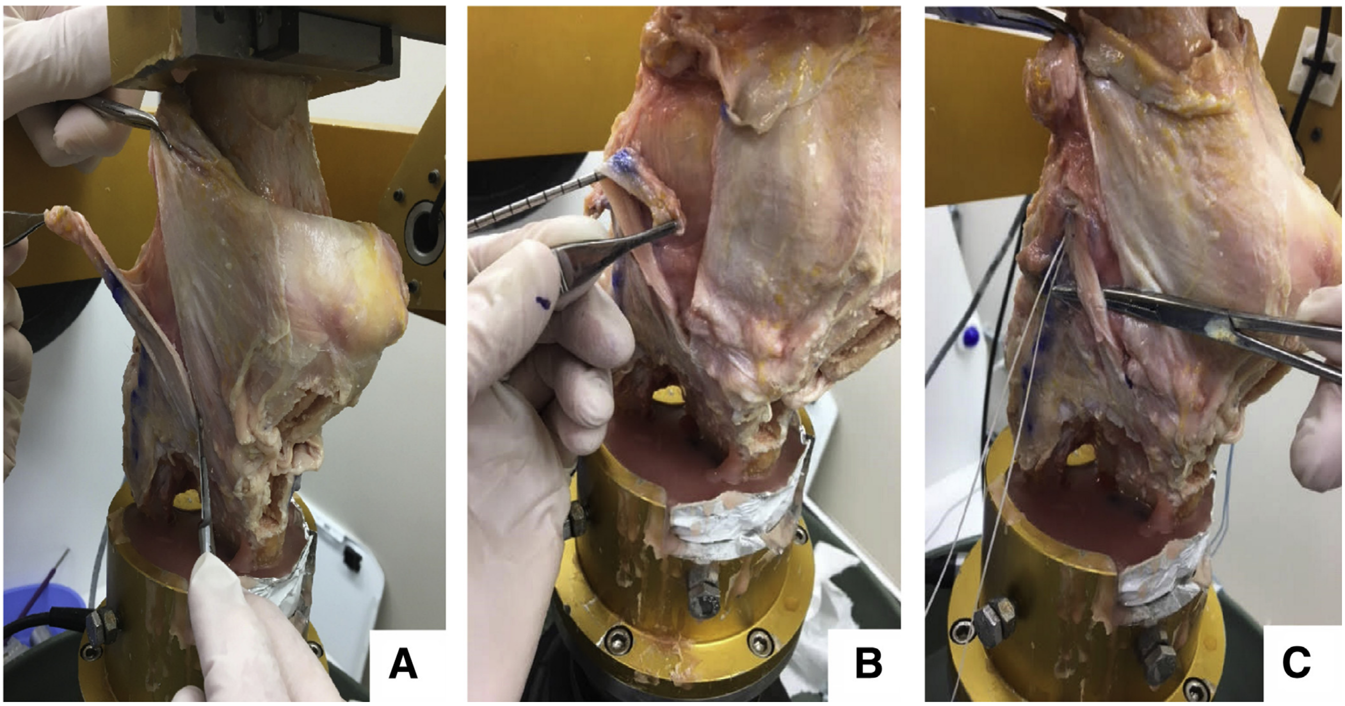

Fig 2. In a right knee, (A) The 10-mm strip of the posterior one-third of the iliotibial band (ITB) used in the group 2 low-tension ITB tenodesis. (B) The femoral tunnel is located 8 mm proximal and 8 mm posterior to the lateral epicondyle and this point is tested for isometricity through knee flexion–extension. (C) The graft is secured under 2 lbs of tension at 30° knee flexion and neutral tibial rotation.

reconstruction using a local ITB graft that avoids a remote graft harvest or allograft and the need for tibial fixation. The proximal graft is fixated at the ALL femoral attachment under a low tensile load to provide the least effect on constraining internal tibial rotation.

Statistical Methods

Tests for statistical equivalence were performed using 2 paired one-sided t-tests[44,45] as previously described[2,24,32,33] to evaluate equivalence between intact-ACL sectioned, intact-ACL reconstructed, ACL reconstructed-ALL/ITB sectioned, and ACL reconstructed-manual tension ITB tenodesis in group 1 specimens, and intact-ALL/ITB sectioned and intact-low tension ITB tenodesis in group 2 specimens. The value of equivalence testing in this type of experiment has been reported elsewhere.[2,24,32,33,44,45] Equivalence limits were set at 2 mm for differences of tibial translation and 2° for differences of tibial internal rotation, as recommended in prior publications.[2,24,32,33] A post hoc power analysis calculated a power of greater than 0.95 for those conditions when equivalence was determined.

Results

Group 1: Manual-Tension ITB Tenodesis Procedure

Increases in translation and rotation for each testing condition are shown in Tables 2 and 3. ACL reconstruction restored lateral and medial compartment translation in the pivot-shift 1 (5 N·m internal rotation) to within 0.7 mm (95% CI, -0.6 to 1.9; P = .07) and 1.0 mm (95% CI, −1.0 to 3.0; P = .13), respectively, with ACL graft forces measuring 153.5 N (95% CI, 108.0-199.0). In the pivot-shift 2 (1 N·m internal rotation), lateral and medial compartment translation differed by 1.0 mm (95% CI, −0.5 to 2.6; P = .14) and 1.2 mm (95% CI, −1.0 to 3.4; P = .18), respectively, from the native state, with ACL graft forces measuring 162.6 N (95% CI, 145.1-180.0). Under 5 N·m internal rotation at 25°, 60°, and 90° knee flexion, internal rotation after the ACL reconstruction differed from the native state by -1.0° (95% CI, −2.3 to 0.2; P = .14), 0.0° (95% CI, −0.4 to 0.4; P = .03), and 0.0° (95% CI, −0.4 to 0.5; P = .03), respectively. ACL graft forces were highest at 25° flexion (54.9 N; 95% CI, 0.9-109.0), but remained at less than 10.0 N at both 60° and 90°.

After ALL/ITB sectioning in the ACL-reconstructed knee, pivot-shift 1 lateral and medial compartment translations increased by 0.3 mm (95% CI, 0.1-0.5; P = .04) and 0.2 mm (95% CI, −0.2 to 0.5; P = .03), respectively. A compartment map showing a representative specimen in this group under pivot-shift 1 loading is shown in Fig 4. In pivot-shift 2, lateral and medial compartment translations increased 0.1 mm (95% CI, -0.3 to 0.6; P = .03) and -0.2 mm (95% CI, −0.6 to 0.2; P = .03), respectively (Fig 3). In the 5 N·m internal rotation tests, ALL/ITB sectioning increased internal rotation by 0.7° (95% CI, 0.3-1.0; P = .07), 2.9° (95% CI, 0.9-4.8; P = .82), and 2.9° (95% CI, 0.6-5.2; P = .82) at 25°, 60°, and 90° flexion, respectively (Fig 5). ACL graft forces increased minimally after ALL/ITB sectioning. A compartment map showing a representative specimen in this group is shown in Fig 6. The greatest mean increase in ACL graft force of 18.8 N (95% CI, −28.5 to 66.2) occurred during 5 N·m internal rotation loading at 60° knee flexion.

Table 2. Mean Difference (95% CI) for the Pivot-Shift 1, Pivot-Shift 2, and Lachman Loading Profiles*

Test condition	Lateral compartment translation, mm	Center translation, mm	Medial compartment translation, mm	Internal rotation, degrees
Pivot-shift 1 (100 N ANT, 5 Nm IR, 7 Nm VAL)				
ACL sectioned	5.8 (3.7 to 7.9)	7.1 (4.3 to 9.9)	8.3 (4.5 to 12.2)	−4.0 (−7.9 to −0.1)
ACL reconstructed	0.7 (−0.6 to 1.9)	0.8 (−0.8 to 2.4)	1.0 (−1.0 to 3.0)	−0.4 (−2.4 to 1.5)
ALL/ITB sectioned	0.3 (0.1 to 0.5)†	0.1 (−0.2 to 0.3)†	0.2 (−0.2 to 0.5)†	−0.1 (−1.0 to 0.8)
Manual-tension ITB tenodesis	−4.8 (−8.8 to −0.9)	−1.6 (−3.7 to 0.4)	1.6 (0.1 to 3.2)	−10.3 (−17.9 to −2.8)
Pivot-shift 2 (100 N ANT, 1 Nm IR, 7 Nm VAL)				
ACL sectioned	8.8 (3.9 to 13.7)	10.4 (6.6 to 14.2)	11.8 (6.8 to 16.9)	−4.6 (−8.9 to −0.2)
ACL reconstructed	1.0 (−0.5 to 2.6)	1.1 (−0.5 to 2.8)	1.2 (−1.0 to 3.4)	−0.1 (−3.5 to 3.2)‡
ALL/ITB sectioned	0.1 (−0.3 to 0.6)†	0.1 (−0.1 to 0.4)†	−0.2 (−0.6 to 0.2)†	0.7 (0.2 to 1.3)†
Manual-tension ITB tenodesis	−4.0 (−7.4 to −0.6)	−1.0 (−2.4 to 0.5)	2.2 (0.1 to 4.2)	−9.7 (−17.9 to −1.6)
Lachman (100N ANT @ 25° flexion)				
ACL sectioned	8.7 (5.6 to 11.8)	10.6 (7.4 to 13.7)	13.4 (9.7 to 17.1)	−6.0 (−9.0 to -3.0)
ACL reconstructed	−1.2 (−2.7 to 0.4)	0.2 (−1.2 to 1.6)‡	2.3 (−0.7 to 5.3)	−4.3 (−8.6 to −0.1)
ALL/ITB sectioned	0.3 (−0.1 to 0.6)	0.1 (−0.2 to 0.4)†	−0.2 (−0.6 to 0.2)†	0.6 (−0.2 to 1.3)
Manual-tension ITB tenodesis	−3.5 (−6.2 to −0.8)	−0.8 (−1.6 to 0.0)	3.2 (0.4 to 6.0)	−8.5 (−15.0 to −1.9)

ACL, anterior cruciate ligament; ALL, anterolateral ligament; ANT, anterior; CI, confidence interval; IR, internal rotation; ITB, iliotibial band; VAL, valgus.

*From intact for the ACL sectioned and ACL reconstructed states, and from the ACL reconstructed state for the ALL/ITB sectioned and manual-tension ITB tenodesis states.

†P < .05 to the ACL reconstructed state.

‡P < .05 to the intact state.

Table 3. Mean Difference (95% CI) for the 5 N-m Internal Rotation Loading Profile at 3 Different Knee Flexion Angles*

Test condition	Lateral compartment translation, mm	Center translation, mm	Medial compartment translation, mm	Internal rotation, degrees
5 N-m IR at 25° flexion				
ACL sectioned	1.1 (−0.3 to 2.5)	1.0 (−0.3 to 2.2)	0.8 (−0.2 to 1.8)	0.6 (−0.3 to 1.4)
ACL reconstructed	−0.6 (−1.8 to 0.6)	−0.2 (−1.7 to 1.3)†	0.1 (−1.7 to 1.9)†	−1.0 (−2.3 to 0.2)
ALL/ITB sectioned	0.3 (0.1 to 0.5)‡	0.1 (−0.2 to 0.4)‡	−0.1 (−0.4 to 0.3)‡	0.7 (0.3 to 1.0)
Manual-tension ITB tenodesis	−4.8 (−8.1 to −1.4)	−2.6 (−4.7 to −0.4)	−0.3 (−1.8 to 1.2)‡	−7.3 (−12.3 to −2.3)
5 N-m IR at 60° flexion				
ACL sectioned	0.1 (−0.1 to 0.3)†	0.1 (−0.1 to 0.3)†	0.1 (−0.1 to 0.3)†	0.0 (−0.1 to 0.2)†
ACL reconstructed	0.6 (−1.8 to 0.7)†	0.6 (−1.7 to 0.6)†	0.6 (−1.7 to 0.6)†	0.0 (−0.4 to 0.4)†
ALL/ITB sectioned	1.4 (0.4 to 2.4)	0.7 (0.0 to 1.4)	−0.1 (−0.6 to 0.4)‡	2.9 (0.9 to 4.8)
Manual-tension ITB tenodesis	−6.7 (−10.0 to −3.4)	−1.9 (−4.7 to 0.9)	2.9 (0.5 to 5.2)	−16.1 (−20.7 to −11.6)
5 N-m IR at 90° flexion				
ACL sectioned	0.0 (−0.1 to 0.2)†	0.0 (−0.1 to 0.2)†	0.0 (−0.1 to 0.2)†	0.0 (−0.2 to 0.2)†
ACL reconstructed	−0.5 (−1.4 to 0.5)†	−0.5 (−1.4 to 0.5)†	−0.5 (−1.4 to 0.5)†	0.0 (−0.4 to 0.5)†
ALL/ITB sectioned	1.7 (0.1 to 3.3)	1.0 (−0.3 to 2.2)	0.2 (−0.5 to 0.9)‡	2.9 (0.6 to 5.2)
Manual-tension ITB tenodesis	−7.7 (−10.5 to −5.0)	−2.1 (−4.4 to 0.3)	3.5 (0.8 to 6.2)	−21.9 (−30.6 to −13.2)

ACL, anterior cruciate ligament; ALL, anterolateral ligament; CI, confidence interval; IR, internal rotation; ITB, iliotibial band.

*From intact for the ACL sectioned and ACL reconstructed states and from the ACL reconstructed state for the ALL/ITB sectioned and manual-tension ITB tenodesis states.

†$P < .05$ to the intact state.

‡$P < .05$ to the ACL reconstructed state.

After performing the manual-tension ITB tenodesis procedure, lateral compartment translation in the pivot-shift 1 differed from the ACL-reconstructed state by −4.8 mm (95% CI, −8.8 to −0.9; P = .99) and by −4.0 mm (95% CI, −7.4 to −0.6; P = .98; Fig 3) in the pivot-shift 2 (Fig 4). Thus, lateral compartment translation was restricted a total of 5.1 and 4.1 mm, respectively. This corresponded with a decrease of 70.3 N (95% CI, 10.7-129.9) and 57.6 N (95% CI, 4.0-111.3) in ACL graft forces compared with the ACL-reconstructed state. Under 5 N·m internal rotation, internal rotation measurements differed from the ACL-reconstructed state by -7.3° (95% CI, −12.3 to −2.3; P = .99), −16.1° (95% CI, −20.7 to −11.6; P = .99), and −21.9° (95% CI, −30.6 to −13.2; P = .99) at 25°, 60°, and 90° flexion, respectively (Fig 5). ACL graft forces decreased the most at 25° flexion (47.5 N [95% CI, −5.2 to 100.3]) but

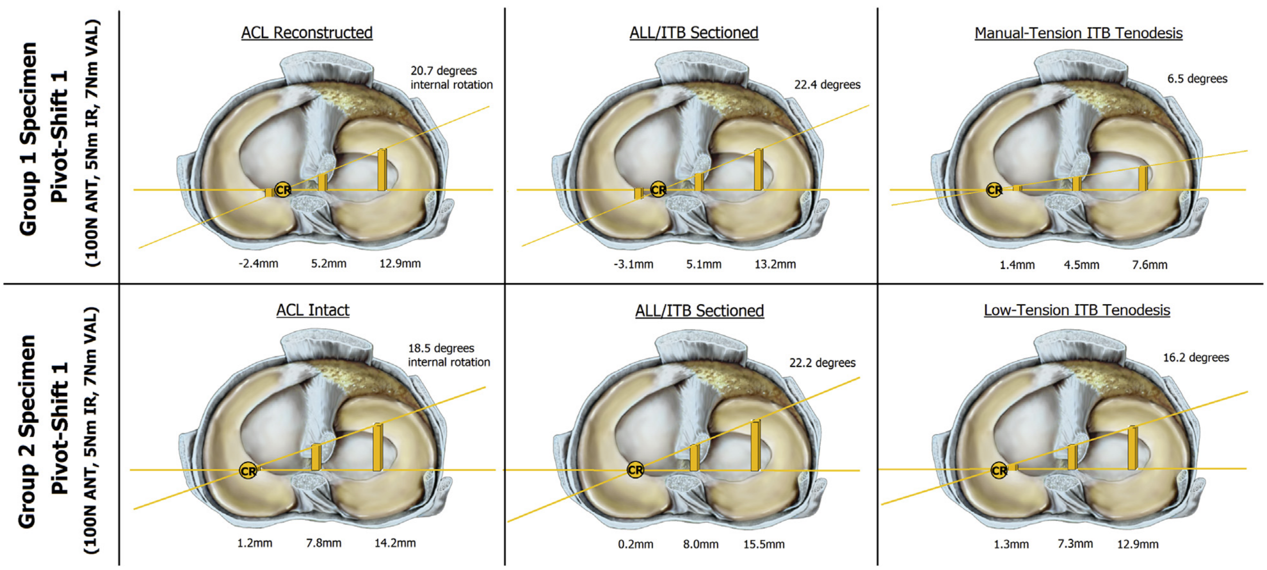

Fig 3. Compartment maps of a representative specimen for group 1 manual-tension iliotibial band (ITB) tenodesis (top) and group 2 low-tension ITB tenodesis (bottom) under pivot-shift 1 loading conditions (100 N ANT, 5 N·m internal rotation, 7 N·m VAL). Specimens are right knees (medial compartment on the left, lateral compartment on the right). The center of rotation (CR) is accurate from medial to lateral and approximated from anterior to posterior. Note the minimal increases in lateral compartment translation with anterolateral ligament/ITB sectioning. Also note the medial shift in the CR in the group 1 manual-tension ITB tenodesis procedure. This is a result of the overconstraint from that procedure. ACL, anterior cruciate ligament.

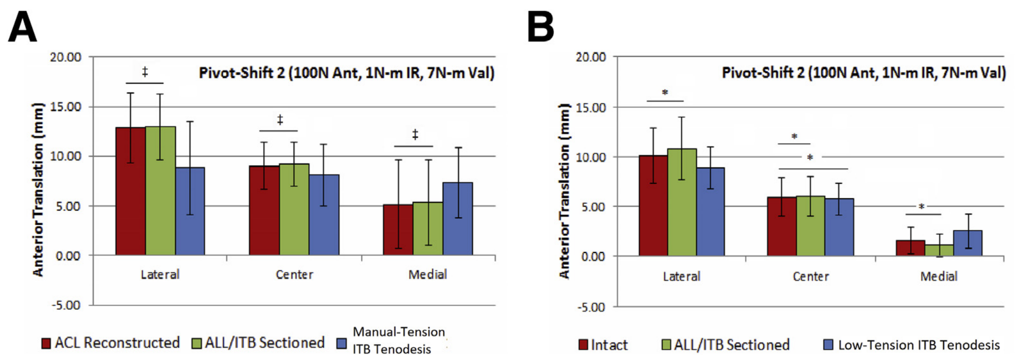

Fig 4. Mean lateral, central, and medial compartment anterior translations and standard deviations for (A) group 1 specimens (anterior cruciate ligament [ACL] reconstructed, anterolateral ligament [ALL]/iliotibial band [ITB] sectioned, and manual-tension ITB tenodesis states) and (B) group 2 specimens (intact, ALL/ITB sectioned, and low-tension ITB tenodesis states) under a Pivot-shift 2 loading (100 N ANT, 1 N·m internal rotation, 7 N·m VAL). ‡Statistical equivalence ($P < .05$) to the ACL reconstructed state. *Statistical equivalence ($P < .05$) to the ACL intact state.

decreased by no more than 4.0 N at either 60° or 90° flexion owing to the already low load of the ACL-reconstructed state alone.

Group 2: Low-Tension ITB Tenodesis Procedure

Increases in translation and rotation for each testing condition are shown in Tables 4 and 5. After ALL/ITB sectioning in the pivot-shift 1, lateral and medial compartment translations increased by only 1.2 mm (95% CI, 0.4-2.1; $P = .18$) and -0.5 mm (95% CI, −1.0 to 0.0; $P = .02$), respectively, compared with intact conditions. A compartment map showing a representative specimen in this group under pivot-Shift 1 loading is provided in Fig 3. In the pivot-shift 2, lateral and medial compartment translations increased 0.6 mm (95% CI, 0.0-1.2; $P = .03$) and -0.5 mm (95% CI, −1.1 to 0.1; $P = .02$), respectively (Fig 4). In the 5 N·m internal rotation tests, ALL/ITB sectioning increased internal rotation by 2.2° (95% CI, 0.5-3.9; $P = .65$), 4.3° (95% CI, 1.9-6.8; $P = .99$), and 3.8° (95% CI, 2.1-5.5; $P = .99$) at 25°, 60°, and 90° flexion, respectively (Fig 5).

After the low-tension ITB tenodesis procedure, lateral compartment translation in the pivot-shift 1 differed from the intact state by -0.8 mm (95% CI, −2.2 to −0.6; $P = .04$) and by −1.3 mm (95% CI, −2.6 to 0.1; $P = .16$; Fig 4) in the pivot-shift 2. Thus, lateral compartment translation was restricted a total of 2.0 and 1.9 mm, respectively. Under 5 N·m internal rotation, internal rotation measurements differed from the native state by −1.9° (95% CI, −4.6 to 0.8; $P = .39$), −4.2° (95% CI, −9.8 to 1.4; $P = .99$), and −6.9° (95% CI, −11.6 to −2.1; $P = .99$) at 25°, 60°, and 90° flexion, respectively (Fig 5). A compartment map showing a representative specimen in this group is presented in Fig 6.

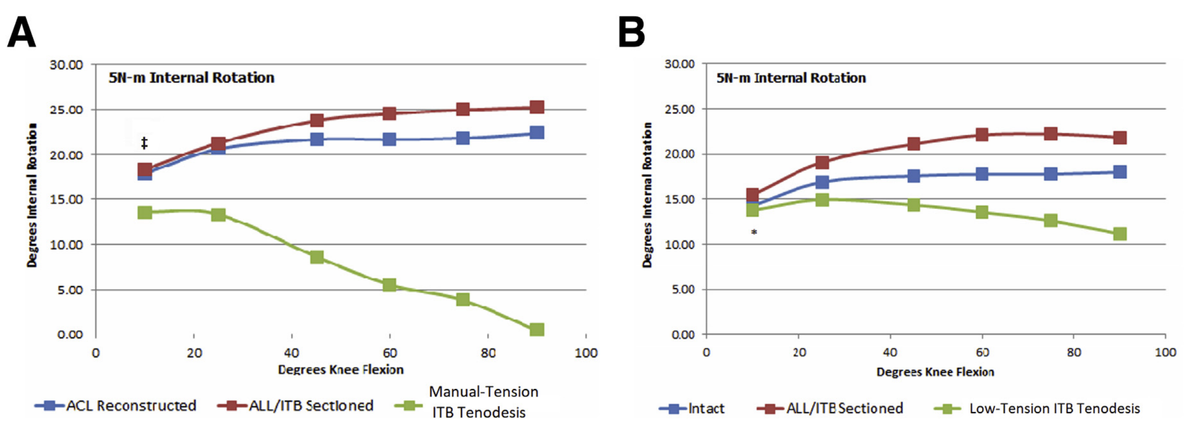

Fig 5. Mean internal rotation for (A) group 1 specimens (anterior cruciate ligament [ACL] reconstructed, anterolateral ligament [ALL]/iliotibial band [ITB] sectioned, and manual-tension ITB tenodesis) and (B) group 2 specimens (intact, ALL/ITB sectioned, and low-tension ITB tenodesis) under a 5 N·m internal rotation moment over a range of flexion. ‡Statistical equivalence ($P < .05$) to the ACL reconstructed state. *Statistical equivalence ($P < .05$) to the ACL intact state. Note the overall small abnormal increase in the internal rotation limit after ALL/ITB sectioning. Also note the gross overconstraint of the manual-tension ITB tenodesis as opposed to the small overconstraint of the low-tension ITB tenodesis at greater degrees of flexion.

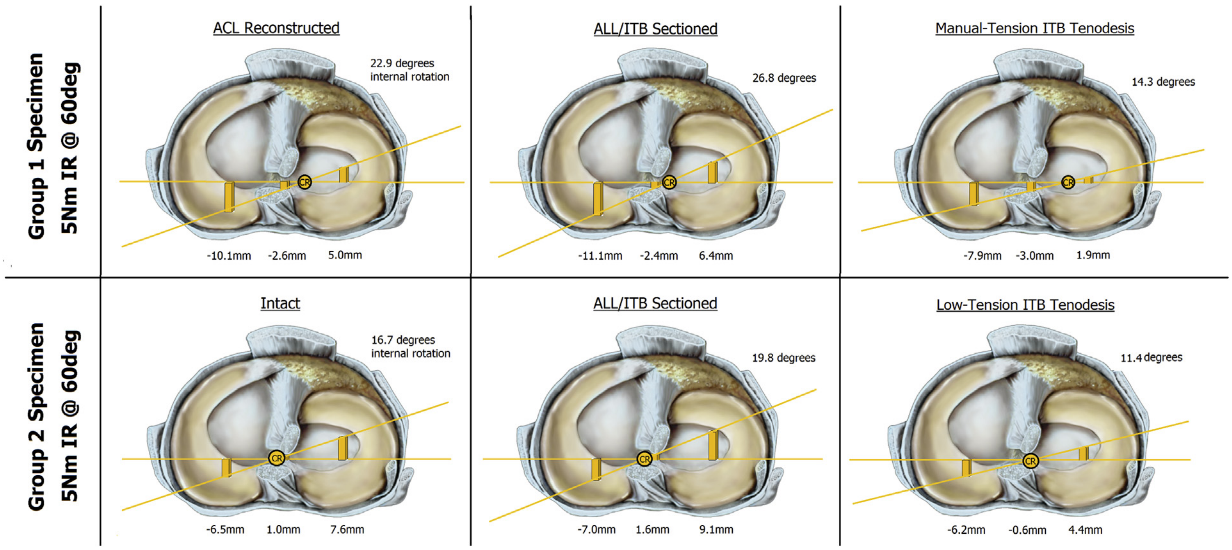

Fig 6. Compartment maps of a representative specimen for group 1 manual-tension iliotibial band (ITB) tenodesis (top) and group 2 low-tension ITB tenodesis (bottom) under 5 N·m internal rotation torque at 60° knee flexion. Specimens are right knees (medial compartment on the left, lateral compartment on the right). The center of rotation (CR) is accurate from medial to lateral and approximated from anterior to posterior. Note the minimal increases in internal rotation and lateral compartment translation with anterolateral ligament [ALL]/ITB sectioning. Also note the decrease in internal rotation with the 2 ITB extra-articular procedures.

Discussion

One of the important findings in this study is that an ACL BPTB graft restores the pivot-shift medial and lateral tibiofemoral compartment translations to normal, even with associated injury to the anterolateral structures. This finding affirms the first hypothesis and agrees with other publications.[2] These results apply to the specific in vitro BPTB graft tensioning and placement conditions of this study. With anterolateral injury, there was a residual increase in internal rotation at high degrees of flexion of, at most, 2.9° in group 1 specimens and, at most, 4.3° in group 2 specimens.

Second, the results affirm the second hypothesis that a low-tension ITB tenodesis (group 2, tensile load 8.9 N, 30° knee flexion, neutral rotation) decreased the small abnormal increases in internal tibial rotation with no effect in resisting pivot-shift anterior subluxations. The decrease of internal rotation was not found to be statistically equivalent to the native state as the range of equivalence was small (in this case, 2°). However, the low-tension ITB tenodesis restricted internal rotation, at most, 6.9° as compared with the native state.

A manual-tension ITB tenodesis (group 1, approximately 13-22 N, 10° flexion, neutral rotation), overconstrained internal tibial rotation and decreased pivot-shift compartment translations. For example, at 90° flexion, internal rotation was overconstrained by 21.9°, and lateral compartment translation in the pivot-shift was constrained by 4.8 mm. From a clinical

Table 4. Mean Difference (95% CI) under the Pivot-Shift 1, Pivot-Shift 2, and Lachman Loading Profiles*

Test condition	Lateral compartment translation, mm	Center translation, mm	Medial compartment translation, mm	Internal rotation, degrees
Pivot-shift 1 (100 N ANT, 5 Nm IR, 7 Nm VAL)				
ALL/ITB sectioned	1.2 (0.4 to 2.1)	0.4 (0.1 to 0.7)†	−0.5 (−1.0 to 0.0)†	2.8 (0.5 to 5.1)
Low-tension ITB tenodesis	−0.8 (−2.2 to −0.6)†	−0.2 (−0.6 to 0.1)†	0.4 (−0.5 to 1.4)†	−1.8 (−5.3 to 1.8)
Pivot-shift 2 (100 N ANT, 1 Nm IR, 7 Nm VAL)				
ALL/ITB sectioned	0.6 (0.0 to 1.2)†	0.1 (−0.1 to 0.1)†	−0.5 (−1.1 to 0.1)†	1.8 (−0.2 to 3.8)
Low-tension ITB tenodesis	−1.3 (−2.6 to 0.1)	−0.2 (−0.8 to 0.4)†	1.0 (0.2 to 1.7)	−3.3 (−6.0 to −0.6)
Lachman (100 N ANT at 25° flexion)				
ALL/ITB sectioned	0.5 (0.0 to 1.0)†	0.1 (−0.3 to 0.4)†	−0.4 (−1.0 to 0.2)†	1.4 (−0.2 to 2.7)
Low-tension ITB tenodesis	−1.3 (−2.7 to 0.1)	−0.2 (−0.9 to 0.6)†	1.0 (0.4 to 1.6)	−3.4 (−5.8 to −1.1)

ALL, anterolateral ligament; ANT, anterior; CI, confidence interval; IR, internal rotation; ITB, iliotibial band; VAL, valgus.

*From intact for the ALL/ITB Sectioned and low-tension ITB tenodesis states.

†$P < .05$ to the intact state.

Table 5. Mean Difference (95% CI) at 3 Different Knee Flexion Angles*

Test condition	Lateral compartment translation, mm	Center translation, mm	Medial compartment translation, mm	Internal rotation, degrees
5 N-m IR at 25° flexion				
ALL/ITB sectioned	1.2 (−0.1 to 2.5)	0.5 (−0.3 to 1.4)†	−0.2 (−0.6 to 0.2)†	2.2 (0.5 to 3.9)
Low-tension ITB tenodesis	−1.8 (−4.1 to 0.4)	−1.2 (−2.6 to 0.3)	−0.5 (−1.3 to 0.3)†	−1.9 (−4.6 to 0.8)
5 N-m IR at 60° flexion				
ALL/ITB sectioned	2.6 (0.8 to 4.3)	1.3 (0.2 to 2.3)	−0.1 (−0.7 to 0.5)†	4.3 (1.9 to 6.8)
Low-tension ITB tenodesis	−2.3 (−4.9 to 0.4)	−0.9 (−2.0 to 0.3)†	0.7 (−1.3 to 2.6)	−4.2 (−9.8 to 1.4)
5 N-m IR at 90° flexion				
ALL/ITB sectioned	2.0 (1.1 to 2.9)	0.8 (0.3 to 1.3)	−0.4 (−0.8 to 0.1)†	3.8 (2.1 to 5.5)
Low-tension ITB tenodesis	−2.9 (−4.7 to −1.1)	−0.7 (−1.5 to 0.2)†	1.8 (−0.1 to 3.7)	−6.9 (−11.6 to −2.1)

ALL, anterolateral ligament; CI, confidence interval; IR, internal rotation; ITB, iliotibial band.

*From intact for the ALL/ITB Sectioned and low-tension ITB tenodesis states under the 5 N-m Internal Rotation loading profile.

†$P < .05$ to the intact state.

standpoint, this ITB tenodesis would have the advantage of limiting pivot-shift subluxations and decreasing ACL graft forces, but at the unacceptable expense of limiting normal internal tibial rotation.

Many recent studies have shown an abnormal residual increase of 2 to 6° internal rotation, especially at high degrees of flexion, in the setting of an ACL reconstruction and concurrent injury to the anterolateral structures.[2,12,14,17,18,28] This finding agrees with the current study, which showed a 4.3° increase with ALL/ITB sectioning predominantly at high flexion angles. The differences between published studies are how these results are interpreted, and if this modest increase in internal rotation is deemed to be clinically relevant and indicative of an added lateral extra-articular procedure. For example, a previous study found a 5.1° increase in internal rotation with ALL/ITB sectioning under 5 N·m at 60° flexion that was not corrected with a BPTB ACL reconstruction.[2] It was concluded that this increase in internal rotation would not seem to warrant a concurrent ALL reconstruction.[2] In contrast, Nitri et al.[17] reported a residual 2.2° increase in internal rotation under the same conditions and concluded that an ALL reconstruction should be considered to restore stability. A second study also reported a 2.1° increase in internal rotation after sectioning the ALL and recommended an ALL reconstruction.[14] In both studies, it is not clear if there is a clinical symptomatic state requiring treatment. It should be noted there is a small percentage of knees with greater increases in internal tibial rotation with ALL/ITB injury that may be an exception. A prior study reported physiologic variability in the degrees of abnormal internal tibial rotation after ALL/ITB sectioning in an ACL-deficient knee; 21% of the specimens showed an 8 to 12° increase in internal rotation.[24] In these select knees, the rationale for a concurrent anterolateral reconstruction requires further study. The diagnosis of increased internal tibial rotation may be qualitatively detected using the supine Dial test at both 30° and 90° knee flexion as commonly used for posterolateral ligament injuries.[46]

Lateral extra-articular procedures as an addition to an ACL reconstruction have been studied in vitro in various forms, either with an ALL reconstruction or an ITB tenodesis. Schon et al.[18] tested an ALL reconstruction after ACL reconstruction and ALL injury with the ALL reconstructions fixed at different flexion angles between 0° and 90°. The authors report minimal increases in the internal rotation limit in the ACL-reconstructed state after cutting the ALL (maximum 0.9° increase), which agrees with the results of this current study. The ALL reconstruction tensioned at 88 N overconstrained the joint when fixed at 30° knee flexion or greater, although internal rotation was constrained by no more than 5°, which differs from our results. Samuelson et al.[28] tested an ACL reconstruction with an anterolateral injury and found a residual internal rotation of approximately 2°, which also agrees with the current study. A concurrent Müller ITB tenodesis overconstrained the internal rotation by 16° at high degrees of flexion, agreeing with our results. In contrast, Inderhaug et al.[14] performed both Lemaire and MacIntosh ITB tenodesis procedures and found no overconstraint in internal rotation when both procedures were tensioned at less than 20 N.

In general, the published studies on extra-articular reconstructions report an overconstraint of internal tibial rotation but differ as to the magnitude or degrees of overconstraint. In Table 1, the in vitro and in vivo publications are summarized as to graft tensioning conditions and degrees of internal tibial rotation that are constrained. Of interest, the in vivo studies show decreased knee internal rotation remained in the postoperative analysis,[5,6,13,16] although that accurate measurement of internal tibial rotation is subject to error.

A possible benefit of a concurrent lateral extra-articular procedure is the potential unloading effect it may have on the ACL graft.[47] A prior study showed an ALL reconstruction had only a modest effect of unloading a BPTB in the range of 70 to 80 N, during the pivot-shift and internal rotation tests when the ALL reconstruction was tensioned at 60° flexion.[2] In the current study, an ITB tenodesis tensioned at 10° flexion (group 1) partially unloaded ACL graft forces in the range of 50 to 70 N. Compared with BPTB fixation strengths and graft stiffness, these loads are modest and of unknown clinical benefit.

One of the problems in performing an extra-articular reconstruction is determining the so-called isometric femoral point to fixate the graft so that it does not exhibit major elongation or loosening through the range of knee flexion-extension. The most ideal graft fixation point on the femur with the least graft tension has been well-defined and can be verified at surgery.[43] However, this does not describe the graft elongation or shortening effects based on the effects of tibial rotation. The graft location at the lateral tibial margin moves anteriorly and posteriorly under an internal-external rotation torque. The data from this study show a graft attachment point at the lateral tibial margin moves anteriorly approximately 15 mm and posteriorly approximately 10 mm under a 5 N·m torque (Fig 7). This means the lateral extra-articular graft is markedly loose in external tibial rotation, markedly tight in internal tibial rotation, and slack at neutral rotation.

The advantage of an ITB tenodesis over other considered extra-articular reconstructions is that the lower border of the ITB is available as opposed to harvesting a hamstring tendon or using an allograft. Thus, distal fixation is not required and proximal fixation by an interference screw or an adjustable-loop construct is the only internal graft fixation necessary. Although 1 study showed an advantage to place the ITB graft underneath the fibular collateral ligament,[14] this current study showed this step was not necessary. The skin incision length can be minimized by mobilization of the adjacent skin area to address cosmetic issues. Also, a 12-mm strip of ITB has a maximum load of 161.1 N, which is greater than the reported maximum load of the ALL of 141 N.[48]

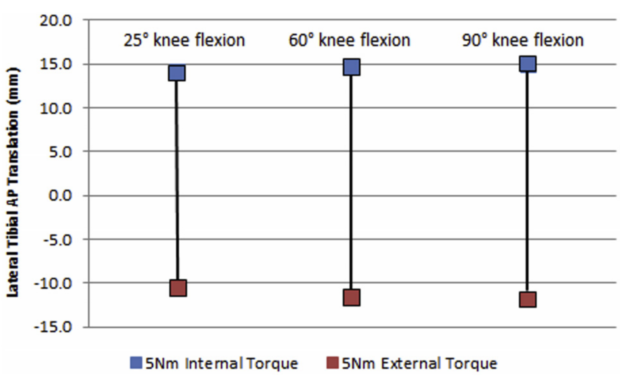

Fig 7. Internal rotation produces an anterior translation and the external rotation produces a posterior translation at the lateral margin of the tibia. An extra-articular graft under internal rotation would be subjected to stretching if tensioned at neutral rotation, because the mean lateral margin translation of the tibia approaches 15 mm anterior translation at the 3 flexion angles shown. Correspondingly, the graft would be loose with external tibial rotation. This assumes the graft is placed in the most isometric point for knee flexion-extension. AP, anteroposterior.

A recent clinical publication recommending concurrent ALL reconstruction in addition to a 3-strand semitendinosus ACL graft reported favorable outcomes. Of interest, the patient characteristics showed that of the 83 patients, 41 (49%) had a grade 1 pivot-shift, implying intact ALL structures, and only 19 patients (23%) had a grade 3 pivot-shift, which implies loss of the ALL structures.[19] The authors quote in a second study a 4% failure rate for the ACL/ALL reconstruction compared with 17% failure rate for their BPTB patients, which is one of the highest reported in the literature.[49] The important problem of repeat ACL injuries in athletes documents the need for objective return-to-activity guidelines and specific neuromuscular training before return to athletic activities.[50] Future studies need to document the rehabilitation and return-to-activity guidelines that were followed before allowing return-to-sports activity.[51] There is an added clinical recommendation to consider in selecting the ACL graft type. Publications on the indications for extra-articular reconstructions are most commonly using an soft-tissue graft rather than a BPTB graft, as used in this study. Accordingly, when an soft-tissue autograft is selected in a grade 3 pivot-shift knee, for an athlete returning to twisting and cutting activities, there may be an indication for a concurrent extra-articular procedure to back up the soft-tissue graft that requires future Level 1 studies.

In summary, the clinical indications for an ITB tenodesis procedure seem to be limited. The procedure does correct the few degrees of abnormal internal rotation at high flexion angles when there is an associated ALL/ITB injury; however, these increases in internal rotation are small and are presumed to be of limited clinical significance. A manual-tension ITB tenodesis does function along with the ACL reconstruction to limit pivot-shift subluxations and produces a modest decrease in ACL graft forces; however, the limitation of normal internal tibial rotation is presumed not to seem to be desirable from a clinical standpoint.

Limitations

Limitations exist in the current study. As a laboratory study, it was not possible to simulate in vivo dynamic loading conditions. This study examined only the effect of the distal ITB static attachments and not the function of the proximal ITB restraint. ACL graft force measurements were not obtained for group 2 specimens, because we sought to determine the deficit and role of an ITB tenodesis without the variability of an ACL graft imposing additional effects. The conditions of this study represent time-zero graft behaviors of both the ACL graft and ITB tenodesis. ACL graft healing with residual laxity could increase the functional significance of the anterolateral ligamentous restraints and extra-articular reconstructions. The reported results apply to BPTB ACL grafts and not soft tissue grafts with less rigid internal graft fixation or less graft-construct stiffness.[52,53]

Conclusions

A low-tension ITB tenodesis, fixated at neutral tibial rotation to avoid constraining internal tibial rotation, has no effect in limiting abnormal pivot-shift subluxations.

Acknowledgment

The authors thank Edward Grood, Ph.D. (University of Cincinnati), for expert consultation and continued support with knee robotic studies.

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