A Biomechanical Study of the Role of the Anterolateral Ligament and the Deep Iliotibial Band for Control of a Simulated Pivot Shift With Comparison of Minimally Invasive Extra-articular Anterolateral Tendon Graft Reconstruction Versus Modified Lemaire Reconstruction After Anterior Cruciate Ligament Reconstruction

Patrick A. Smith, M.D., Dimitri M. Thomas, M.D., Ryan J. Pomajzl, M.D., Jordan A. Bley, B.A., Ferris M. Pfeiffer, Ph.D., and James L. Cook, D.V.M., Ph.D.

Purpose: To determine whether the deep fibers of the iliotibial band (dITB) or the anterolateral ligament (ALL) provides more control of a simulated pivot shift and whether a minimally invasive anterolateral reconstruction (ALR) designed to functionally restore the ALL and dITB is mechanically equivalent to a modified Lemaire reconstruction (MLR). **Methods:** Six matched pairs of cadaveric knees (N = 12) were subjected to a simulated pivot shift to evaluate anteroposterior translation; internal rotation; and valgus laxity at 0°, 30°, and 90° of flexion. The anterior cruciate ligament (ACL) was sectioned in all specimens, and retesting was performed. Within each pair, sequential sectioning of the ALL and dITB was performed, followed by testing; the contralateral knee was sectioned in reverse order. Knees underwent ACL reconstruction (ACLR) and repeat testing. Then, MLR (n = 6) or ALR (n = 6) was performed on matched pairs for final testing. **Results:** Sectioning of the dITB versus ALL (after ACL sectioning) produced significantly more anterior translation at all flexion angles ($P = .004$, $P = .012$, and $P = .011$ for 0°, 30°, and 90°, respectively). The ACL-plus-dITB sectioned state had significantly more internal rotation at 0° versus ACL plus ALL ($P = .03$). ACLR plus ALR restored native anterior translation at all flexion angles. ACLR plus MLR restored anterior translation to native values only at 0° ($P = .34$). We found no statistically significant differences between ACLR plus ALR and ACLR plus MLR at any flexion angle for internal rotation or valgus laxity compared with the native state. **Conclusions:** ALR of the knee in conjunction with ACLR can return the knee to its native biomechanical state without causing overconstraint. The dITB plays a more critical role in controlling anterior translation and internal rotation at 0° than the ALL. The minimally invasive ALR was functionally equivalent to MLR for restoration of knee kinematics after ACLR. **Clinical Relevance:** The dITB is more important than the ALL for control of the pivot shift. A minimally invasive extra-articular tendon allograft reconstruction was biomechanically equivalent to a modified Lemaire procedure for control of a simulated pivot shift.

From the Department of Orthopaedic Surgery (P.A.S., D.M.T., R.J.P., F.M.P., J.L.C.) and Thompson Laboratory for Regenerative Orthopaedics (J.L.C.), University of Missouri, Columbia; Columbia Orthopaedic Group (P.A.S., J.A.B.), Columbia; and SSM Health Medical Group (R.J.P.), Bridgeton, Missouri, U.S.A.

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Address correspondence to Patrick A. Smith, M.D., Columbia Orthopaedic Group, Department of Orthopaedic Surgery, Sports Medicine, University of Missouri, 1 S Keene St, Columbia, MO 65201, U.S.A. E-mail: psmithmudoc@aol.com

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Anterior cruciate ligament (ACL) tears are among the most common knee injuries. Restoration of rotational control of the knee after ACL reconstruction (ACLR) is often suboptimal,[1-4] which can result in adverse sequelae, including meniscal tears and premature osteoarthritis.[5,6] Although these consequences may be attributable to surgical technique or biological factors, unaddressed injury to lateral extra-articular structures after ACL injury may also play a significant role.[7,8]

The work of Claes et al.[9] in 2013 has refocused attention to the lateral side of the knee and its importance relative to rotational stability after an ACL tear. In their anatomic study, they reported that 40 of 41 unpaired knees contained a clearly defined ligamentous structure that was distinct from the anterolateral joint capsule; they termed this structure the “anterolateral ligament” (ALL). This study described the ALL femoral attachment as anterior and distal to the lateral epicondyle. Claes et al. concluded that the ALL plays an important role in controlling internal tibial rotation because transection created a 3+ pivot shift. Other studies have corroborated the importance of the ALL for control of internal rotation.[10-12]

In addition to the importance of the ALL for anterolateral stability of the knee, it is essential to recognize the importance of the deep fibers of the iliotibial band (dITB), as noted by Hughston et al.[13,14] Terry et al.[15] described separate components of the dITB—named the “capsulo-osseous fibers”—that play a role in controlling internal tibial rotation toward extension with their proximal capsular origin and distal insertion at the Gerdy tubercle. In a prescient way, Terry et al.[15,16] described these capsulo-osseous fibers as functioning as an “anterolateral ligament of the knee.” It is important to note that Rasmussen et al.[12] showed that the iliotibial band (ITB) is the most important restraint for internal rotation in the knee and suggested that not accounting for this structure could easily overestimate the importance of the ALL. Kittl et al.[17] further highlighted this, showing that the ITB was the primary restraint to internal rotation for both the ACL-intact and ACL-deficient knee from 30° to 90° of flexion, with the capsulo-osseous fibers and dITB providing more restraint at lower flexion angles. Furthermore, these authors reported the ITB to be the primary restraint to internal tibial rotation induced by the application of a simulated pivot-shift test at 30° to 45° of flexion.

Extra-articular reconstructions to augment restoration of rotational stability to the knee in combination with ACLR have been thoroughly described, including the Lemaire procedure as well as numerous modifications.[18] Extra-articular reconstructions alone have also been described for treatment of the ACL-deficient knee, although a systematic review showed a high likelihood of overconstraint of the joint with this method of treatment.[19] As such, most recent publications have focused on the potential benefits of extra-articular ALL reconstruction in conjunction with ACLR for optimizing knee stability, the revision rate, and functional outcomes.[20] A recent study by Geeslin et al.[21] compared an anatomic ALL reconstruction with a modified Lemaire procedure and did not find superiority of either technique. However, this study also showed that an isolated ACLR could not restore normal knee kinematics when anterolateral structures were injured. Sonnery-Cottet et al.[20,22,23] have recently provided initial evidence suggesting that lateral extra-articular reconstruction in conjunction with ACLR can yield better clinical outcomes than ACLR alone in some cases. Given the renewed interest in extra-articular reconstruction to augment rotational stability in the ACL-reconstructed knee, we have pursued techniques to address all anterolateral structures (ALL plus dITB). This anterolateral reconstruction (ALR) approach strives to optimally control the pivot shift using a graft that both parallels the ALL and, in particular, reconstructs the dITB[9] following the philosophy of anterolateral rotatory instability of Hughston et al.[14]

The purpose of this study was to determine whether the dITB or the ALL provides more control of a simulated pivot shift and whether a minimally invasive ALR designed to functionally restore the ALL and dITB is mechanically equivalent to a modified Lemaire reconstruction (MLR). The hypotheses tested were as follows: (1) The dITB would be more important than the ALL for controlling a simulated pivot shift; (2) ACLR alone would not restore native knee kinematics after injury to the ACL and anterolateral structures; and (3) lateral extra-articular reconstruction in conjunction with ACLR would restore native knee kinematics after injury to the ACL and anterolateral structures.

Methods

Mechanical Testing Protocol

Six matched pairs (mean age, 35.8 years; age range, 29-51 years) of human knees ($N = 12$) were acquired from a tissue bank (ScienceCare, Phoenix, AZ). Specimens were stored at −80°C before testing. Each specimen was allowed to thaw at room temperature before being evaluated arthroscopically to confirm the absence of damage or abnormalities of the ACL, posterior cruciate ligament, menisci, or articular cartilage. Cadaveric knee range of motion required for testing, 0° to 90°, was also verified in each specimen before testing. None of the specimens were noted to have hyperextension. To facilitate biomechanical testing, soft tissues were dissected away from the proximal femur and distal tibia, leaving approximately 8 cm of bone for subsequent potting in testing fixtures. All soft tissue that was

15 cm on either side of the knee joint was preserved. Once prepared, specimens were potted by attaching 1-inch-diameter copper tubes onto the exposed femur and tibia to facilitate reproducible application of loading. The potted femur was attached to the table of a biaxial servohydraulic materials testing machine (model 8821s; Instron, Norwood, MA) using a multi-position 2-*df* fixture (medial-lateral [x-axis] and superior-inferior [y-axis]; the z-axis was along the ram of the materials testing machine) that allowed for orientation of the femur at 0°, 30°, or 90° relative to the tibia. The multi-position fixture on the femur was prevented from translating in the anterior direction but was unconstrained in the 2 remaining translation directions (medial-lateral and superior-inferior) (Fig 1). The femur was fixed against rotation in all rotational degrees of freedom to allow for loading. The potted tibia was attached to the ram of the Instron machine through a custom-designed 3-*df* fixture (anterior displacement, valgus, and internal rotation about the tibia), which allowed for a simulated pivot shift, similarly to previous studies.[24,25] The applied simulated pivot shift included 100 N of anterior translation, 10 Nm of valgus, and 5 Nm of internal rotation. Anterior translation was applied using the axial axis of the Instron machine in displacement control. Valgus loading was applied using the Instron rotational axis under displacement control. Internal rotation was applied using a hanging weight applied to a 25.4-cm offset arm (Fig 1). Joint contact was maintained throughout testing based on the preserved soft-tissue anatomy of the specimens in conjunction with the applied loads.

Each specimen was first evaluated arthroscopically to verify joint anatomy and to identify internal joint tracking marker locations. Internal joint tracking marker locations were identified by placing virtual points using the digitizing probe from an optical tracking system (Certus; NDI, Waterloo, Canada) and in accordance with previous studies.[26-29] Internal marker locations included the center of the ACL footprint on the femur, as well as the center of the ACL footprint on the tibia. The virtual internal marker locations were registered to the physical rigid body marker targets attached to the femur and tibia so that displacement of the ACL footprint could be tracked in real time during testing. All knees were first tested with intact anatomy followed by repeated testing at 0°, 30°, and 90° of flexion after each step of successive sectioning and repair according to Figure 2. All displacement and/or rotational measurements were taken using the internal and rigid body markers for the optical tracking system after the application of all pivot-shift loads. Anterior displacement was measured as the maximum displacement of the tibia relative to the femur. Internal rotation was defined as the rotation of the tibia relative to the femur about the tibial axis of rotation. Valgus rotation was defined as the rotation of the tibia relative to the femur about the femoral axis of rotation.

Sectioning

The ITB was split from the Gerdy tubercle proximally in the line of its fibers; 1 knee in each matched pair underwent ALL sectioning (ALLx) by identifying the ALL with internal rotation of the tibia with the knee at 45° of flexion. The lateral capsular tissue—including the ALL—was transected with a scalpel from the popliteus attachment on the femur anteriorly to the fibular head posteriorly above the lateral meniscus. The contralateral knee underwent dITB sectioning (ITBx) sharply, releasing all fibers beginning at the lateral

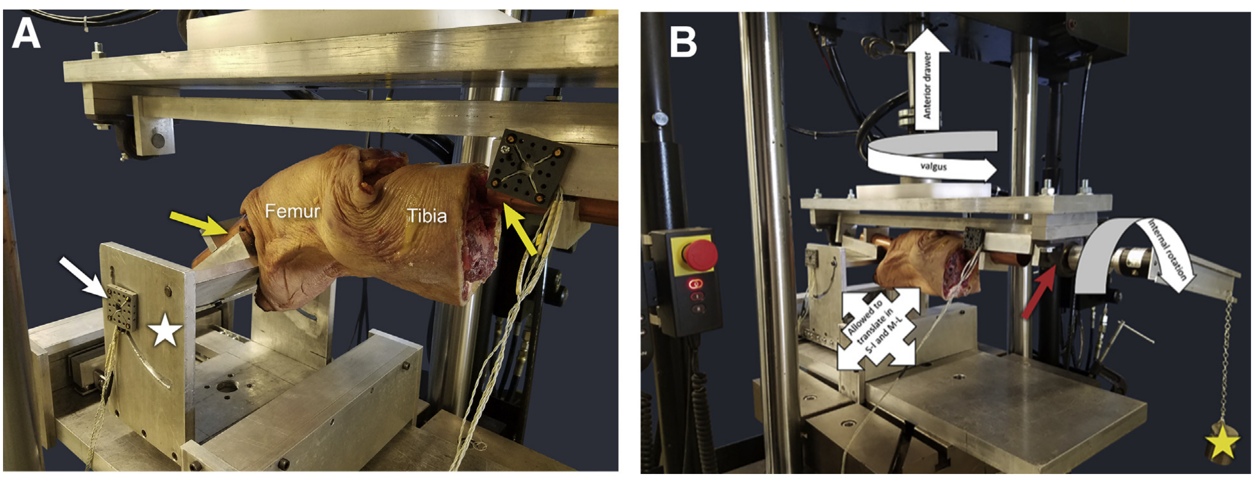
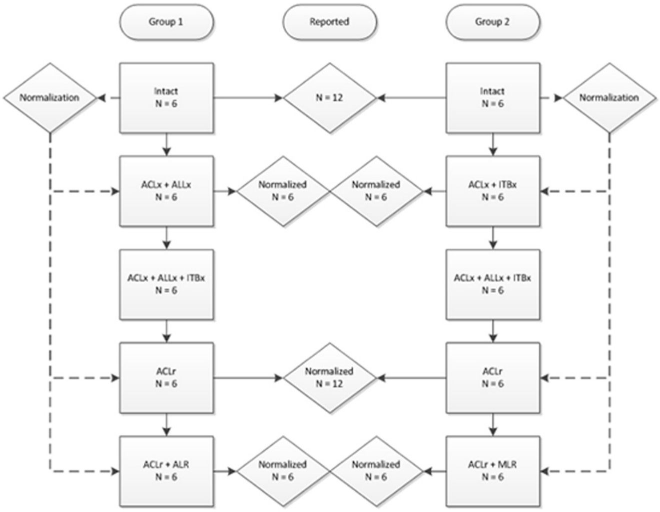


Fig 1. Testing setup using Instron 8821s machine. (A) Specimen at 30° of flexion. The yellow arrows indicate 1-inch copper tubes connecting to the bones. The star indicates a metal block attached to the Instron table to allow for alteration of the knee flexion angle using a sliding metal bolt (white arrow). (B) Specimen in full extension. The red arrow points to the ram of the Instron machine. The star indicates the 2.27-kg hanging weight. Translational and rotational degrees of freedom are defined using white arrows. (S-I, superior-inferior; M-L, medial-lateral.)



Step	Group 1	Group 2
1	Intact	Intact
2	Test	
3	Transect ACL	Transect ACL
4	Test	
5	Transect ITB deep fibers	Transect ALL
6	Test	
7	Transect ALL	Transect ITB deep fibers
8	Test	
9	Reconstruct ACL (GraftLink)	Reconstruct ACL (GraftLink)
10	Test	
11	Reconstruct ALL	Lemaire
12	Test	

Fig 2. Flowchart of testing algorithm, showing sectioning and then anterior cruciate ligament reconstruction (ACLr) and extra-articular procedures. (ACL, anterior cruciate ligament; ACLx, anterior cruciate ligament sectioning; ALL, anterolateral ligament; ALLx, anterolateral ligament sectioning; ALR, anterolateral reconstruction; ITB, iliotibial band; ITBx, iliotibial band sectioning; MLR, modified Lemaire reconstruction.)

intermuscular septum and extending to the posterior split of the ITB including the capsulo-osseous fibers originating from the posterolateral capsule. The specimens then underwent retesting. A final sectioning of the last remaining intact structure was performed. Measurements of the 3 parameters of interest were obtained at each flexion angle after each sectioning.

ACL Reconstruction

All-inside ACLR using dual suspensory fixation was performed in all 12 specimens. From the anteromedial portal, a 10-mm socket was drilled at the anatomic attachment of the ACL based on remnant fibers there. The socket depth was 25 mm. On the tibial side, a 10-mm FlipCutter (Arthrex, Naples, FL) was used with a tibial guide positioned in the tibial ACL remnant fibers there to retro-cut a socket depth of 30 mm to allow for graft tensioning. A 10-mm-diameter premade GraftLink allograft (Joint Restoration Foundation, Centennial, CO) was then passed across the joint with suspensory TightRope RT fixation (Arthrex) on the femur and suspensory No-Button TightRope loop fixation (Arthrex) after attaching a button on the tibia. The graft was tensioned at full extension in neutral rotation, and the specimens then underwent retesting.

Anterolateral Reconstruction

One knee in each matched pair underwent an ALR. This was performed with a single-bundle graft as described by Smith and Bley[30] (Fig 3). A pre-sutured 5-mm-wide and 150-mm-long soft-tissue allograft (Joint Restoration Foundation) was used. After thawing, it was pre-tensioned at 75 N. Femoral graft fixation was performed at the fixed anatomic landmark of the lateral gastrocnemius tubercle located distal to the lateral

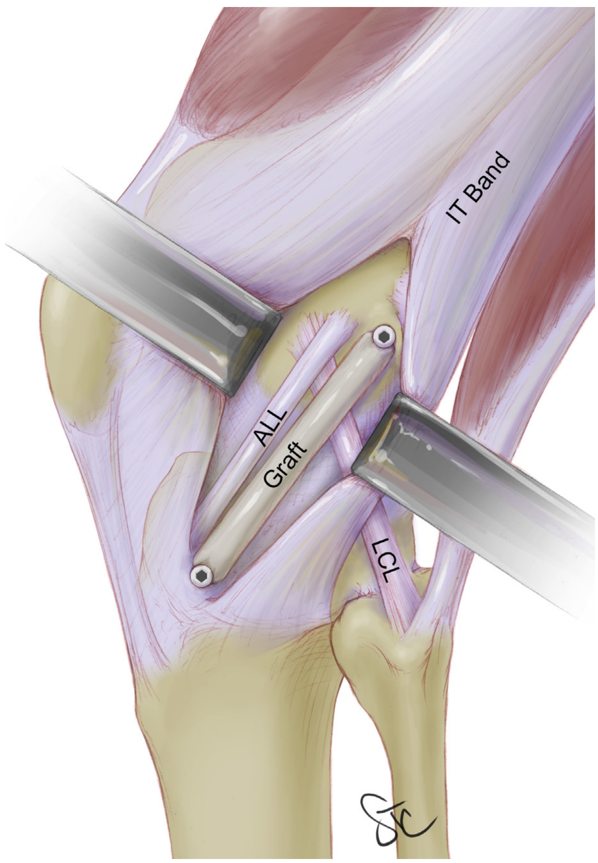


Fig 3. Anterolateral reconstruction, which was performed with a single-bundle graft. Reproduced with permission from The Curators of the University of Missouri (© 2018 by The Curators of the University of Missouri). (ALL, anterolateral ligament; IT, iliotibial; LCL, lateral collateral ligament.)

Table 1. Distances of Femoral Attachment Site of ALR Graft at Lateral Gastrocnemius Tubercle to LCL Origin

	Proximal Distance, mm	Posterior Distance, mm
Specimen		
ALR 1	10.08	4.38
ALR 2	10.98	4.91
ALR 3	9.55	4.93
ALR 4	10.11	4.25
ALR 5	9.69	4.08
ALR 6	10.33	4.71
Mean ± SD	10.12 ± 0.51	4.54 ± 0.36

ALR, anterolateral reconstruction; LCL, lateral collateral ligament; SD, standard deviation.

intermuscular septum. The relation to the lateral collateral ligament (LCL) origin was measured and recorded (Table 1). A 3.2-mm guide pin was drilled there. There was no tunnel interference with the ACL socket owing to the proximal and posterior position of the femoral ALR insertion. Furthermore, given the cadaveric nature of this study, the suspensory fixation button for the ACL could be visualized in each specimen, further confirming the divergence of the tunnels. Next, the anatomic ALL attachment to the tibia was identified halfway between the Gerdy tubercle and the center of the fibular head, 1.5 cm below the joint line. A second 3.2-mm guide pin was drilled there. A No. 2 FiberWire suture (Arthrex) was then used to confirm a non-isometric pattern of 2 to 3 mm of lengthening as the knee was taken from 100° of flexion to full extension. The femoral guide pin was overdrilled with a 4.5-mm reamer to a depth of 20 mm. Femoral graft fixation was achieved with a 4.75-mm Biocomposite SwiveLock anchor (Arthrex) as shown in Figure 4A. The graft was passed underneath the ITB distally to the tibial incision. On the tibia, a 7.0-mm reamer was drilled over the guide pin to a depth of 20 mm. A 7.0-mm fork-tipped Biocomposite SwiveLock (Arthrex) was used to secure the graft in full extension and neutral rotation (Fig 4B). The final construct, with the relation to the LCL, is shown in Figure 4C.

Modified Lemaire Reconstruction

The contralateral knee underwent an MLR as described by Spencer et al.[31] A 10-mm-wide strip of the ITB was left intact to the Gerdy tubercle, released proximally, and passed deep to the LCL; it was fixed with a staple at the metaphyseal flare proximal to the

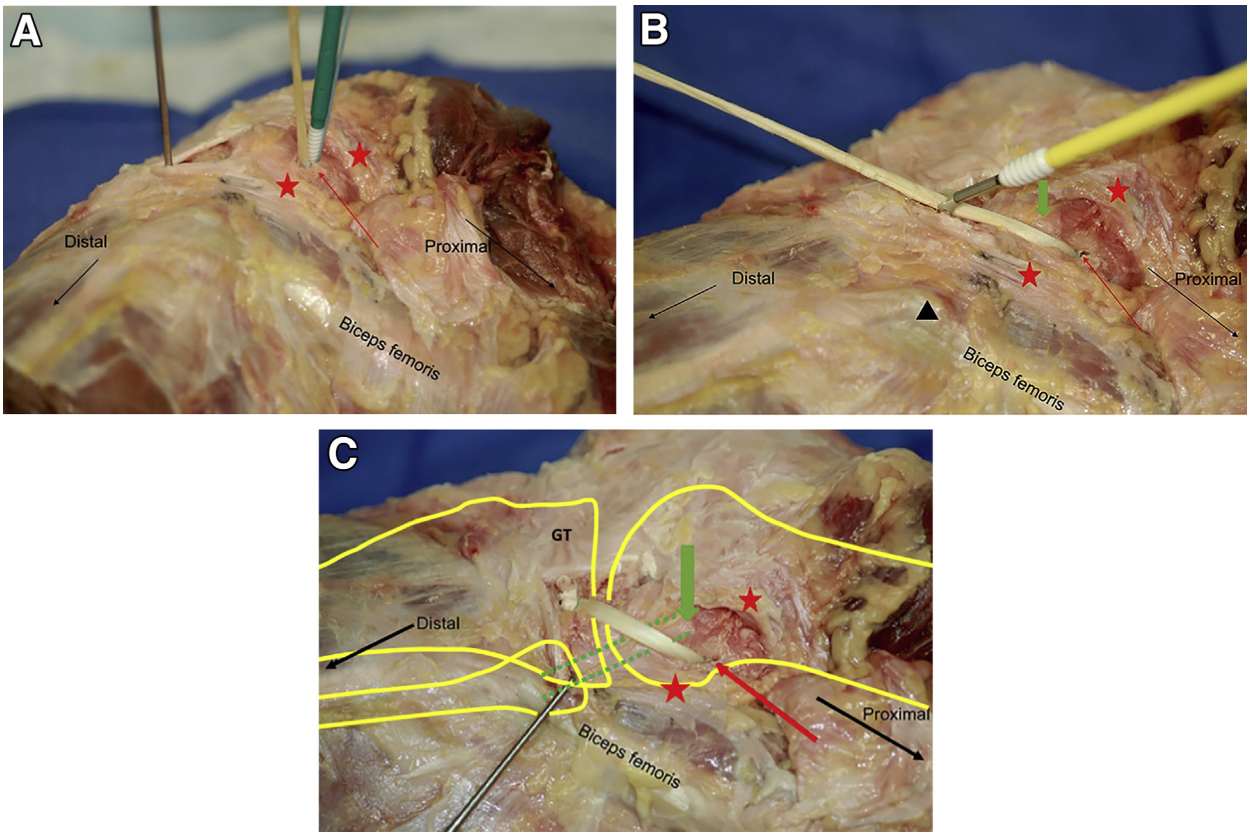


Fig 4. (A) Femoral insertion with 4.75-mm SwiveLock. (B) Tibial attachment with 7.0-mm fork-tipped SwiveLock. The black arrowhead represents the fibular head. (C) Final construct. Note the graft passage superficial to the lateral collateral ligament (LCL) and the femoral attachment remote to the LCL origin. Anterolateral reconstruction has been performed. The yellow lines outline the femur, tibia, and fibula. The red arrows indicate the lateral gastrocnemius tubercle. The red stars indicate the split iliotibial band. The green arrows mark the LCL origin, and the dotted green lines outline the LCL. (GT, Gerdy tubercle.)

LCL. The graft was then passed back underneath the LCL and sutured back to itself with No. 2 FiberWire suture at 70° of flexion and neutral rotation with minimal tension to create a tenodesis effect as the knee went to extension. Measurements were obtained in all specimens after each reconstruction. We chose specifically to use the modified Lemaire technique because Spencer et al. reported on the superiority of the MLR to a tendon allograft ALL reconstruction positioned anterior and distal to the lateral epicondyle in a biomechanical study of a simulated pivot shift. Furthermore, other authors performing biomechanical analyses of lateral extra-articular reconstruction have used the modified Lemaire procedure as the reference standard based on prevalence of clinical use.[21,32]

Statistical Methods

All data were normalized to their respective intact state to account for inherent differences in laxity or other variables that may affect the results from specimen to specimen. This was achieved by subtracting the intact-state displacement value from the measured reading for each specimen. This is a common method for analyzing repeated-measures data, such as intact state, transected, and treated, for inhomogeneous specimen testing (ligaments in different knees) as described in Milles et al.[28] and Nuelle et al.[33] A 1-sample t test was used to determine whether the normalized mean for each treatment was significantly different from 0, suggesting a statistical difference from the intact state. The primary hypothesis was analyzed using a 1-way repeated-measures analysis of variance to compare the reconstructed states (ACLR, ACLR plus ALR, and ACLR plus MLR). The secondary hypothesis was analyzed using a 2-tailed t test to compare differences between the ACL sectioning (ACLx)—plus-ALLx state and ACLx-plus-ITBx state.

Power Analysis

On the basis of an α of .05 and power requirement of 0.8, 6 matched pairs of knees were sufficient to detect an effect size (Cohen d) of 1.4, 1.8, and 2.3 for the 1-sample t test, 2-sample t test, and analysis of variance, respectively.

Results

Anteroposterior Translation

When subjected to a pivot-shift external force that caused anteroposterior translation, both transection states after the ACL was cut showed significant increases in translation over the native intact state. When compared directly, ITBx created significantly more anterior translation than ALLx in the setting of a deficient ACL at all flexion angles (Table 2).

When the ACL alone was reconstructed, significant differences in motion were seen at 0° and 30° compared with the native state (increases of 0.4 mm ± 0.5 mm, P = .034, and 0.6 mm ± 0.6 mm, P = .004, respectively). When the ALR was added, anterior translation was not significantly increased compared with the native state at any angle. With the MLR instead of the ALR, significant differences in motion were seen at 30° and 90° compared with the native state (increases of 1.0 mm ± 0.8 mm, P = .027, and 1.3 mm ± 0.9 mm, P = .018, respectively). Compared directly with each other, no statistically significant differences were noted between the ACLR-plus-ALR group and the ACLR-plus-MLR group (Table 3).

Internal Rotation

When subjected to a pivot-shift external force causing internal rotation, a significant difference was found between the native state and the ACLx-plus-ALLx transection state only in full extension (increase of

Table 2. Transection States Compared With Intact State

		ACLx Plus ALLx		ACLx Plus ITBx		
	Intact	Normalized	P Value vs Intact	Normalized	P Value vs Intact	P Value for ALLx vs ITBx
Anterior translation, mm						
0°	2.8 ± 1.0	2.0 ± 1.7*	.036*	6.2 ± 2.0*	.001*	.004*
30°	2.6 ± 0.7	3.2 ± 2.0*	.011*	7.1 ± 2.3*	.001*	.012*
90°	2.5 ± 0.7	3.6 ± 1.5*	.002*	6.2 ± 2.1*	.001*	.011*
Internal rotation, °						
0°	9.3 ± 1.8	1.4 ± 0.7*	.004*	4.0 ± 2.5*	.011*	.030*
30°	9.8 ± 3.0	1.6 ± 3.7	.332	3.7 ± 3.6	.054	.358
90°	9.8 ± 2.9	1.2 ± 3.5	.457	3.5 ± 2.7*	.026*	.231
Valgus, °						
0°	4.5 ± 1.9	5.2 ± 2.9*	.007*	5.5 ± 3.4*	.011*	.859
30°	4.9 ± 1.4	4.5 ± 3.1*	.016*	5.9 ± 2.1*	.001*	.385
90°	4.9 ± 1.1	3.8 ± 3.0*	.026*	5.9 ± 2.1*	.001*	.185

NOTE. Data are presented as mean ± standard deviation.
ACLx, anterior cruciate ligament sectioning; ALLx, anterolateral ligament sectioning; ITBx, iliotibial band sectioning.
*Statistically significant.

Table 3. Reconstruction States Compared With Intact State

		ACLR		ACL Plus ALR		ACL Plus MLR		
	Intact	Normalized	*P* Value vs Intact	Normalized	*P* Value vs Intact	Normalized	*P* Value vs Intact	*P* Value for ALR vs MLR
AP translation, mm								
0°	2.8 ± 1.0	0.4 ± 0.5*	.034*	0.0 ± 1.4	.987	0.4 ± 0.9	.336	.750
30°	2.6 ± 0.7	0.6 ± 0.6*	.004*	0.4 ± 0.9	.305	1.0 ± 0.8*	.027*	.906
90°	2.5 ± 0.7	0.5 ± 1.1	.147	0.4 ± 0.8	.347	1.3 ± 0.9*	.018*	.105
Internal rotation, °								
0°	9.3 ± 1.8	0.7 ± 1.2	.094	1.4 ± 2.5	.214	−0.1 ± 0.5	.886	.700
30°	9.8 ± 3.0	0.3 ± 2.7	.676	1.8 ± 3.7	.284	−1.0 ± 2.8	.443	.780
90°	9.8 ± 2.9	0.3 ± 3.5	.799	1.2 ± 3.0	.377	−1.0 ± 2.2	.332	.983
Valgus, °								
0°	4.5 ± 1.9	1.0 ± 0.9*	.002*	1.3 ± 1.6	.120	0.8 ± 0.9	.103	.954
30°	4.9 ± 1.4	0.8 ± 1.7	.157	1.4 ± 2.3	.192	0.1 ± 1.7	.946	.980
90°	4.9 ± 1.1	0.6 ± 1.6	.236	2.1 ± 2.5	.093	−0.1 ± 2.0	.953	.758

NOTE. Data are presented as mean ± standard deviation.

ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ALR, anterolateral reconstruction; AP, anteroposterior; MLR, modified Lemaire reconstruction.

*Statistically significant.

1.4° ± 0.7°, *P* = .004). When ACLx plus ITBx was tested, significant increases in internal rotation were seen in full extension and at 90° of flexion (4.0° ± 2.5°, *P* = .011, and 3.5° ± 2.7°, *P* = .026, respectively). A greater increase in internal rotation was seen in the ACLx-plus-ITBx group versus the ACLx-plus-ALLx group in full extension (*P* = .030, Table 2).

When we looked at reconstructions, the ACLR state showed no changes in internal rotation compared with the native state. The same was noted for the ACLR-plus-ALR state. The ACLR-plus-MLR state showed slight decreases in internal rotation at all angles, although these were not significant. Compared directly with each other, no differences were seen between the ACLR-plus-ALR group and the ACLR-plus-MLR group (Table 3).

Valgus Rotation

When subjected to the pivot-shift force causing a valgus moment, both the ACLx-plus-ALLx and ACLx-plus-ITBx sectioned states showed significant increases compared with the native state (Table 2). In the ACLR state, only in full extension was a significant increase in valgus opening seen compared with the native state (1.0° ± 0.9°, *P* = .002).

In the ACLR-plus-ALR and ACLR-plus-MLR states, no difference were noted from the intact state. Compared directly with each other, no differences were seen between the ACLR-plus-ALR group and the ACLR-plus-MLR group (Table 3).

Discussion

Our first hypothesis was accepted in that the dITB provided significantly more restraint to simulated pivot shift than the ALL. Each anatomic structure showed significant differences in translation compared with the native state; however, when compared against each other, the dITB contributed significantly more to anterior stability at all flexion angles tested versus the ALL. For internal rotation, the dITB proved to be more important to restraint than the ALL in full extension. Because subluxation of the pivot shift occurs in extension with subsequent reduction at 30° of knee flexion, these results suggest clinical importance for the dITB over the ALL for controlling both anterior translation and internal rotation in association with the pivot-shift mechanism.[34,35]

Our second hypothesis was also accepted in that ACLR alone (in the setting of transected ACL and anterolateral structures) was unable to restore anterior translation at 0° and 30° or valgus rotation at 0° compared with the native state. The absolute degree of these differences, although statistically significant compared with the native state, may not be clinically significant. Our findings correspond well with recently published studies by Inderhaug et al.[32] and Geeslin et al.,[21] which also found that an isolated ACLR could not restore all native knee kinematics. However, they run contrary to the results reported by Noyes et al.,[36] which showed restoration of normal tibiofemoral translation as well as rotatory parameters in ACL-, ITB-, and ALL-deficient knees treated with only ACLR.

Our third hypothesis was also accepted in that the lateral extra-articular reconstruction techniques performed in conjunction with ACLR restored native knee kinematics without overconstraint after transection of the ACL and anterolateral structures. It is important to note that the ACLR plus ALR was the only reconstruction technique that did not show any significant kinematic differences in any parameter for any flexion angle tested compared with the native state.

The seemingly paradoxical increases in anterior translation with ACLR plus MLR, although statistically significant compared with the native state, may not be clinically relevant. Such counterintuitive findings have been noted in other biomechanical studies, such as the study by Nielsen et al.,[37] who showed a significant increase in internal rotation for their ACL- and ALL-reconstructed state but not for their ACL-reconstructed, ALL-deficient state. This may be related to the disruption of native tissues required for performing the MLR procedure and subsequent repetitive measures of only static contributions to knee stability. Even so, all knees were tested in the same standardized manner such that the key findings remain, showing no significant differences in any testing parameter between ALR and MLR in this study.

Generally speaking, it is ideal to protect the normal anatomy when performing any surgical procedure. One potential advantage of the ALR technique compared with other techniques is the avoidance of the LCL. If sockets are created at the anatomic femoral insertion location of the ALL as described by Dodds et al.[38] (8 mm and 4 mm proximal and posterior to the lateral epicondyle, respectively) or Kennedy et al.[39] (4.7 mm proximal and posterior to the LCL origin), an increased risk of iatrogenic LCL injury exists.[40] The ALR avoids this potential issue by using a femoral insertion at the lateral gastrocnemius tubercle, an anatomic landmark even more proximal and posterior to the lateral epicondyle. It is near the lateral intermuscular septum and the origin of the dITB, just above the over-the-top position of the femur in the vicinity of the isometric point of Krackow and Brooks.[41] As shown in Table 1 and Figures 3 and 4, the ALR femoral fixation was well away from the LCL origin (mean, 10.12 mm) to confer a comfortable degree of safety to this reconstruction technique. In addition, positioning a graft at this location could simulate the dITB including the capsulo-osseous fibers, as well as the ALL, ergo the designation “anterolateral reconstruction.”

Another potential clinical advantage of the ALR technique is the ability to avoid routing the graft underneath the LCL, further preventing the risk of trauma to this important anatomic structure. In addition, the ITB itself is not violated as is incumbent with a Lemaire procedure. The results after specific structure sectioning in this study, potential technique advantages, and kinematic equivalence to the MLR highlight the importance of both the ALL and the dITB for restraint to anterior translation and internal rotation (pivot shift) of the ACL-deficient knee and lend credence to the minimally invasive extra-articular technique described involving a single-bundle graft designed to incorporate the functions of the dITB and the ALL.[30]

A key point about this ALR procedure is that graft position is non-isometric, dictated by the chosen femoral position as it lengthens in extension but remains slightly lax in flexion; furthermore, the graft is fixed in extension. This similar non-isometric pattern of lengthening toward full extension and being lax in flexion was shown by Kittl et al.[17] for a graft positioned near the over-the-top position. The goal of this procedure is to provide optimal control of anterior translation and internal rotation toward full extension for controlling the pivot-shift phenomenon. In that regard, an important finding in this study was that the dITB was significantly more important than the ALL for controlling internal rotation at full extension. Moreover, this non-isometric pattern with the graft in extension preserved the normal knee internal rotation at 90° with no overconstraint.

A number of studies have investigated the biomechanical performance of anterolateral tenodesis in combination with intra-articular ACLR.[1,8,9,39] Only 3 have evaluated the procedures used in our work. Spencer et al.[31] performed an ALL reconstruction using braided suture tape and a modified Lemaire procedure using a 1-cm strip of the ITB. The ALL procedure used in their study was unable to restore internal rotation, whereas the Lemaire procedure had favorable effects, showing significant improvements in rotational control; however, the ALL femoral insertion was anterior and distal to the lateral epicondyle. This is a nonanatomic location. Furthermore, their construct was tightened in flexion, which is the position of shortest ligament length; this would allow for graft stretching to attain extension, where the pivot-shift mechanism comes into play. Unlike their study, our study was able to restore internal rotation to within native parameters with the graft position posterior and well proximal to the lateral epicondyle. Besides different femoral graft positions accounting for this difference, the other key is tensioning the graft in extension, allowing for laxity in flexion.

Inderhaug et al.[32] compared the kinematic patterns of several anterolateral procedures including a modified Lemaire procedure and an anatomic ALL reconstruction. The Lemaire tenodesis restored intact knee kinematics, whereas the ALL reconstruction left residual laxity. Inderhaug et al.[42] also performed a related study in which they examined the effect of the flexion angle on fixation. They found that the Lemaire procedure combined with ACLR restored all knee parameters when fixed at all flexion angles tested (0°, 30°, and 60°). The combined ACL and ALL reconstruction restored normal parameters only when fixed in full extension.

The recent study by Geeslin et al.[21] was similar to our study in trying to determine differences between reconstruction of the ALL and ITB; however, there were 2 important differences: First, their method of ALL reconstruction was different with respect to the femoral attachment site; theirs was referenced off the LCL attachment, whereas ours was referenced from the lateral gastrocnemius tubercle. Second, Geeslin et al. also showed overconstraint (defined as reduced anterior translation and decreased tibial internal rotation compared with the native state) in their extra-articular reconstructions. In our study, neither the ALR nor MLR groups showed any overconstraint. Notably, Geeslin et al. showed that reconstruction of the ACL alone could not fully restore native kinematics, which was corroborated by our study. However, it is important to note that effective ACLR is the cornerstone to restoring normal knee kinematics; Noyes et al.[43] showed that reconstruction of the anterolateral structures alone (both ITB and ALL) in the setting of a deficient ACL could not eliminate the pivot shift.

Limitations

The limitations of this study include those inherent to any cadaveric study. First, this time-zero biomechanical study does not account for soft-tissue healing or the effects of dynamic muscle forces, range of motion, and weight bearing. Although the lateral structures, including the ITB, were preserved a distance of 20 cm above the knee joint, sacrifice of the more proximal ITB could have altered overall knee kinematics. Another limitation to the study involves the biomechanical testing methods used. We used a biaxial materials testing machine with multi-position fixture to provide 3 *df*. Although this is not as elegant as use of a robotic arm providing 6 *df*, it is a valid model for simulating and assessing pivot shift and has been the most common methodology used for previous testing in this area. In addition, we chose to perform testing at 0°, 30°, and 90° of knee flexion and did not include any of the many other angles that could be considered. This choice was based on intended clinical application with respect to 30° of knee flexion being most important for pivot shift[44,45] and 90° being standard for assessing potential for overconstraint. Furthermore, other studies either have not tested higher flexion angles or have shown that higher flexion angles may not be as significant as the values tested in this study. Geeslin et al.[21] tested internal rotation at 15° and 30° without any higher flexion values. Anterior translation was tested at 30° and 90°. Schon et al.[46] and Nitri et al.[10] both showed that 45° and 60° flexion angles performed similarly to 30° without significant differences when studying ALL reconstruction based on a simulated pivot shift. Another limitation was the use of a relatively small number of cadaveric knees that were not from young, athletic individuals with spontaneously occurring ACL tears; as a result, factors contributing to abnormal knee kinematics may not have been replicated in this study. Specifically, none of the specimens showed hyperextension or recurvatum, which has been noted to place excess stresses on ACL grafts[47] and is considered a primary indication for lateral extra-articular reconstruction.[30] This presents a target of opportunity for further research. Because our cadaveric study showed that a standard all-inside ACLR could return most (but not all) of the motion parameters to within statistical equivalence of the native state, being able to replicate hyperextension may allow one to determine whether this subset of patients would truly benefit from an extra-articular augmentation.

Conclusions

ALR of the knee in conjunction with ACLR can return the knee to its native biomechanical state without causing overconstraint. The dITB plays a more critical role in controlling anterior translation and internal rotation at 0° than the ALL. The minimally invasive ALR was functionally equivalent to MLR for restoration of knee kinematics after ACLR.

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