An Overview of Clinically Relevant Biomechanics of the Anterolateral Structures of the Knee

Mitchell I. Kennedy, BS, Christopher M. LaPrade, MD,**
Andrew G. Geeslin, MD,† and Robert F. LaPrade, MD, PhD‡*

Summary: Residual anterolateral rotatory laxity following injury and reconstruction of the anterior cruciate ligament (ACL) has become a popular topic and has generated interest in characterizing the relative contribution from the anterolateral structures of the knee. Studies have reported on the anatomic and biomechanical features of the anterolateral ligament (ALL), revealing a role in restraining internal tibial rotation in both ACL-intact and ACL-deficient knees. The Kaplan fibers of the iliotibial band have also been reported to provide significant restraint to internal tibial rotation. The ACL is the primary restraint to anterior tibial translation, and both the proximal and distal bundles of the iliotibial band, with a divergent orientation, also provide significant static restraint against internal tibial rotation, and each bundle may have a distinct individual role. In the setting of ACL deficiency, subsequent sectioning of the ALL and Kaplan fibers led to further increases in anterior tibial translation. Residual rotatory laxity that may be seen clinically following ACL reconstruction may be attributable to an associated anterolateral structure injury even in the setting of an anatomic ACLR, leading to consideration for a concomitant anterolateral structure reconstruction. Studies evaluating the kinematic influence of anatomic ALL reconstruction or lateral extra-articular tenodesis have focused on internal rotation, axial plane translation, and anterior tibial translation, with variable results having been reported. Further, despite the long history of anterolateral structure reconstruction, most commonly with a lateral extra-articular tenodesis, the clinical use of these combined techniques is still in its relative infancy, and long-term patient outcomes have yet to be published for relative comparisons.

Key Words: anterolateral ligament—iliotibial band—Kaplan fibers—anterior cruciate ligament—internal rotation—laxity.

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The condition of residual anterolateral rotatory laxity following injury and reconstruction of the anterior cruciate ligament (ACL) has received significant attention in recent years, mainly due to the large amount of literature pertaining to the anterolateral structures of the knee. Beginning with the description by Segond in 1879, a pearly, fibrous band has been described spanning the anterolateral aspect of the knee and is believed to restrain tibial internal rotation. Small anterolateral tibial avulsion fractures associated with ACL injuries have been attributed to this structure and named for the original source (ie, Segond fracture).[1] This structure was referred to by variable names until it was ultimately deemed the anterolateral ligament (ALL).[2,3]

Further studies reported on the anatomic attachment sites and biomechanical features of the anterolateral ligament (ALL), and it was found that this structure withstood significant force before injury, and sectioning resulted in increased internal tibial rotation in both ACL-intact and ACL-deficient knees; the latter having a greater increase in rotation.[4–8] In addition to the ALL, the Kaplan fibers of the iliotibial band (ITB) have been reported to provide significant restraint against internal rotation of the tibia.[6,9,10] Foundational quantitative anatomic characterization of the Kaplan fibers was recently performed by Godin et al,[11] supporting future studies to characterize a potential individual role for these structures (Fig. 1).

ANATOMY

Structures of the anterolateral aspect of the knee that primarily provide restraint to internal tibial rotation consist of the ITB (including the Kaplan fibers) and ALL. Reports on the characteristics of the ITB are relatively variable. From the original description by Kaplan of the "longitudinal fibers" adhering firmly to the lateral intermuscular septum, further characterizations have emerged. Lobenhoffer and colleagues reported 3 distinct segments: the supracondylar bundle, fibers near the intermuscular septum, and a

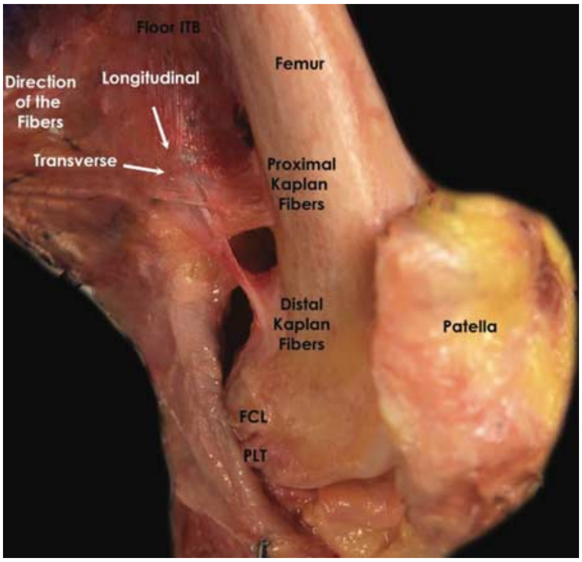

FIGURE 1. Cadaveric specimen demonstrating the fiber orientation of the proximal and distal iliotibial band fibers (Kaplan fibers) in a right knee. FCL indicates fibular collateral ligament; ITB, iliotibial band; PLT, popliteus tendon. Reprinted with permission from SAGE Publications Inc., from Godin et al.[11] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder. full color online

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From the *Steadman Philippon Research Institute; ‡The Steadman Clinic, Vail, CO; and †Borgess Orthopedics, Kalamazoo, MI.

The authors declare that they have nothing to disclose.

For reprint requests, or additional information and guidance on the techniques described in the article, please contact Robert F. LaPrade, MD, PhD, at rlaprade@thesteadmanclinic.com or by mail at 181 West Meadow Drive, Suite 400, Vail, CO 81657. You may inquire whether the author(s) will agree to phone conferences and/or visits regarding these techniques.

retrograde tract extending proximally from the Gerdy tubercle.[12,13] Godin and colleagues most recently described the Kaplan fibers as 2 distinct layers of the distal ITB (proximal and distal) and 3 bony landmarks; the proximal bundle coursing from the undersurface of the superficial ITB to the proximal ridge of the distal femoral diaphysis by a transverse orientation, 53.6 mm proximal to the lateral epicondyle, whereas the distal bundle originated from the superficial ITB and coursed from proximal and lateral to distal and medial before inserting on a bony prominence on the supracondylar flare of the distal femur, 31.4 mm proximal to the lateral epicondyle[11] (Fig. 2).

Lutz et al[9] reported that the distal insertion of the Kaplan fibers shared an attachment with the superficial part of the iliotibial band on the subcondylar tubercle, and inserted proximally at the diaphyseal-metaphyseal junction of the femur opposite the linea aspera. Upon removal of the iliotibial band, the anterolateral capsule was identified.[4,9] The ALL was reported to be the most anterior aspect of the "triangular anterolateral capsular complex."[9] The posterior aspect consisted of capsular fibers inserting onto the FCL, and the distal aspect inserted on the tibia.[9] This triangular formation measured 43.00 ± 4.43 mm for the posterior edge, 24.22 ± 5.65 mm for the base, and 49.88 ± 4.65 mm for the anterior edge (Fig. 3).

At approximately 30 degrees of knee flexion and internal rotation, the ALL becomes noticeably taut.[4] Among firm bony attachments, the ALL coursed anterolaterally from its femoral attachment, slightly posterior and proximal from the femoral attachment of the FCL, 2.7 mm and 2.8 mm, respectively, and 26.1 mm [95% confidence interval (CI), 5.6-8.4 mm] proximal to the joint line.[4] Other variable findings have been reported for the femoral attachment, with its relative location ranging from anterior-distal to posterior-proximal to the FCL femoral attachment.[4,14–20] With slight variations in syntax, the tibial attachment was consistently reported across all studies to insert approximately mid-way between the center of the Gerdy tubercle and the anterior margin of the fibular head, 24.7 mm posterior and 26.1 mm proximal and slightly anterior, respectively, and 9.5 mm (95% CI, 8.6-10.4 mm) distal to the joint line.[4] Fine fascial expansions of the ALL were also found which extended anterior and distal over the FCL attachment adjacent to the lateral epicondyle, in addition to an attachment between the ALL and lateral meniscus (Fig. 4).

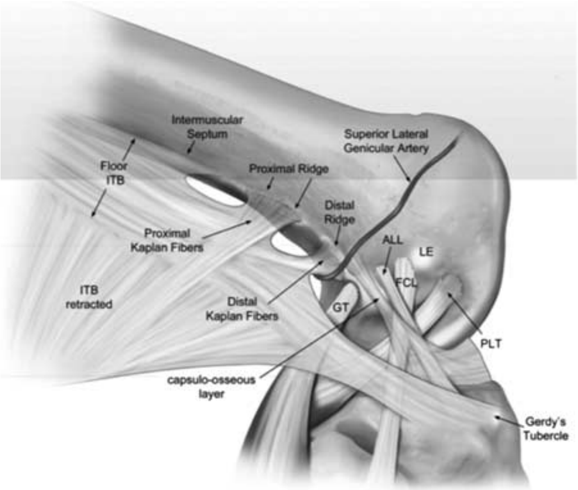

FIGURE 2. Illustration depicting the insertions of the proximal and distal Kaplan fibers on the proximal and distal ridges, respectively, in a right knee. Note the relationship of the superior lateral genicular artery with the distal Kaplan fibers. ALL indicates anterolateral ligament; FCL, fibular collateral ligament; GT, lateral gastrocnemius tendon; ITB, iliotibial band; LE, lateral epicondyle; PLT, popliteus tendon. Reprinted with permission from SAGE Publications Inc., from Godin et al.[11] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder.

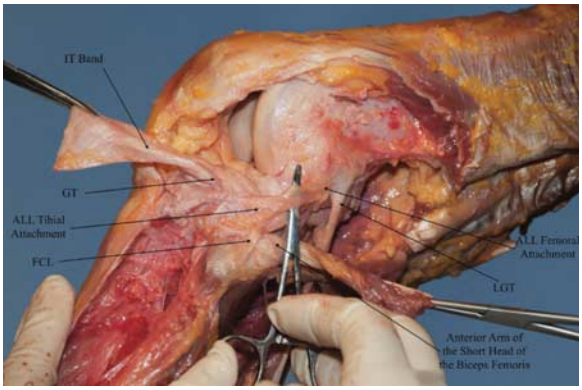

FIGURE 3. The attachments of the main lateral knee structures relative to the anterolateral ligament (lateral view, left knee). The anterolateral ligament courses distal and lateral over the fibular collateral ligament to its attachment midway between the fibular head and the Gerdy tubercle. ALL indicates anterolateral ligament; FCL, fibular collateral ligament; GT, Gerdy tubercle; IT, iliotibial; LGT, lateral gastrocnemius tendon. Reprinted with permission from SAGE Publications Inc., from Kennedy et al.[4] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder. full color online

BIOMECHANICS

Structural Properties and Length Change

In a study by Rahnemai-Azar et al,[21] the anterolateral capsule and ITB structures were found to have a relative thickness of 4.0 ± 1.5 and 2.0 ± 0.5 mm, respectively. Maximum load-at-failure and stiffness values were determined subsequently, finding the capsule withstanding a force of 319.7 ± 212.6 N with a stiffness of 26.0 ± 11.5 N/mm, and the ITB with a load to failure force of 487.9 ± 156.9 N and a stiffness of 73.2 ± 24.1 N/mm.[21] Godin et al[11] more specifically measured load-to-failure of the individual bundles of the distal deep (Kaplan) fibers, and reported values of 71.3 N (95% CI, 41.2-101.4 N) and 170.2 N (95% CI, 123.6-216.8 N), with respective stiffness measurements of 22.6 N/mm (95% CI, 9.8-35.4 N/mm) and 36.3 N/mm (95% CI, 23.2-49.4 N/mm) (Table 1).

In a study by Kennedy et al,[4] the ALL sustained an average maximum load of 175 N (95% CI, 139-211 N), with a measured stiffness of 20 N/mm (95% CI, 16-25 N/mm). Upon completion of the load-to-failure testing, the most common occurrence of failure was of Segond-type avulsion fractures of the anterolateral tibia[4] (Table 2).

Across multiple flexion angles ranging from full extension (0) to 90 degrees, Kennedy et al[4] reported that the respective length of the ALL varied from 36.8 mm (95% CI, 34.9-38.8 mm) to 41.6 mm (95% CI, 28.4-44.8 mm), respectively, whereas Dodds et al[16] found the length to increase upon internal rotation, and decrease upon external rotation. Upon internal rotation, this length has been reported to reach 49.88 ± 5.30 mm.[9] Kernkamp and colleagues calculated ALL length utilizing nonweight

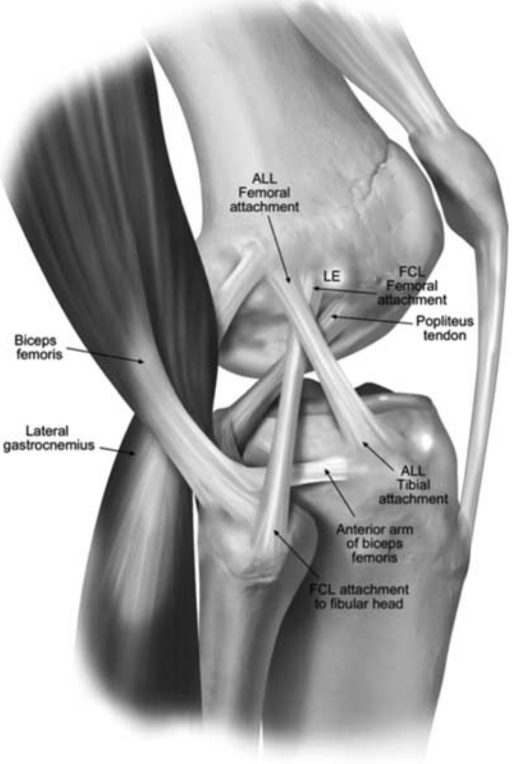

FIGURE 4. The osseous landmarks and attachment sites of the main structures of the lateral knee (iliotibial band and non-ALL-related capsule removed) (lateral view, right knee). The ALL attaches posterior and proximal to the FCL femoral attachment and courses anterodistal to its anterolateral tibial attachment between the center of the Gerdy tubercle and the anterior margin of the fibular head. The short head of the biceps femoris tendon has a direct arm that attaches to the fibular head and an anterior arm that attaches to the anterolateral tibia. ALL indicates anterolateral ligament; FCL, fibular collateral ligament; LE, lateral epicondyle. Reprinted with permission from SAGE Publications Inc., from Kennedy et al.[4] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder.

bearing MR imaging and compared 2 commonly referenced femoral attachment sites; they reported that the ALL-Claes described attachment (anterior-distal to the FCL) measured 33.9 mm (95% CI, 32.5-35.4 mm) and the ALL-Kennedy described attachment (posterior-proximal to the FCL) measured 44.0 mm (95% CI, 41.8-46.2 mm).[4,5,15] For step-up motion, over approximately 55 degrees of flexion as compared with each respective MR length, both ALL-Claes and ALL-Kennedy femoral attachments showed consistent and significant decreases in length from lower flexion angles, of 21.2% and 24.3%, respectively.[5] Similarly, sit-to-stand measurements were observed to consistently result in a decrease in ALL length by 35.2% (95% CI, 28.2-42.2) and 39.2% (95% CI, 32.4-46.0) over approximately 90 degrees of knee flexion.[5] In conclusion, ALL length measurements were consistently lower when the knee was at lower knee flexion angles.

Internal Rotation Restraint

Initial internal rotation restraint has been observed by tension of the posterior fibers of the iliotibial band.[9] Because of their anatomic attachment sites, the Kaplan fibers approximate the ITB to the lateral epicondyle, allowing the distal portion of the iliotibial band to act as a ligament and tighten amidst internal rotation; sectioning of the Kaplan fibers may effectively result in a complete release of restraint by the iliotibial band.[9]

The previously described biomechanical properties and anatomic insertions of both the proximal and distal Kaplan bundles of the ITB, the divergent orientation of each bundle may also provide a distinct and significant static restraint against internal tibial rotation.[11] Kittl et al[6] reported that tibial internal rotation above 30 degrees of knee flexion was primarily restrained by the superficial and deep layers of the ITB, accounting for > 50% of total resistance; this portion increased to 74% at 60 degrees of flexion. In addition, their results revealed a relatively small contribution of the ALL in restraining tibial internal rotation.[6] Wroble et al[10] sectioned the entire anterolateral structures of the knee and reported a significant increase in internal rotation at 30 degrees of knee flexion and above.

During a simulated pivot shift test, Rasmussen and colleagues reported a significant increase in axial plane translation

TABLE 1. Biomechanical Properties and Failure Locations of the Proximal and Distal Kaplan Fibers of the Iliotibial Band

		Proximal Kaplan Fibers				Distal Kaplan Fibers			
Specimen No.	Age (y)	Maximum Load (N)	Stiffness (N/mm)	Elastic Limit (N)	Failure Location	Maximum Load (N)	Stiffness (N/mm)	Elastic Limit (N)	Failure Location
1	55	50.3	12.4	38.6	Midsubstance	258.0	57.2	258.0	Midsubstance
2	62	52.2	16.1	29.0	Midsubstance	223.8	59.7	187.1	Midsubstance
3	56	36.2	5.5	10.2	Midsubstance	150.8	38.7	119.7	Midsubstance
4	36	70.6	12.2	11.0	Midsubstance	183.0	19.9	26.9	Midsubstance
5	49	75.7	14.3	22.5	Midsubstance	191.0	44.1	172.5	Midsubstance
6	52	49.0	18.0	48.3	Midsubstance	107.5	20.9	38.5	Midsubstance
7	57	20.0	11.6	20.0	Midsubstance	175.5	27.1	63.7	Midsubstance
8	59	118.7	45.1	92.3	Midsubstance	170.1	31.7	78.7	Midsubstance
9	58	136.3	47.4	111.7	Midsubstance	192.4	50.7	176.2	Midsubstance
10	59	104.1	43.6	100.7	Midsubstance/ partial bony avulsion	49.6	12.9	22.9	Midsubstance
Mean	54.3	71.3	22.6	48.4	—	170.2	36.2	114.4	—
(95% CI)		(41.2-101.4)	(9.8-35.4)	(17.4-79.4)		(123.6-216.8)	(23.2-49.4)	(49.7-179.1)	

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TABLE 2. Ultimate Tensile Loads and Failure Locations for Structural Testing of the Anterolateral Ligament*

Specimen No.	Age (y)	Load-at-Failure (N)	Stiffness (N/mm)	Mechanism of Failure
1	65	93	15	Ligamentous tear at femoral location
2	55	207	27	Segond fracture
3	39	357	39	Ligamentous tear at femoral location
4	64	189	21	Ligamentous tear at femoral location
5	63	192	30	Segond fracture
6	68	93	15	Midsubstance tear
7	67	183	14	Midsubstance tear
8	59	159	28	Segond fracture
9	66	168	14	Midsubstance tear
10	59	183	15	Midsubstance tear
11	50	213	17	Ligamentous tear at femoral location
12	48	144	13	Segond fracture
13	60	93	9	Segond fracture
14	69	193	26	Ligamentous tear at femoral location
15	41	156	20	Segond fracture
Mean†	58	175 (139-211)	20	—

*Values were determined by Instron pull-to-failure testing of the anterolateral ligaments.

†Mean with the 95% CI, calculated by the use of the appropriate *t* score.

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and internal rotation following a combined injury to the ACL and ALL at all flexion angles (0 to 120 degrees), whereas an isolated ACL injury resulted in a small but significant increase in internal rotation at lower flexion angles (0 to 45 degrees). Noyes and colleagues found minor added increases in pivot-shift compartment translations and tibial internal rotations from ALL or ITB sectioning in the ACL deficient knee, whereas Parsons and colleagues similarly found the ALL to contribute to internal rotatory restraint, more specifically at higher degrees of knee flexion (> 35 degress).[7,8,22] In addition, in an ACL deficient knee, anterior tibial translation increased following sectioning of the ALL.[8] The authors theorized that these results demonstrate that the residual rotatory instability commonly seen following ACL reconstruction (ACLR) may be attributable to deficiency and failure to address the ALL.[8]

Biomechanics of Anterolateral Reconstructions

A few recent studies have evaluated the biomechanics of a reconstructed ALL following an anatomic ALL reconstruction (ALLR) or lateral extra-articular tenodesis (LET), with most of the studies focusing on internal rotation, axial plane translation during a simulated pivot shift, and anterior tibial translation. However, these recent studies have reported conflicting results, as summarized below, and further investigation is warranted (Fig. 5).

A recent robotic study by Nitri et al[23] reported that, when pooling across all flexion angles, internal rotation was significantly decreased after an ACLR and ALLR in comparison to the ACLR with an ALL sectioned state both during a simulated pivot shift and with an applied internal rotation torque. In contrast, Spencer et al[24] reported that both an anatomic ALLR and a LET did not significantly reduce internal rotation in comparison to all other sectioning states during a simulated early-phase pivot shift when using a hip simulator testing design. Inderhaug et al[25] performed testing in a 6 degree-of-freedom rig with a concomitant ACLR and multiple methods of fixing the anterolateral complex: ALLR, modified MacIntosh LET, deep (medial) modified Lemaire LET, and superficial (lateral) modified Lemaire LET. At 20 N and 40 N of graft tension, the modified MacIntosh LET and deep modified Lemaire LET were not significantly different from the intact

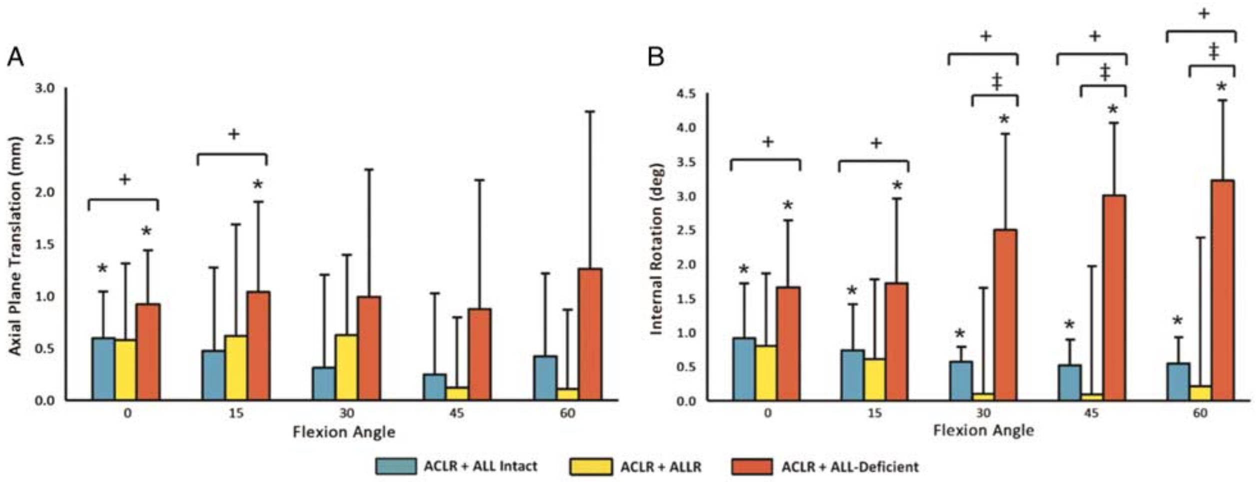

FIGURE 5. Change from intact state for axial plane translation (A) and internal rotation (B) in response to a simulated pivot shift (coupled 5-N m internal rotation and 10-N m valgus torques) for ACLR with ALL–intact, ACLR with ALLR, and ACLR with ALL-deficient states. Statistically significantly different *from intact, $^{+}$between ACLR 1 ALL-intact and ACLR 1 ALL-deficient, and ^{z}between ACLR 1 ALLR and ACLR 1 ALL-deficient ($P < 0.05$). ACLR indicates anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction. Reprinted with permission from SAGE Publications Inc., from Nitri et al.[23] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder. full color online

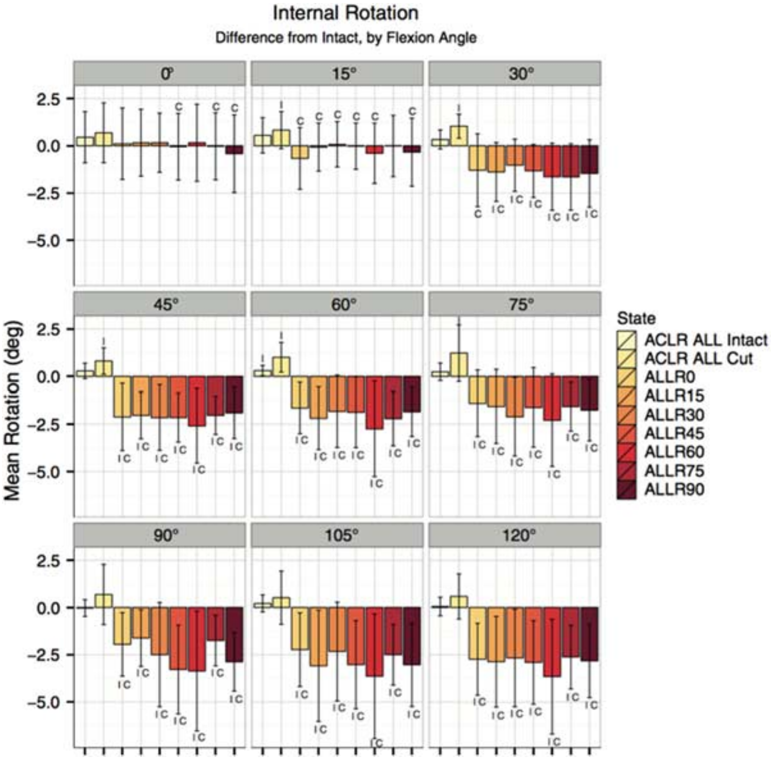

FIGURE 6. Mean changes in internal rotation (error bars represent 1 SD) in response to an applied 5-N m internal rotation torque after ACLR 1 intact ALL, ACLR 1 ALL cut, and ACLR 1 ALLR with varying graft fixation angles. Significantly different ($P<0.05$) $^{\text{I}}$from intact state and $^{\text{C}}$from ACLR with ALL cut state. ACLR indicates anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction. Reprinted with permission from SAGE Publications Inc., from Schon et al.[26] Copyright SAGE Publications Inc., Thousand Oaks, CA. All permission requests for this image should be made to the copyright holder. full color online

knee in terms of internal rotation at any flexion angles. However, the ALLR was significantly different from the intact knee at 50, 60, and 70 degrees at 20 N of graft tension and 0 and 30 degrees at 40 N. The superficial modified Lemaire LET was significantly different from the intact state at 10, 40, and 50 degrees, at which angles the knee was over constrained in internal rotation at both 20 N and 40 N of graft tension. Lastly, Schon and colleagues reported an ACLR plus an anatomic ALLR resulted in significant rotational over constraint of the knee joint for most flexion angles and for all ALLR graft fixation angles. This over constraint was present even though the anatomic ALLR was able to significantly decrease internal rotation in comparison to the ALL sectioned state at the majority of flexion angles.[26] As studies have shown a restoration to biomechanics of the knee relative to intact structures using newly modified procedures, over constraint remains a potential issue that has yet to be determined in the clinical outcomes setting (Fig. 6).

Furthermore, multiple studies have investigated the effects of an ACLR and ALLR on axial plane translation and anterior tibial translation. Nitri et al[23] reported that axial plane translation was significantly decreased after an ACLR and ALLR, when pooled across all flexion angles, in comparison to the ACLR with a sectioned ALL state during a simulated pivot shift test. In addition, they reported that after an ACLR with an ALLR, there was significantly increased anterior tibial translation in comparison to the intact knee with an applied anterior tibial load; however, there were no significant differences between an ACLR with an intact ALL and ACLR with ALLR.[23] During a simulated early-phase pivot-shift, Spencer et al[24] reported the ALLR with a LET resulted in significantly decreased anterior tibial translation in comparison to the sectioned ALL state, whereas the ALLR alone did not significantly reduce anterior tibial translation. Using the same testing groups as above, Inderhaug and colleagues reported the ACLR and ALLR group resulted in significantly increased anterior tibial translation at 20 N of graft tension in comparison to the intact state at all angles between 0 and 70 degrees (with the exception of 10 degrees), but was not significantly different from the intact knee at 40 N at any flexion angle.[25] In addition, the modified Lemaire and the modified MacIntosh were found to significantly over constrain the knee in anterior tibial translation in comparison with the intact knee at 70 to 90 and 80 degrees, respectively. Lastly, Schon and colleagues reported that during a simulated pivot-shift, there were multiple angles of ACLR and anatomic ALLR graft fixation (15, 45, and 75 degrees) that resulted in significant over constraint in axial plane translation in comparison to the intact knee at 45 and 60 degrees of knee flexion. They also reported that all graft fixation angles of an ACLR and an anatomic ALLR resulted in similar anterior translation to the ACLR and ALL sectioned state during an applied anterior load.[26]

CONCLUSIONS

The ALL has been consistently identified anatomically across the anterolateral aspect of the knee joint, and seems to display a small, but significant role in restraint of internal tibial rotation, which seems to be more prominent with more extensive dissection of surrounding structures. Recent research pertaining to the deep fibers of the distal ITB (Kaplan fibers) has clarified the anatomic location of its attachment sites in addition to describing radiographic landmarks. An approach for reestablishing native biomechanics following the development of instability because of injury of these anterolateral knee structures is not yet consistent across the literature. Further, reconstruction of the ALL is still highly debated, with mid-term outcomes not yet available. The LET has a rich history, although modern application of these techniques combined with intra-articular ACL reconstruction also requires greater follow-up. With further research to amend these conflicting findings on the biomechanics of the ALL, and further definition of an ideal lateral extra-articular procedure, a proper surgical technique may be established to possibly improve outcomes following combined injury to the ACL and anterolateral knee structures.

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