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SYMPOSIUM: IMPROVING CARE FOR PATIENTS WITH ACL INJURIES: A TEAM APPROACH

High Interspecimen Variability in Engagement of the Anterolateral Ligament: An In Vitro Cadaveric Study

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Abstract

Background Anterolateral ligament (ALL) reconstruction as an adjunct to anterior cruciate ligament (ACL) reconstruction remains a subject of clinical debate. This uncertainty may be driven in part by a lack of knowledge regarding where, within the range of knee motion, the ALL begins to carry force (engages).

Questions/purposes (1) Does the ALL engage in the ACL-intact knee; and (2) where within the range of anterior tibial translation occurring in the ACL-sectioned knee does the ALL engage?

Methods A robotic manipulator was used to measure anterior tibial translation, ACL forces, and ALL forces in 10 fresh-frozen cadaveric knees (10 donors; mean age, 41 ± 16 years; range, 20-64 years; eight male) in response to applied multiplanar torques. The engagement point of the ALL was defined as the anterior tibial translation at which the ALL began to carry at least 15% of the force carried by the native ACL; a threshold of 15% minimized the sensitivity of the engagement point of the ALL. This engagement point was compared with the maximum anterior tibial translation permitted in the ACL-intact condition using a paired Wilcoxon signed-rank test ($p < 0.05$). Normality of each outcome measure was confirmed using Kolmogorov-Smirnov tests ($p < 0.05$).

Results The ALL engaged in five and four of 10 ACL-intact knees in response to multiplanar torques at 15° and 30° of flexion, respectively. Among the nine of 10 knees in which the ALL engaged with the ACL sectioned, the ACL-intact motion limit, and ALL engagement point, respectively, averaged 1.5 ± 1.1 mm and 5.4 ± 4.1 mm at 15° of flexion and 2.0 ± 1.3 mm and 5.7 ± 2.7 mm at 30° of flexion. Thus, the ALL engaged 3.8 ± 3.1 mm (95% confidence interval [CI], 1.4-6.3 mm; p = 0.027) and 3.7 ± 2.4 mm (95% CI, 2.1-5.3 mm; p = 0.008) beyond the maximum anterior tibial translation of the ACL-intact knee at 15° and 30° of flexion, respectively.

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Each author certifies that his institution approved or waived approval for the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.
This work was performed within the Department of Biomechanics at the Hospital for Special Surgery, New York, NY, USA.

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Conclusions In this in vitro, cadaveric study, the ALL engaged in up to half of the ACL-intact knees. In the ACL-sectioned knees, the ALL engaged beyond the ACL-intact limit of anterior subluxation on average in response to multiplanar torques, albeit with variability that likely reflects interspecimen heterogeneity in ALL anatomy.

Clinical Relevance The findings suggest that surgical variables such as the joint position and tension at which lateral extraarticular grafts and tenodeses are fixed might be able to be tuned to control where within the range of knee motion the graft tissue is engaged to restrain joint motion on a patient-specific basis.

Introduction

Anterior cruciate ligament (ACL) rupture can be associated with concomitant injury to the portion of the anterolateral capsule that has been described as the anterolateral ligament (ALL), a secondary stabilizing ligament of the knee [2, 8, 19, 27, 32]. Therefore, the biomechanical role of the ALL has been studied to discern its contribution to knee function in addition to providing guidance and rationale for its reconstruction [4, 10, 16, 27, 31–33]. However, previous biomechanical approaches do not consider where, within the ROM of the tibiofemoral joint, the ALL begins to carry force and restrain motion (that is, where it engages). For example, the ALL is known to carry appreciable force (approximately 50 N on average) at the peak load applied to the ACL-sectioned knee [32]. Studies also report that sectioning both the ALL and the ACL results in more laxity in response to multiplanar torques than sectioning the ACL alone [27, 32, 35]. Together, these findings suggest that the ALL is an important restraint in the setting of ACL deficiency, but it remains unclear whether the ALL begins to carry appreciable force within the ROM of the intact knee.

Knowing if and where within the tibiofemoral ROM the ALL engages on a patient-specific basis is important because it could inform more personalized surgical guidelines to mitigate tibiofemoral instability and restore function. For example, in the ACL-deficient knee, if the ALL engages closer to the ROM of the intact knee in response to the same applied loads, it may play a critical role in restraining knee motions. Therefore, it might be a candidate for surgical reconstruction or augmentation. Conversely, if the ALL only engages beyond the ROM of the intact knee, it may play a less critical role in maintaining the joint within its intact ROM; therefore, augmenting it through extraarticular tenodesis or anatomic ALL reconstruction could overconstrain the knee or cause the graft to bear supraphysiological loads [9, 23, 28, 29]. In addition to determining whether these procedures should be conducted, characterizing ALL engagement on a patient-specific basis could inform surgical decisions such as the knee flexion angle, axial tibial rotation, and tension at which the graft should be fixed [16].

The objective of this study was to characterize the engagement of the ALL in response to multiplanar torques, a loading scenario known to generate anterior subluxation of the tibia [5, 12]. To this end, we asked (1) does the ALL engage in the ACL-intact knee; and (2) where within the range of anterior tibial translation occurring in the ACL-sectioned knee does the ALL engage? We hypothesized that the ALL would engage in a minority of knees with the ACL intact. Moreover, we hypothesized that, in the ACL-sectioned knee, the ALL would engage beyond the range of anterior tibial translation of the ACL-intact knee.

Materials and Methods

Ten fresh-frozen human cadaveric knees from 10 different donors were obtained from a nonprofit anatomic donation organization for testing (mean age, 41 ± 16 years; range, 20-64 years; eight male). Medial parapatellar arthrotomies, CT scans, and reviews of the medical histories of each knee were performed to confirm that the specimens were uninjured and free of malalignment, chondral damage, prior surgery, osteophytes, and other osseous abnormalities. The femur and tibia were fixed to a six degrees-of-freedom robotic manipulator (absolute position accuracy: ± 0.3 mm; payload: 165 kg) (ZX165U; Kawasaki Robotics, Wixom, MI, USA) that was equipped with a universal force (F)/moment (T) sensor (resolution: Fx = Fy = 0.13 N, Fz = 0.25 N, Tx = Ty = Tz = 0.008 Nm; limits: Fx = Fy = 1500 N, Fz = 3750 N, Tx = Ty = Tz = 240 Nm) (Theta; ATI, Apex, NC, USA) [11]. A subset of these biomechanical data was published in a previous study of the ALL by Thein et al. [32], but with this work, we present a novel means of characterizing ligament function that quantifies where within the ROM the ALL engages in the ACL-intact and -sectioned knee. Details on specimen preparation, definition of the anatomic coordinate system, and joint preconditioning can be found in our previous work [11, 32].

After preconditioning, multiplanar valgus and internal rotation torques were applied to the tibia. These torques, when applied in combination, generate anterior translation of the tibia relative to the femur [12, 14, 22], which is a hallmark characteristic of giving-way events after ACL rupture [6, 18]. With the knee starting from 15° and 30° of

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passive flexion, valgus torque was increased to 8 Nm in the following increments: 0.8, 2, 4, 6, 7, and 8 Nm. Then, with valgus torque held constant at 8 Nm, internal rotation torque was increased to 4 Nm in the following increments: 0.4, 0.8, 1.2, 2, 3, and 4 Nm. These applied torques are within a range known to generate anterior subluxation of the tibia in the ACL-deficient knee [22, 27, 29]. The study focused on 15° and 30° flexion because both the ACL and the ALL carry force at these angles [14, 32], and these flexion angles are within a range where clinical and functional pivoting events occur [6, 17, 18]. With the ACL intact, changes in the position and orientation of the tibia in response to the applied loads were determined under load control. The resultant force carried by the ACL throughout the ACL-intact kinematic trajectory was then determined using the principle of superposition [34]. This was done by sectioning the ACL and then repeating the kinematic path of the ACL-intact knee while measuring the reaction forces. Subsequently, multiplanar torques were applied to the knee under load control to determine the kinematics of the ACL-sectioned knee.

The protocol used to identify and section the ALL has been described previously: the distal insertion was identified by applying varus and internal rotation moments while flexing the knee from 60° to 90°, and the proximal insertion either fanned around or blended in with the femoral insertion of the lateral collateral ligament (Fig. 1) [3, 4, 32]. The resultant forces carried by the ALL throughout the ACL-intact and -sectioned kinematic trajectories were then determined using the principle of superposition [34]. This was done by sectioning the ALL from its insertions and the adjacent capsule and then moving the knee through the kinematic paths of the ACL-intact and -sectioned condition again while measuring the reaction forces. The anterolateral capsule carries both transverse and axial forces [7]; however, only the net force carried across the tibiofemoral joint by the ALL was measured because component force data were not necessary to answer the research question of where within the range of anterior tibial translation the tissue began to carry force.

In each condition, the ALL was considered to have engaged when it carried 15% of the resultant force borne by the ACL in the same knee in response to the applied multiplanar torques. In other words, the force borne by the ACL, a primary stabilizer against multiplanar torques, served as a reference from which ALL engagement could be defined in each knee. The force carried by the ACL in response to multiplanar torques, respectively, averaged 100 ± 27 N and 104 ± 36 N at 15° and 30° of flexion. The threshold of 15% of the ACL force used to identify ALL engagement, respectively, averaged 15 ± 4 N and 16 ± 5 N at 15° and 30° of flexion. Variations in the engagement point of the ALL were not related to variations in this force threshold (adjusted $r^2 \leq 0.14$; $\beta = 0.52 \pm 1.04$ at 15°, 0.11 ± 0.54 at 30°; $p \geq 0.17$). The threshold of 15% was chosen for the following reasons. As the threshold was increased from 0% to 15%, the engagement point of the ALL became less sensitive to changes in the threshold. However, thresholds higher than 15% began to exceed the maximum force carried by the ALL in multiple knees, decreasing the number of ALLs that engaged in the ACL-sectioned condition (Supplemental Fig. 1 [Supplemental materials are available with the online version of *CORR*®.]). In the ACL-sectioned condition, the engagement point of the ALL was the focus of this work (rather than the number of ALLs that engaged); thus, a threshold that optimized the number of data points while minimizing sensitivity was most appropriate for this study.

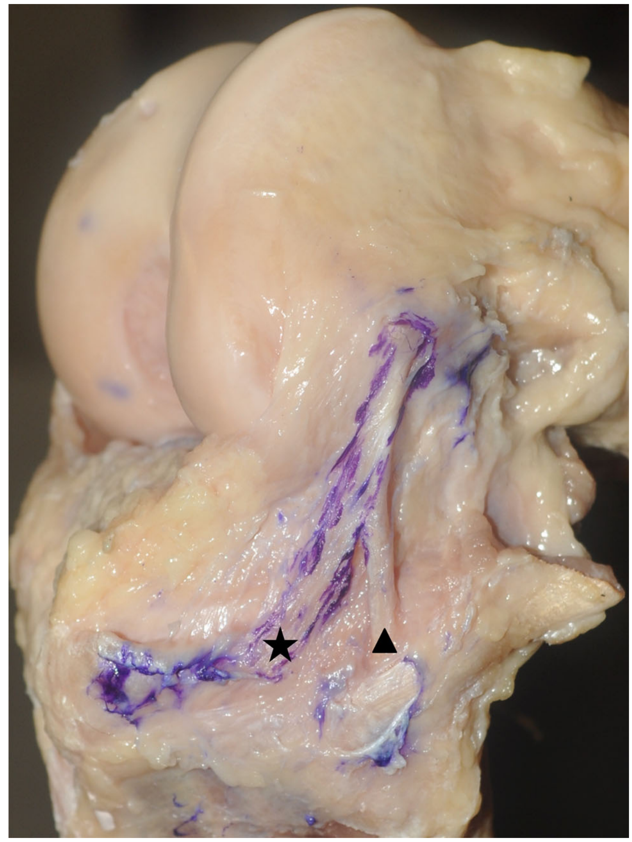

Fig. 1 The dissected ALL is outlined with purple ink, and its tibial insertion is marked with a black star. The tibial insertion of the lateral collateral ligament is marked with a black triangle.

The AP position where ALLs met the force threshold of 15% peak ACL force (that is, engaged) in the ACL-sectioned knee was identified as its “engagement point,” measured in millimeters (Fig. 2). Ligament forces as a function of anterior tibial translation were targeted because anterior subluxation is the hallmark feature of giving-way events that occur in the ACL-deficient knee; it is also the direction of greatest increase in motion in response to multiplanar torques as a result of sectioning the ACL

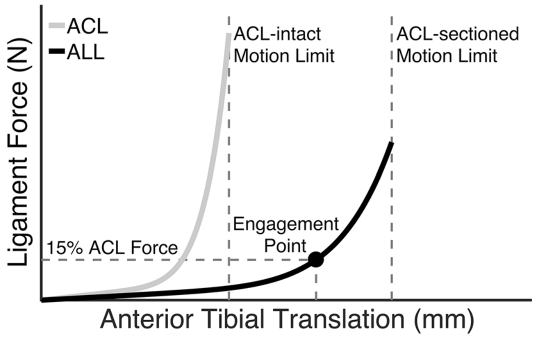

Fig. 2 This illustration showing resultant forces in the ALL and ACL as a function of anterior tibial translation in response to combined valgus and internal rotation torques. Dashed, vertical gray lines indicate the anterior limits of motion in the ACL-intact and -sectioned conditions as well as the engagement point of the ALL in the ACL-sectioned condition. The dashed, horizontal, gray line marks the engagement threshold of the ALL (15% ACL force). In each knee, the engagement point of the ALL, measured in millimeters, was compared with the anterior motion limit of the ACL intact knee, also measured in millimeters.

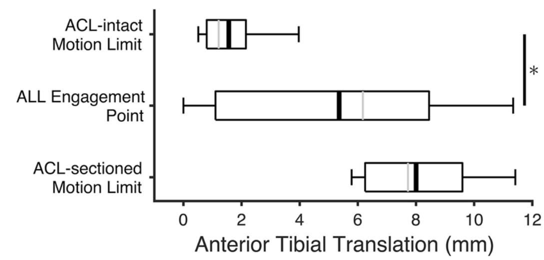

Fig. 3 At 15° of flexion, maximum anterior tibial translation of the ACL-intact and -sectioned knee compared with the engagement point of the ALL after the ACL was sectioned. Thick, black lines and thin, gray lines represent means and medians, respectively, and boxes span interquartile ranges. *$p < 0.05$.

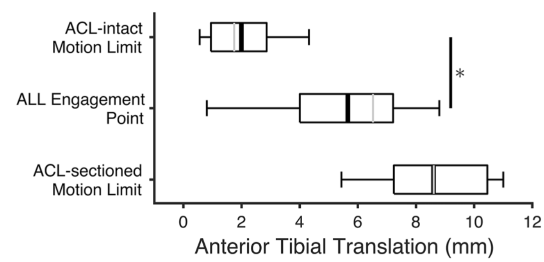

Fig. 4 At 30° of flexion, maximum anterior tibial translation of the ACL-intact and -sectioned knee compared with the engagement point of the ALL after the ACL was sectioned. Thick, black lines and thin, gray lines, respectively, represent means and medians, and boxes span interquartile ranges. Outliers are indicated with black circles. *$p < 0.05$.

[1, 12, 14, 15]. The maximum anterior tibial translations of the ACL-intact and -sectioned knee were determined relative to the initial position of the knee, which was identified from the previously determined flexion path. The engagement point of each ALL in the ACL-sectioned condition was then compared with the maximum anterior tibial translation of the ACL-intact and -sectioned knee (ie, ACL-intact and -sectioned motion limits) (Fig. 2). Additionally, ALL engagement points were normalized to the increase in maximum, anterior tibial translation between the ACL-intact and -sectioned knee (the ACL-intact limit was 0% and the ACL-sectioned limit was 100%). This permitted comparison of ALL engagement points that were independent of interspecimen variability in ACL-intact and -sectioned limits of anterior tibial translation.

To address the first research question, a count of ALLs that engaged in the ACL-intact knee was reported. To address the second research question, the engagement point of the ALL in the ACL-sectioned knee was compared with the ACL-intact motion limit using a paired, nonparametric Wilcoxon signed-rank test ($p < 0.05$). Although Kolmogorov-Smirnov tests confirmed that the data were normally distributed ($p < 0.05$), more conservative, nonparametric statistical analyses were used due to the low sample size.

Results

The ALL engaged in the ACL-intact condition in five of 10 knees at 15° of flexion and in four of 10 knees at 30° of flexion in response to the combined multiplanar torques.

In the nine (of 10) ACL-sectioned knees in which the ALL engaged, at 15° flexion, the ACL-intact motion limit and the engagement point of the ALL averaged 1.5 ± 1.1 mm and 5.4 ± 4.1 mm, respectively (Fig. 3); thus, the ALL engaged 3.8 ± 3.1 mm beyond the ACL-intact motion limit on average (95% confidence interval [CI], 1.4-6.3 mm) ($p = 0.027$) (Fig. 3). At 30° flexion, the ACL-intact motion limit and the engagement point of the ALL averaged 2.0 ± 1.3 mm and 5.7 ± 2.7 mm, respectively (Fig. 4); thus, the ALL engaged 3.7 ± 2.4 mm beyond the ACL-intact motion limit on average (95% CI, 2.1-5.3 mm; $p = 0.008$; Fig. 4). Normalized to the increase in maximum anterior tibial translation between the ACL-intact and -sectioned conditions, the ALL engaged at 61% ± 48% (95% CI, 25%-89%) and 56% ± 30% (95% CI, 34%-74%) of this range at 15° and 30° of flexion, respectively (Fig. 5).

Discussion

Lateral, extraarticular augmentation as an adjunct to ACL reconstruction remains a subject of clinical debate [9, 13]. It is known that the ALL bears appreciable force in response to multiplanar torques applied to the ACL-

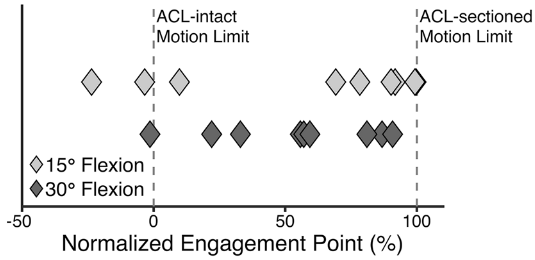

Fig. 5 Normalized engagement points of the ALL in response to combined valgus and internal rotation torques are shown individually for each knee that was tested. Light and dark gray diamonds represent the normalized engagement point of the ALL in each knee at 15° and 30° of flexion, respectively. The engagement points are expressed as a percentage of the difference between the ACL-intact and -sectioned motion limits (dashed gray lines) in the same knee. A negative percentage indicates engagement within the ACL-intact motion limit.

deficient knee [32]. However, our work expands on this knowledge by considering where in the range of anterior tibial translation the ALL begins to play a biomechanical role in resisting multiplanar torques. In our cadaveric study, we found that the ALL typically engages outside of the ROM of the ACL-intact knee, albeit with a high degree of variability. This novel framework for characterizing the biomechanics of the ALL could lead to surgical guidelines (such as fixation tension) for adjunctive, lateral augmentation that achieves a desired engagement point on a patient-specific basis.

This study has limitations. First is that cadaveric material was used to answer our research question, which limits our ability to transfer these findings to a clinical setting; however, doing so was necessary for controlled measurement of joint kinematics and ligament forces. Second, variations in ALL engagement between specimens could have been driven by variations in the force threshold used to define ALL engagement. However, this was not the case because linear regression analyses revealed no such relationship ($p \geq 0.17$). Third, our main finding that the ALL engaged beyond the ACL-intact motion limit might be sensitive to the percentage of ACL force used to define ALL engagement. However, the sensitivity of the engagement point was minimized by higher thresholds (Supplemental Fig. 1). Moreover, thresholds above 15% began to exceed the peak force carried by the ALL, prohibiting calculation of an engagement point (Supplemental Fig. 1). Fourth, cadavers were sectioned at the midshaft of the femoral diaphysis and therefore did not include the proximal insertions of the quadriceps, hamstrings, or iliotibial band (ITB). Even in this scenario, which minimized the contribution of these structures and, thus, likely maximized the contribution of the ALL, the ALL engages outside the envelope of motion of the native knee. Therefore, inclusion of the ITB and dynamic stabilizers is not likely to change our conclusions.

A fifth limitation is that interspecimen variability in the engagement point of the ALL may have been driven by an inconsistent sectioning protocol. However, in addition to the 10 specimens included in this work, we collected data from the contralateral limb of one of the donors (woman, age 58 years); inclusion of either paired specimen yielded an almost identical set of results (Supplemental Table 1 [Supplemental materials are available with the online version of *CORR*®.]). Sixth is that there are other load combinations that maximize anterior subluxation of the tibia [20, 24, 25]. Nevertheless, the magnitude of anterior subluxation in response to combined valgus and internal rotation torques distinguished the variability in ALL engagement points in the ACL-sectioned knee. Seventh is that internal rotation of the tibia was not included in our analysis; we did not focus on the internal rotation because studies have shown that the increase in internal rotation resulting from ACL sectioning is small, averaging approximately 3° [15, 27, 32]. Finally, the ALL plays a more important role at higher flexion angles than those tested in this study [7, 24]. That said, we decided that it was more useful to investigate the function of the ALL at 15° and 30° of flexion, where pivoting events occur [6, 17, 18].

The frequency of ALL engagement in the ACL-intact condition was greater than we had hypothesized; the ALL engaged in up to half of the knees (five of 10) tested in this study in response to multiplanar torques at 15° and 30° of flexion. Although the ALL engages in some ACL-intact knees, Thein et al. [32] reported that it does not subsequently build appreciable force, carrying an average of 15 N at the peak applied torques. We appreciate the apparent contradiction that the ALL engaged in some ACL-intact knees although it typically engaged outside of the native range of anterior tibial translation after the ACL was sectioned. This was likely because, with the ACL intact, internal tibial rotation alone removed the slack in the ALL in some knees without the anterior tibial subluxation that occurs after sectioning the ACL. In this subset of specimens, after the ACL was sectioned, the ALL engaged within or near the ACL-intact motion limit. Sectioning the ACL imparts small increases in internal tibial rotation (approximately 3°) in response to multiplanar torques at 15° and 30° flexion [15, 27, 32]. Therefore, pathologic anterior tibial translation is required in addition to internal rotation to build appreciable force in the ALL at these flexion angles as reported by Thein et al. (approximately 50 N, or approximately 50% of the peak ACL force on average) [32]. This reasoning explains why cadaveric photographs from our work and others' featuring a taut ALL show the tibia subluxated anteriorly (Fig. 1) [26, 32].

In accordance with our second hypothesis, on average, the ALL engaged about halfway through the range of additional anterior tibial translation that occurs after sectioning the ACL in response to multiplanar torques at 15° and 30° of flexion (Figs. 3, 4, 5). Thein et al. [32] have shown that the ALL carries force at the peak applied multiplanar torques in the ACL-sectioned knee; however, our findings indicate that, on average, the ALL engages only after the ACL-sectioned knee has subluxated approximately 4 mm anteriorly. Thus, although the ALL resists additional anterior subluxation from occurring after the ACL is sectioned [27, 32], it usually does not prevent the initial, pathologic anterior subluxation. However, there was a wide range in the engagement point of the ALL (Fig. 5), corroborating the interpersonal variability observed in the stabilizing role of the lateral capsular tissues in resisting multiplanar torques [21].

Surgical augmentation of the lateral, extraarticular tissue as an adjunct to ACL reconstruction has been reintroduced in an effort to restore rotational stability [30]. However, use of these combined surgeries remains a subject of debate as a result of variable outcomes as described in a recent meta-analysis by Hewison et al. [9]. Knowledge of where in the ROM of the knee the ALL engages in response to multiplanar torques may help explain some of this variability. Specifically, we found a subgroup of three knees in which the ALL engages within 10% of the ACL-intact ROM in the ACL-sectioned knee at 15° flexion (Fig. 5). In the ACL-intact condition, these ALLs carried 36 ± 7 N. In contrast, ALLs that engaged later in the ACL-sectioned knee carried less force (12 ± 7 N) with the ACL intact. We speculate that this inconsistent function may be driven by interspecimen variability in the anatomy (eg, thickness and isometry) of the ALL [4, 10, 26, 30]. This finding may be relevant for identifying those ACL-injured patients who rely more on this tissue and may therefore benefit from its augmentation or reconstruction. Such a distinction may prove to be important because augmentation of the anterolateral capsule, although beneficial to some knees, may overconstrain others, which may lead to long-term joint degeneration [13, 23, 28, 29, 31].

In conclusion, in this in vitro, biomechanical study of 10 cadaveric specimens, we found that, in response to combined valgus and internal rotation torques at 15° and 30° of flexion, the ALL engaged in approximately half of the ACL-intact knees. Furthermore, the average engagement point of the ALL in the ACL-sectioned knee was beyond the ACL-intact limit of anterior tibial translation. Thus, in our cadaveric sample, on average, the ALL does not restrain the knee within the range of anterior tibial translation of the ACL-intact knee in response to combined torques. However, in a minority of ACL-sectioned knees, the ALL engaged within or near the ACL-intact limit of anterior motion and also engaged in the ACL-intact condition. These findings are clinically relevant because they suggest that surgical decisions such as the joint position and tension at which lateral extraarticular grafts and tenodeses are fixed could be tuned to control where within the ROM of the knee the graft tissue is engaged on a patient-specific basis. However, additional work is required to understand the relationship between these surgical parameters and graft engagement before this framework could be used to establish more precise, personalized guidelines for surgical augmentation of the lateral joint capsule.

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