# Engagement of the Secondary Ligamentous and Meniscal Restraints Relative to the Anterior Cruciate Ligament Predicts Anterior Knee Laxity

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**Background:** Patients with high-grade preoperative side-to-side differences in anterior laxity as assessed via the Lachman test after unilateral anterior cruciate ligament (ACL) rupture are at heightened risk of early ACL graft failure. Biomechanical factors that predict preoperative side-to-side differences in anterior laxity are poorly understood.

**Purpose:** To assess, in a cadaveric model, whether the increase in anterior laxity caused by sectioning the ACL (a surrogate for preoperative side-to-side differences in anterior laxity) during a simulated Lachman test is associated with two biomechanical factors: (1) the tibial translation at which the secondary anterior stabilizers, including the remaining ligaments and the menisci, begin to carry force, or *engage*, relative to that of the ACL or (2) the forces carried by the ACL and secondary stabilizers at the peak applied anterior load.

**Study Design:** Controlled laboratory study.

**Methods:** Seventeen fresh-frozen human cadaveric knees underwent Lachman tests simulated through a robotic manipulator with the ACL intact and sectioned. The net forces carried by the ACL and secondary soft tissue stabilizers (the medial meniscus and all remaining ligaments, measured as a whole) were characterized as a function of anterior tibial translation. The engagement points of the ACL (with the ACL intact) and each secondary stabilizer (with the ACL sectioned) were defined as the anterior translation at which they began to carry force, or engaged, during a simulated Lachman test. Then, the relative engagement point of each secondary stabilizer was defined as the difference between the engagement point of each secondary stabilizer and that of the ACL. Linear regressions were performed to test each association ($P < .05$).

**Results:** The increase in anterior laxity caused by ACL sectioning was associated with increased relative engagement points of both the secondary ligaments ($\beta = 0.87$; $P < .001$; $R^2 = 0.75$) and the medial meniscus ($\beta = 0.66$; $P < .001$; $R^2 = 0.58$). Smaller changes in anterior laxity were also associated with increased in situ medial meniscal force at the peak applied load when the ACL was intact ($\beta = -0.06$; $P < .001$; $R^2 = 0.53$).

**Conclusion:** The secondary ligaments and the medial meniscus require greater anterior tibial translation to engage (ie, begin to carry force) relative to the ACL in knees with greater changes in anterior laxity after ACL sectioning. Moreover, with the ACL intact, the medial meniscus carries more force in knees with smaller changes in anterior laxity after ACL sectioning.

**Clinical Relevance:** Relative tissue engagement is a new biomechanical measure to characterize in situ function of the ligaments and menisci. This measure may aid in developing more personalized surgical approaches to reduce high rates of ACL graft revision in patients with high-grade laxity.

**Keywords:** graft rupture; meniscus; ACL reconstruction; ligament engagement; laxity

Based on large-scale registry data, failure rates of anterior cruciate ligament (ACL) grafts are 3% to 5% within 4 years of ACL reconstruction, but reports have also shown failure rates as high as 18% in younger athletes less than two years after surgery.[5,32,34,39,43] Biological, biomechanical, and behavioral risk factors may all play a role in ACL graft failure.[6,10,24,30] From the biomechanical perspective, Magnussen et al[23,24] reported that large preoperative side-to-side (ie, contralateral) differences in anterior laxity after unilateral ACL rupture are related to increased risk of graft failure. Therefore, standardized treatments for unilateral ACL rupture may not be optimal for those with large preoperative side-to-side differences in anterior laxity.

Concomitant meniscal damage, generalized ligamentous laxity, and the chronicity of the ACL injury all contribute to increased risk of anterior laxity after ACL rupture.[25,28] Yet, biomechanical factors that predict preoperative side-to-side differences in anterior laxity after ACL rupture are

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poorly understood. One potential biomechanical explanation for the highly variable increase in side-to-side anterior laxity caused by ACL deficiency may lie in the biomechanical function of the ACL and the secondary anterior restraints to the Lachman test (including the remaining ligaments and the menisci).[9,14] This explanation stems from a previous cadaveric study that reported a relationship between the anterior laxity during a simulated Lachman test of the ACL-intact knee and the tibial position at which the ACL begins to carry force (ie, the engagement point of the ACL) but, surprisingly, not the force that it carried at the peak applied load.[14] Accordingly, the engagement points of secondary ligamentous and meniscal stabilizers relative to that of the ACL may help explain preoperative side-to-side differences in anterior laxity after unilateral ACL rupture.

Quantifying the engagement point of the ACL graft and that of the secondary tissues is clinically important because it could provide a biomechanical rationale to tune ligament function to achieve knee laxity that reduces risk of graft failure. For example, surgeons must select from numerous variables (eg, doubling over grafts, type of graft fixation, tunnel location, pretension, knee position during graft fixation) to reconstruct the ACL and the secondary soft tissues. Novel measures that quantify the effect of these surgical variables on graft engagement during ligament reconstruction could inform surgical decision making toward improved treatment, especially in at-risk patients with high-grade laxity.

The purpose of this biomechanical study was to determine whether the biomechanical function of the ACL, the remaining ligamentous restraints besides the ACL, and the menisci predict preoperative side-to-side differences in anterior laxity after ACL rupture. To this end, we used repeated measures of knee laxity in a cadaveric model before and after sectioning the ACL as a more controlled surrogate for side-to-side clinical comparisons of knee laxity. We specifically assessed whether the increase in anterior laxity caused by sectioning the ACL is associated with (1) the tibial translation at which the remaining ligamentous restraints and the menisci begin to carry force, or engage, relative to that of the ACL or (2) the forces carried by the ACL and secondary anterior stabilizers at the peak applied anterior load.

## METHODS

With institutional review board approval, 17 fresh-frozen human cadaveric knees were obtained from a nonprofit anatomic donation organization (mean ± SD age, 45 ± 13 years; range, 20-64 years; 13 men; mean tibial plateau size: 54.3 ± 4.3 mm, anteroposterior [AP] width; 81.9 ± 5.8 mm, mediolateral width).[3] Specimens were stored at –20°C and then thawed at room temperature for 24 hours before testing. Each specimen was transected at the midshaft of the femoral and tibial diaphyses, and the ligaments, capsular tissues, and popliteal muscle-tendon complex were left intact while skin and superficial leg muscles were removed.[15] The absence of ligamentous and meniscal injury, gross chondral damage, and osteophytes, as well as evidence of prior surgery, was confirmed with medial parapatellar arthrotomies, computed tomography scans, reviews of medical histories, and physical examinations. After the fibula was fixed to the proximal tibia with a transverse screw, it was transected just distal to the screw. Finally, the tibial and femoral diaphyses were potted in bonding cement (Bondo; 3M).

Specimens were mounted to a 6 degrees of freedom serial robot (±0.3-mm repeatability; ZX165U, Kawasaki Robotics) equipped with a universal force-moment sensor (Theta; ATI). With custom fixtures, the femur was rigidly attached to the ground while the tibia was attached to the robot's end effector with the knee at full extension. A digitizing arm (Microscribe G2X; Immersion, Inc) with an accuracy of ±0.23 mm was used to build a coordinate system based on anatomic landmarks and through which all translations and rotations of the tibia were described.[13,15] Throughout testing, specimens were kept covered in saline-soaked gauze to maintain tissue hydration.[41]

In 1° increments, the robot flexed the knee from full extension to 90° of flexion with 10 N of compression. Throughout flexion, all forces and torques were respectively minimized to within 5 N and 0.4 N·m of the targeted loads via a force-feedback algorithm programmed with MATLAB (R2018a MathWorks).[15,31] All subsequent loading protocols at a given flexion angle began from the linear and angular position of the tibia defined by the passive flexion path.

The soft tissues of the knee were preconditioned by applying 134 N of anterior force to the tibia at 30° of flexion and rotatory torques at 15° of flexion.[15] As these loads were applied, the knee was free to move in 5 degrees of freedom while the flexion angle was held constant. The resulting kinematics were recorded and then repeated 10 times.[15] These anterior and rotatory applied loads preconditioned the anteromedial and posterolateral portions of the ACL.[12,33]

After preconditioning, the robot simulated a Lachman test by increasing the anterior force on the tibia to 134 N at 30° of flexion in the following increments: 0, 10, 25,

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50, 75, 100, and 134 N. To characterize the AP laxity of each knee, posterior loads were also applied in the same increments used to assess anterior laxity. In both directions, the inflection point where the load-displacement response of the joint transitioned from a low- to high-stiffness region, or the point of maximum curvature, was identified with an objective algorithm.[35] The point of maximum curvature was calculated in each discrete curve by first defining a vector between the 2 endpoints of the curve and then identifying the data point through which the longest perpendicular to this vector could be drawn. The center of the AP laxity profile was defined as the midpoint of these inflection points, and this served as the neutral position from which AP translations were described for each specimen.[14]

Anterior loads were applied with the ACL intact and sectioned, and the resulting tibiofemoral kinematics were measured. ACL-intact kinematics were repeated before and after serial sectioning of (1) the ACL, (2) all remaining secondary ligaments, (3) the medial meniscus, and (4) the lateral meniscus. ACL-deficient kinematics were also repeated before and after the secondary anterior stabilizers (as a whole) and each meniscus were sectioned (Figure 1).

The menisci were sectioned before the secondary ligaments in 1 specimen to build confidence that sectioning order was not likely to influence our findings. Forces carried by the ligamentous and meniscal tissues with the ACL intact and sectioned were determined as a function of anterior tibial translation with the principle of superposition.[11] The maximum applied anterior load (134 N) was <10% of the maximum payload of the robot (165 kg); therefore, deflection (ie, bending) of the robot was minimal, allowing knee joint congruency to be maintained during selective cutting of the secondary restraints. This study focused on characterizing how the menisci and the ligamentous tissues as a whole built force, or engaged, as the tibia translated anteriorly; therefore, the net forces carried by all of the ligaments other than the ACL were considered as a group rather than individually. In other words, forces carried by the secondary ligaments during the simulated Lachman test were defined as the sum of forces carried by all the ligamentous tissues spanning the tibiofemoral joint except the ACL. This consisted of all medial, lateral, and posterior ligaments, including the medial collateral ligament, posterior oblique ligament, lateral collateral ligament, posterior cruciate ligament, and the anterolateral and posterior capsular tissues.

Engagement of the secondary ligaments and the menisci in the ACL-sectioned knee relative to that of the ACL was determined with an objective algorithm and the following 3 steps.[35] First, the engagement point of the ACL was defined as the anterior tibial translation from the neutral position to the point where the ACL began to carry force (Figure 2). Second, the engagement points of the secondary ligaments and the menisci in the ACL-sectioned condition were defined via the same method. Third, engagement of the secondary ligaments and the menisci relative to the ACL was determined by taking the difference of the engagement point of the ACL and the engagement points of the secondary ligaments and the menisci. This difference was defined as the relative engagement point of the secondary stabilizers.

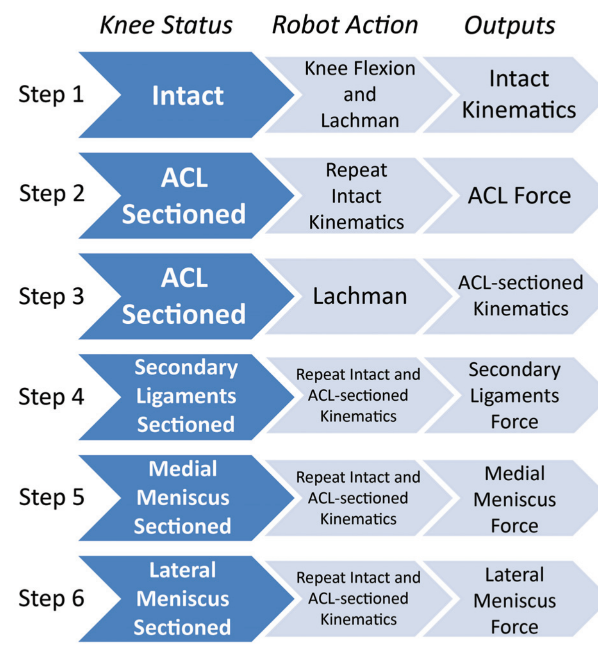


**Figure 1.** Flowchart summarizing the major stages of the protocol (steps 1-6), including knee status, robot action, and outputs. First, a simulated Lachman test was conducted with the ACL intact (step 1). Next, the ACL was sectioned to determine the force that it carried (step 2); then, the simulated Lachman test was again conducted (step 3). Subsequently, the secondary ligaments (all remaining ligaments) were removed to determine the forces that they carried with the ACL intact and sectioned (step 4). Similarly, the medial meniscus (step 5) and then the lateral meniscus (step 6) were sectioned to determine the forces that they carried. ACL, anterior cruciate ligament.

The outcome measures were as follows: First were the anterior laxities (mm) of each specimen with the ACL intact and sectioned; these were used to calculate the increase in laxity (mm) resulting from ACL sectioning. Second were the forces (N) carried by the ACL at the peak applied anterior load and those of each secondary stabilizer at the peak applied anterior load in the intact and ACL-sectioned knee. Finally, the relative engagement points (mm) of each secondary stabilizer were determined by subtracting the engagement point of the ACL from the engagement point of each secondary stabilizer in the ACL-sectioned condition (Figure 2).

To address each research question, simple linear regressions were used to evaluate whether the increase in anterior laxity resulting from ACL sectioning could be predicted by (1) the relative engagement points of the secondary ligaments and the menisci and (2) the forces carried by the ACL and secondary stabilizers. Regression coefficients (β; $P < .05$), their standard deviations and 95% CIs, and adjusted coefficients of determination[27] (adjusted $R^2$) were reported for each linear regression. Normality of all outcome measures was confirmed with Kolmogorov-Smirnov tests ($P < .05$).

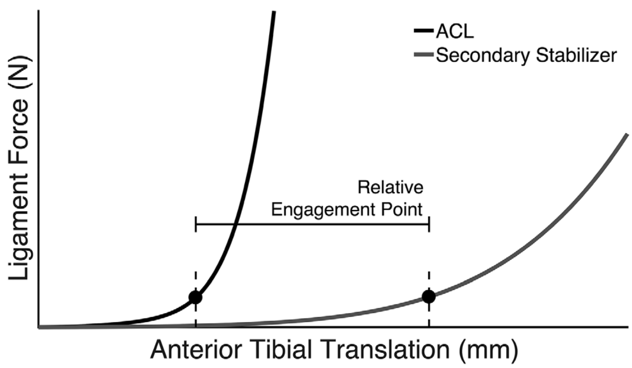


**Figure 2.** Illustration of the definition of the relative engagement point of each secondary stabilizer (either the menisci or the secondary ligaments) to an anteriorly applied load at 30° of flexion, which simulated a Lachman test. The resultant forces carried by the ACL and a representative secondary stabilizer are respectively shown as a function of anterior tibial translation in the ACL-intact and ACL-sectioned conditions. Solid black circles indicate the engagement points of each tissue, and the relative engagement point was defined as the difference between these engagement points in millimeters. ACL, anterior cruciate ligament.

## RESULTS

Anterior laxities averaged 7.0 ± 1.7 mm and 18.4 ± 2.9 mm with the ACL intact and sectioned, respectively. Thus, the increase in anterior laxity resulting from ACL sectioning was 11.4 ± 2.7 mm. With the ACL intact, the ACL carried 153.8 ± 15.9 N at the peak applied anterior load, while the secondary ligaments carried 44.9 ± 15.6 N, the medial meniscus 54.0 ± 31.8 N, and the lateral meniscus 7.4 ± 8.4 N. With the ACL sectioned, the secondary ligaments carried 156.2 ± 36.1 N at the peak applied anterior load, while the medial meniscus carried 115.8 ± 45.9 N and the lateral meniscus carried 5.6 ± 7.1 N. Based on the resultant tissue force–tibial translation responses (Figure 3), the engagement point of the ACL was 3.3 ± 1.9 mm, and the engagement points of the secondary ligaments and medial meniscus relative to the ACL (ie, their relative engagement points) were, respectively, 8.0 ± 2.7 mm and 8.4 ± 3.1 mm. Forces and engagement points of the lateral meniscus were not utilized in subsequent regression analyses because of the low force carried by this tissue at the peak applied load.

During the simulated Lachman test, the engagement points of the secondary ligaments and medial meniscus with respect to the ACL were positively associated with the increased anterior laxity caused by ACL sectioning (Figure 4); each 1-mm increase in the relative engagement point of the secondary ligaments and medial meniscus during the simulated Lachman corresponded to respective increases in anterior laxity after sectioning of the ACL: 0.87 ± 0.52 ($P$ < .001; adjusted $R^2$ = 0.75) and 0.66 ± 0.57 mm ($P$ < .001; adjusted $R^2$ = 0.58) (Figures 3 and 5).

In response to the simulated Lachman test, increased force on the medial meniscus in the ACL-intact condition

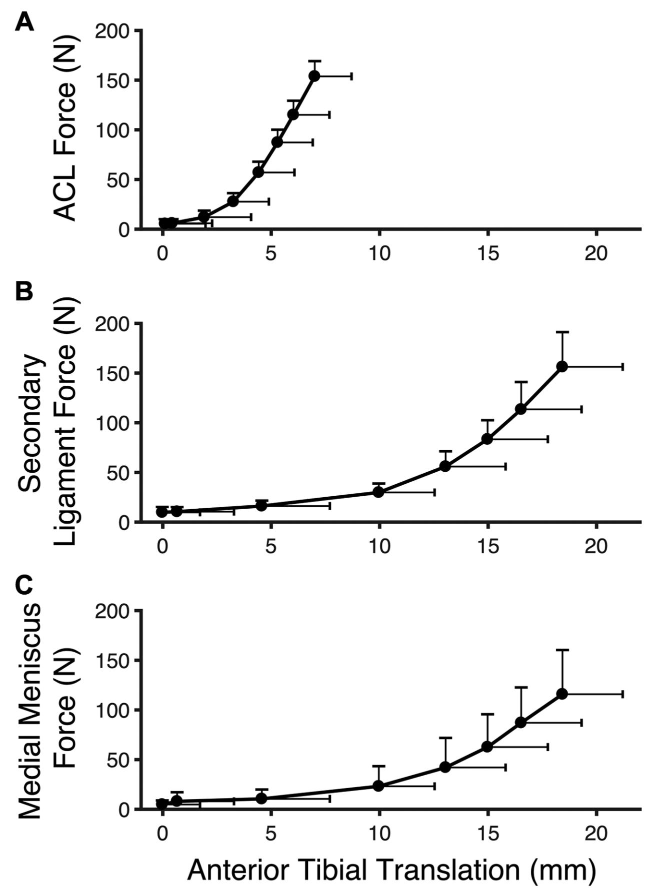


**Figure 3.** Resultant tissue force–anterior tibial translation responses for (A) the ACL, (B) the secondary ligaments with the ACL sectioned, and (C) the medial meniscus with the ACL sectioned. Plotted points and whiskers denote the mean and SD of resultant tissue forces and anterior tibial translations in response to 0, 10, 25, 50, 75, 100, and 134 N of anterior load. ACL, anterior cruciate ligament.

was associated with less change in the anterior laxity caused by ACL sectioning; each 1-N increase in force carried by the medial meniscus at the peak applied load corresponded to 0.06 ± 0.06–mm smaller change in anterior laxity owing to ACL sectioning ($P$ < .001; adjusted $R^2$ = 0.53) (Table 1). For example, in the knees with the smallest and largest changes in anterior laxity caused by ACL sectioning, the forces carried by the medial meniscus at the peak applied load were 105.6 and 31.4 N, respectively, when the ACL was intact.

## DISCUSSION

High-grade preoperative side-to-side differences in anterior knee laxity are associated with increased risk of subsequent revision ACL surgery.[6,24,26] Therefore, our goal was to develop biomechanical measures that predict side-to-side difference in anterior laxity to inform treatments that reduce chances of revision surgery in these patients

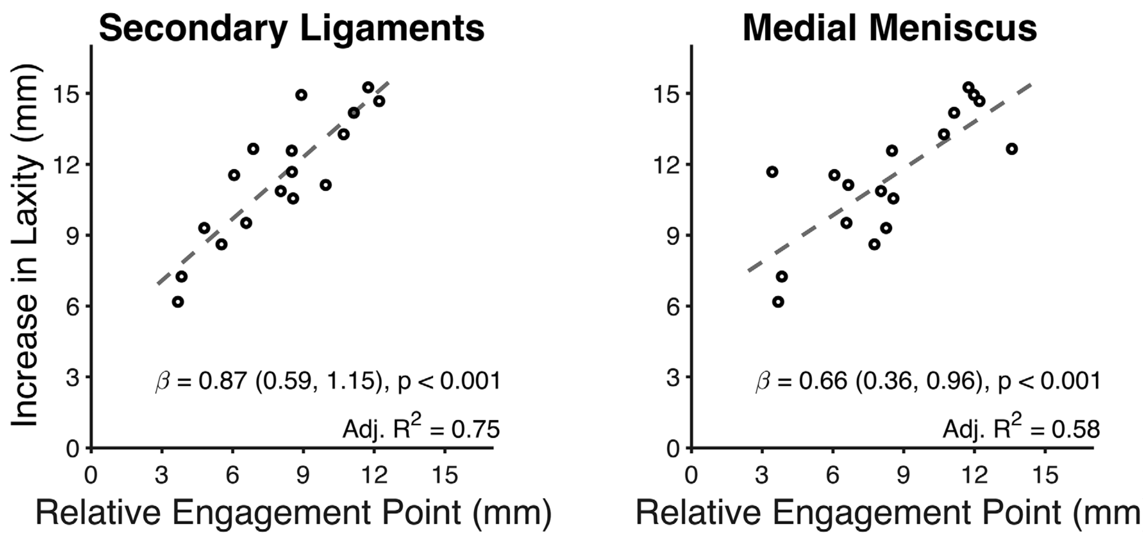


**Figure 4.** Univariate regressions between the relative engagement points of secondary anterior stabilizers—namely, the secondary ligaments and the medial meniscus—and the increase in anterior laxity resulting from anterior cruciate ligament (ACL) sectioning during a simulated Lachman test. Black circles represent individual knees, and dashed gray lines indicate linear regressions. Adjusted coefficients of determination (Adj $R^2$), regression coefficients (β) with their 95% CIs, and *P* values are indicated for each regression.

at risk. Specifically, we introduced the measure *relative tissue engagement*, which characterizes how force builds in situ in the secondary soft tissue stabilizers relative to the ACL as the knee joint moves through its passive envelope of motion. We then used this measure in a cadaveric biomechanical model to predict the increase in anterior laxity caused by sectioning the ACL during a simulated Lachman test. This laxity increase served as a controlled in vitro surrogate for side-to-side preoperative differences in anterior laxity after unilateral ACL rupture. During a simulated Lachman test, knees with larger changes in anterior laxity after ACL sectioning had a greater relative engagement point of the secondary ligaments (Figure 2), but surprisingly, the secondary ligaments did not carry increased force at the peak applied load (Figure 4, Table 1). Like the secondary ligaments, the medial meniscus had a greater relative engagement point in knees with larger changes in anterior laxity resulting from ACL sectioning. Unlike the secondary ligaments, the medial meniscus carried more force in knees with smaller changes in anterior laxity caused by sectioning the ACL.

Most important, we found that the relative engagement points of the secondary ligaments and the medial meniscus predict the change in anterior laxity resulting from ACL sectioning during the simulated Lachman test (Figure 4). Thus, knees with a greater change in anterior laxity owing to ACL sectioning exhibit either earlier engagement of the ACL relative to the secondary stabilizers or later engagement of the secondary stabilizers relative to the ACL. In both scenarios, we speculate that the absence of support from secondary stabilizers could expose the ACL or an ACL graft to abnormal loads. The absence of support from secondary stabilizers might be a biomechanical explanation for the increased rates of ACL graft revision reported by Magnussen et al[23,24] in knees with large preoperative side-to-side differences in anterior laxity after unilateral ACL rupture. This speculation requires further biomechanical research targeting ACL-reconstructed knees.

Biomechanical studies typically report the mean force carried at the peak applied load to rank the relative importance of the knee stabilizers.[17,36,42] Our findings extend this previous work by suggesting that the relative engagement points of the secondary ligaments (defined in Figure 2) better predict the increase in anterior laxity caused by sectioning the ACL. In line with our findings, previous work has shown that the engagement point of the ACL, and not the resultant force carried by the ACL at the peak applied load, predicts anterior laxity of the ACL-intact knee.[14] Moreover, we observed that the secondary ligaments and medial meniscus engaged simultaneously with the secondary soft tissues in 11 of 17 knees but engaged asynchronously in the remaining 6 knees. Engagement of the secondary stabilizers relative to each other could also provide a novel outcome measure.

Two biomechanical characteristics of the medial meniscus predict the increase in anterior laxity after sectioning the ACL: its relative engagement point (Figure 4) and the resultant force that it carries at the peak applied load (Table 1) (both $P < .001$). This differs from our findings regarding the secondary ligamentous restraints to the Lachman test and may stem from the structure and function of the menisci as compared with ligaments. Namely, in addition to restraining tibiofemoral shear forces such as ligaments, the menisci carry and distribute compressive loads across the tibiofemoral joint via their wedge-shaped geometry wrapped circumferentially around each femoral condyle.[7,15] To illustrate our findings, our regression analysis revealed that with a 1-mm smaller

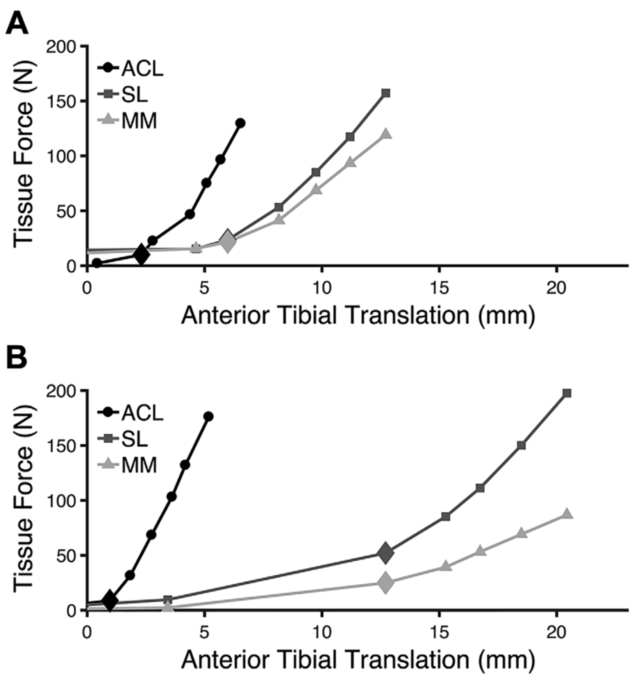


**Figure 5.** Representative plot of the resultant tissue force–anterior tibial translation responses of the ACL (black circles), secondary ligaments (dark gray squares), and medial meniscus (light gray triangles) for the specimen with the (A) smallest and (B) largest increase in anterior laxity resulting from ACL sectioning during a simulated Lachman test. The engagement point (indicated by large diamonds) of the secondary ligaments and medial meniscus relative to the ACL are 3.7 and 11.7 mm for the knees with the smallest and largest increase in anterior laxity, respectively (the secondary ligaments and medial meniscus engaged simultaneously in these 2 knees). ACL, anterior cruciate ligament; MM, medial meniscus; SL, secondary ligaments.

TABLE 1
Linear Regressions of Tissue Force and Increased Anterior Laxity During a Simulated Lachman Test[a]

| Condition: Tissue | β | *P* Value | Adjusted $R^2$ |
|---|---|---|---|
| Intact | | | |
| ACL | 0.04 ± 0.17 (–0.05 to 0.13) | .355 | 0.00 |
| Secondary ligaments | −0.02 ± 0.18 (–0.11 to 0.07) | .623 | 0.00 |
| Medial meniscus | −0.06 ± 0.06 (–0.09 to –0.03) | <.001 | 0.53 |
| ACL Sectioned | | | |
| Secondary ligaments | 0.02 ± 0.08 (–0.02 to 0.06) | .303 | 0.01 |
| Medial meniscus | −0.03 ± 0.05 (–0.06 to 0.00) | .061 | 0.16 |

[a]Data provided as mm/N, mean ± SD (95% CI), unless otherwise stated. ACL, anterior cruciate ligament; β, regression coefficient.

change in anterior laxity after ACL sectioning, the medial meniscus carried 16.7 N more force when the ACL was intact. This finding extends our understanding of meniscal biomechanics beyond the knowledge that force carried by the medial meniscus increases under an applied anterior force after sectioning of the ACL.[2] We speculate that this novel biomechanical finding may have clinical significance because it may help identify the following types of patients: those who are at greater risk for medial meniscal injury, those who may exhibit a less favorable environment for the healing of medial meniscal repairs or meniscal allografts, or those who may be at risk of secondary meniscal damage with ACL reconstruction. This novel relationship may be due to variations in the underlying material properties or geometry of the medial meniscus, the stiffness of the horn or coronary attachments, or tibial plateau morphology. Further studies, especially on the role of compression in meniscal function, are needed to substantiate this speculation and the clinical significance of this finding.

The lateral meniscus was not considered for either research question because it carried <10 N at the peak applied load. In comparison, the secondary ligaments and the medial meniscus both carried >100 N with the ACL sectioned. Our findings corroborate previous studies in which the medial meniscus and the secondary ligaments were found to be the major restraints to anterior loads applied to the ACL-sectioned knee (such as those applied during a Lachman test), while the lateral meniscus was not.[2,17,20,21,42] The role of the relative engagement of the lateral meniscus during the pivot shift, where it is known to be an important secondary stabilizer, was not assessed in this study.[28]

Since risk of ACL graft failure increases with larger preoperative differences in side-to-side laxity,[24] we speculate that the concept of relative tissue engagement may facilitate personalized protocols for ACL reconstruction and adjunctive procedures that could mitigate risk of ACL graft failure, such as extra-articular ligament augmentation. Currently, guidelines for extra-articular augmentation are not well-established and remain a subject of clinical debate.[16,19,22,37] Furthermore, previous randomized cohort studies found no relationship between initial ACL graft tension and clinical, functional, or patient-reported outcomes,[1,29] but they did not control for the difference in laxity between the ACL-deficient and contralateral, uninjured knee. Our work provides novel outcomes to quantify the effect of surgical variables on graft function and knee laxity. Such surgical variables may include graft type, graft thickness, fixation method, tunnel location, pretension, or knee position during graft fixation. By quantifying ligamentous engagement, the surgeon could select the method that is most feasible and appropriate to achieve the desired laxity and relative engagement. As a speculative example, our findings might suggest that during extra-articular augmentation, one should pay particular attention to where within the envelope of anterior translation the lateral tissue becomes taut, or engages, since the engagement point predicts the resulting knee motion.[18] Further work is needed to determine how individual ligaments engage and how surgical parameters as well as biological remodeling of graft tissues modulate relative tissue engagement.

This study has limitations. First, our findings are correlative and therefore indicate no causal relationships. Yet, it is known that increasing graft tension, which would intuitively cause a graft to engage with less tibial translation, reduces the laxity of the ACL-reconstructed knee, suggesting that variations in the engagement point influence knee laxity.[4,29,44] Second, we considered the role of the remaining ligamentous restraints (besides the ACL) as a whole, which highlighted their differential biomechanical function as compared with the medial meniscus. Future work delineating the role of individual ligamentous restraints, such as the anterolateral capsule and medial collateral ligament, is required to inform specific augmentation procedures. Third, the sample size (n = 17) limited our statistical analysis to simple linear regression models. Now that we have established the utility of relative engagement in predicting variations in knee laxity, future work with a larger sample size could incorporate stepwise multiple linear regression,[14] as well as analysis of individual ligaments. Fourth, the increment of applied anterior load does not affect our conclusions, because the average relative engagement point of the medial meniscus was 2.5 times larger than the maximum variation in engagement point of the medial meniscus caused by the load increment (see Appendix 1, available in the online version of the article). We did not consider the role of bony or articular morphology on the relative engagement point, because the focus of this work was on the soft tissues, which are more often and more easily modified during surgery.[8,39,40] Investigating these relationships is another important research direction. Fifth, the forces borne by the secondary ligaments and medial meniscus did not depend on their sectioning order in a single knee, which builds confidence that the results were independent of tissue sectioning order (see Appendix 2, available online). Sixth, the slow quasistatic loading conditions used in this work do not simulate the dynamic loads seen functionally. Finally, this work considered only tissue engagement during a simulated Lachman test; future work should quantify relative tissue engagement under additional loading conditions, including those of compression and the pivot-shift examination. Like the Lachman, a high-grade pivot shift is also independently associated with an increased risk of ACL graft failure.[24,38]

In conclusion, during a simulated Lachman test, the medial meniscus and the secondary ligaments require greater anterior translation to engage (ie, begin to carry force) relative to the ACL in knees with larger changes in anterior laxity caused by ACL sectioning. Additionally, the medial meniscus carries greater force at the peak applied load in knees with smaller changes in anterior laxity caused by ACL sectioning; in contrast, the secondary ligaments do not. Altogether, parameters of tissue engagement may be used to help develop surgical approaches to reduce rates of ACL graft revision in high-risk patients with large side-to-side preoperative differences in anterior laxity after unilateral ACL rupture.

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