In Situ Force in the Anterior Cruciate Ligament, the Lateral Collateral Ligament, and the Anterolateral Capsule Complex During a Simulated Pivot Shift Test

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ABSTRACT: The role of the anterolateral capsule complex in knee rotatory stability remains controversial. Therefore, the objective of this study was to determine the in situ forces in the anterior cruciate ligament (ACL), the anterolateral capsule, the lateral collateral ligament (LCL), and the forces transmitted between each region of the anterolateral capsule in response to a simulated pivot shift test. A robotic testing system applied a simulated pivot shift test continuously from full extension to 90° of flexion to intact cadaveric knees ($n = 7$). To determine the magnitude of the in situ forces, kinematics of the intact knee were replayed in position control mode after the following procedures were performed: (i) ACL transection; (ii) capsule separation; (iii) anterolateral capsule transection; and (iii) LCL transection. A repeated measures ANOVA was performed to compare in situ forces between each knee state ($^{*}p < 0.05$). The in situ force in the ACL was significantly greater than the forces transmitted between each region of the anterolateral capsule at 5° and 15° of flexion but significantly lower at 60°, 75°, and 90° of flexion. This study demonstrated that the ACL is the primary rotatory stabilizer at low flexion angles during a simulated pivot shift test in the intact knee, but the anterolateral capsule plays an important secondary role at flexion angles greater than 60°. Furthermore, the contribution of the "anterolateral ligament" to rotatory knee stability in this study was negligible during a simulated pivot shift test. © 2017 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 36:847–853, 2018.

Keywords: anterolateral capsule; simulated pivot shift; anterior cruciate ligament; ACL; robotic testing system

Injury to the anterior cruciate ligament (ACL) results in pain, instability of the knee, and varying levels of disability ranging from reduced participation in sports to difficulties with activities of daily living. In the long-term, injury to the ACL can lead to secondary meniscus tears and degenerative osteoarthritis.[1,2] Goals for ACL reconstruction are to restore stability of the knee, allow the individual to return to prior activities, and to prevent the development of post-traumatic osteoarthritis.

Recent meta-analyses have concluded that current ACL reconstruction methods fail to restore normal knee function.[3,4] Normal structure and function of the knee is restored in less than 40% of the patients undergoing ACL reconstruction.[3] Specifically, the pivot shift test was positive in 22% of individuals two years after undergoing ACL reconstruction.[4] The pivot shift test has been shown to be the most specific exam for diagnosing an ACL injury.[5] Furthermore, a positive pivot shift test has been shown to correlate with worsening functional outcomes after ACL reconstruction.[6]

In an attempt to restore rotational stability and improve function, techniques to reconstruct the ACL have evolved significantly in recent years. The primary focus was on ACL anatomy which led to the development of an anatomic ACL reconstruction.[7–24]. More recently, the role of the peripheral structures in rotational stability has gained attention again.[7,25–28] However, controversy arose when a "new" anterolateral ligament was proposed.[25] Although injury to the anterolateral capsule can lead to high-grade pivot shift in the ACL-deficient knee,[29] the existence and/or significance of the anterolateral ligament is still under debate.[7,25–28] Therefore, knowledge of the forces in the anterolateral capsule is needed to inform the proposed reconstruction procedures. The objective of this study was to determine the in situ forces in the ACL, the anterolateral capsule, the lateral collateral ligament (LCL), and the forces transmitted between each region of the anterolateral capsule in response to a simulated pivot shift test[30,31] with an intact knee. The simulated pivot shift test is a well-established research method of simulating the loads applied during the pivot shift test using a robotic testing system (or custom-built device).[30] However, the simulated pivot shift test is not necessarily the same motion or loading profile as the clinical pivot shift test. Our hypotheses are: (i) the ACL is the primary restraint; and (ii) the region of the anterolateral capsule that includes the described anterolateral ligament is a secondary restraint during the simulated pivot shift test.

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METHODS

Seven fresh-frozen human cadaveric knees with a mean age of 49 years (range 46–59 years) were examined manually and radiologically before testing to exclude any specimens with ligament or bony abnormalities. Specimens were thawed overnight at room temperature prior to testing.[32] The skin and musculature was removed exposing the femoral and tibial shaft leaving the knee intact and the tibia and femur were cut 20 cm from the joint line. To enable visualization of the anterolateral structures the iliotibial band was carefully dissected from the underlying tissue starting proximal and ending with the disconnection from Gerdy's tubercle (Fig. 1). During the experimental protocol, specimens were kept moist with saline.[32]

The femur and tibia were potted in an epoxy compound (Bondo, Atlanta, GA) and secured with custom-made aluminum clamps. The femur clamp was rigidly fixed relative to the lower plate of a robotic testing system (MJT Model FRS2010, Chino, Japan) (Fig. 2) and the tibia clamp was attached to the upper end plate of the robotic manipulator through a universal force/moment sensor (UFS, ATI Delta IP60 (SI-660-60), Apex, NC). Control of the robotic testing system is accomplished through a LABVIEW Program (Technology Services Inc., Chino, Japan) designed for knee biomechanical testing and is operated in hybrid velocity impedance control. The position and orientation repeatability of the robotic manipulator is less than ± 0.015 mm and $\pm 0.01°$. The unique orthogonal design of the custom robotic manipulator also provides high clamp-to-clamp stiffness (110 ± 30 Nm/degree for rotations and 450 ± 180 N/mm) making it appropriate for mechanical testing of the knee joint.[33,34] Also as presented previously,[35] the test–retest repeatability of the robotic testing systems was determined to be ± 0.21 mm and $\pm 2.45°$ and repeatability of recording the in situ forces in the robotic testing system is ± 2.25 N.

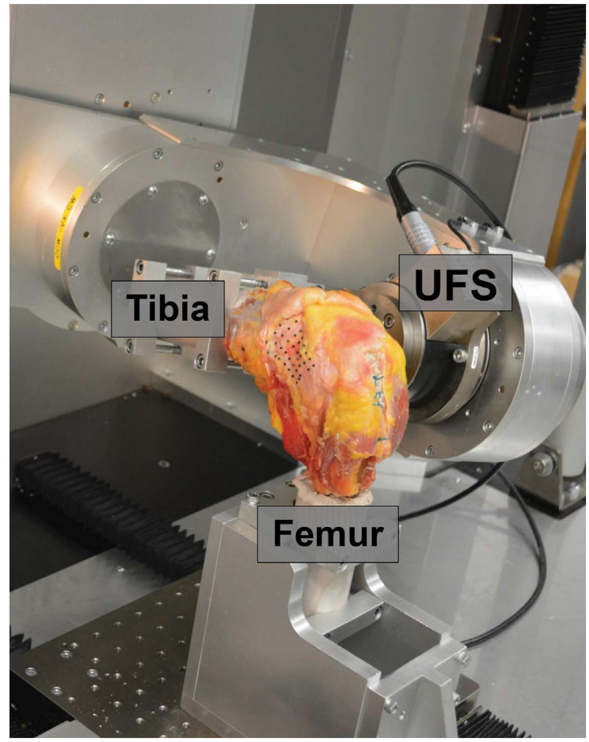

Figure 2. A cadaveric knee mounted in the robotic testing system. The femur was secured rigidly to the lower plate and the tibia was secured to the upper plate through a 6-DOF UFS.

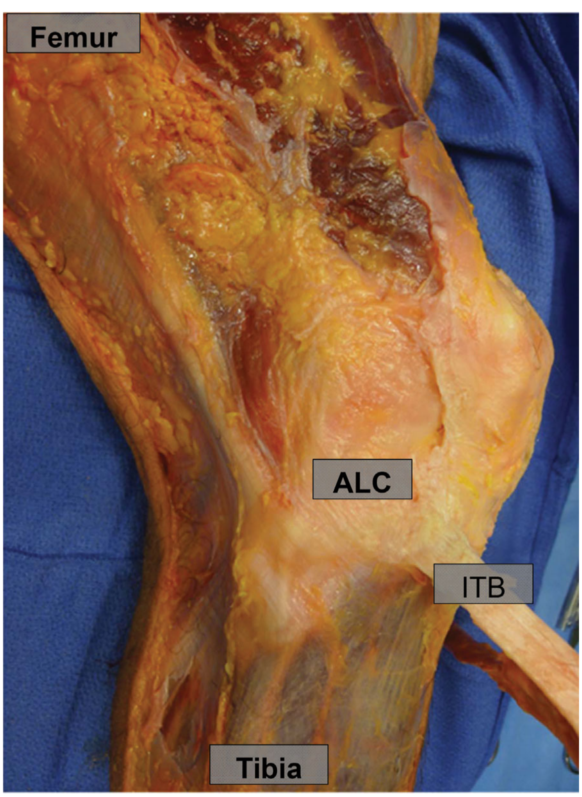

Figure 1. To enable visualization of the anterolateral structures, the iliotibial band was carefully dissected from the underlying tissue starting proximally and ending with the transection from Gerdy's tubercle. ALC, anterolateral capsule; ITB, iliotibial band.

The robotic testing system was utilized to apply a simulated pivot shift test continuously from full extension to 90° of flexion.[35] The simulated pivot shift test was achieved by applying 7 Nm of internal rotation torque combined with 7 Nm of valgus rotation torque to the tibia. These loading conditions have been used previously to approximate those applied during the pivot shift test since the actual loading conditions are unknown. Previous studies have utilized a combination of valgus and internal rotation torques of varying magnitudes[31,36–45] and we chose to apply equal torques based on preliminary studies to elicit greatest kinematic changes. The simulated pivot shift test was applied to the intact knee and then the resulting kinematics were replayed in position control mode after the following procedures were performed: (i) ACL transection; (ii) capsule separation (as shown in Fig. 3, the anterolateral capsule was separated from surrounding tissues to remove the interactions between the capsular and ligamentous components. Incisions were made on both sides of the lateral collateral ligament and a third incision was made to the anterolateral capsule starting lateral to Gerdy's tubercle leaving the insertions and origins intact); (iii) anterolateral capsule transection (transection of longitudinal fibers, inclusive of described anterolateral ligament); and (iv) lateral collateral ligament (LCL) transection (Table 1). Based on the principle of superposition, the in situ forces in the ACL, anterolateral capsule, LCL, and the forces transmitted between each region of the anterolateral capsule in response to the simulated pivot shift test for the intact knee could be determined.[31,46,47] A repeated measures ANOVA was performed using SPSS (version 20.0, SPSS Inc., Chicago, IL) to

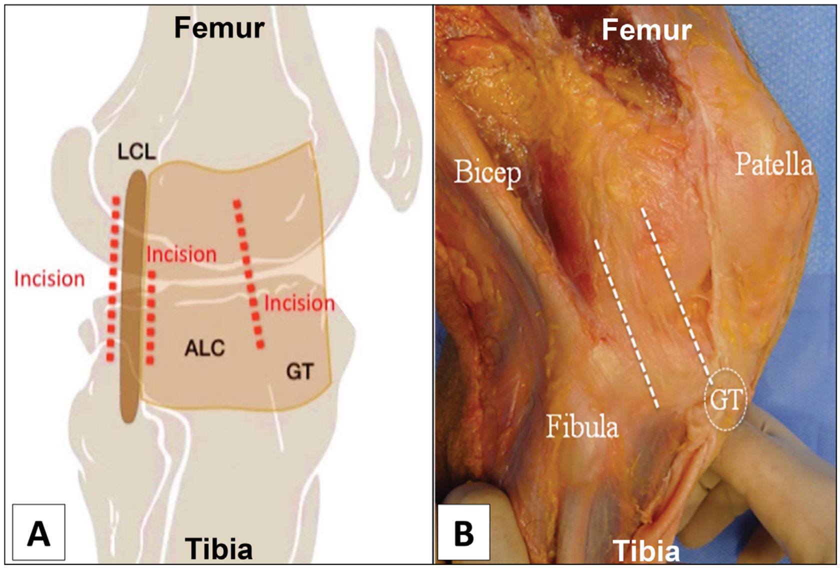

Figure 3. (A) Schematic showing the three incisions made during capsule separation: One incision on either side of the lateral collateral ligament and one incision to the anterolateral capsule (ALC) starting lateral of Gerdy's tubercle (GT) and the lateral collateral ligament were separated from the surrounding tissues, leaving the insertions and origins intact. (B) Corresponding photograph showing representative specimen with capsule separated.

compare the in situ forces at 5°, 15°, 30°, 45°, 60°, 75°, and 90° of knee flexion ($^*p < 0.05$).

RESULTS

The in situ forces in the soft tissues of the knee varied greatly in response to a simulated pivot shift test from full extension to 90° of flexion. (Fig. 4) The in situ force in the ACL was the greatest at low flexion angles; however, at approximately 40° of flexion the forces transmitted between each region of the anterolateral capsule became larger than the in situ force in the ACL. Overall, the anterolateral capsule exhibited the lowest in situ forces in response to a simulated pivot shift test. The in situ force in the LCL experienced small increases with increasing flexion angle and became larger than the in situ forces in the ACL between 60° and 75° of flexion.

The in situ force in the ACL was then compared the other in situ forces at 5°, 15°, 30°, 45°, 60°, 75°, and 90° of knee flexion because the ACL is considered the primary stabilizer for a pivot shift test. The in situ force in the ACL was significantly higher at 5° (percent difference = 324.7%) and 15° (percent difference = 136.8%) of flexion compared to the forces transmitted between each region of the anterolateral capsule ($p < 0.05$), but no differences could be detected at 30° and 45° of flexion ($p > 0.05$). (Table 2) The forces transmitted between each region of the anterolateral capsule became significantly higher than the in situ force in the ACL at 60° (percent difference = 39.6%), 75° (percent difference = 49.0%), and 90° (percent difference = 47.5%) of flexion ($p < 0.05$). The in situ force in the LCL experienced small increases with increasing flexion angle and no difference could be detected between the in situ in the ACL and in situ force in the LCL at 75° ($p > 0.05$).

Table 1. The Testing Protocol and the Data Acquired

Knee State	Loading Conditions	Data Acquired
Intact	Simulated Pivot Shift Test	Kinematics of intact knee (a)
Transect ACL	Replay (a)	In situ force in the ACL
Capsule Separation	Replay (a)	The forces transmitted between each region of the anterolateral capsule
Transect Anterolateral Capsule	Replay (a)	In situ force in anterolateral capsule
Transect LCL	Replay (a)	In situ force in the LCL

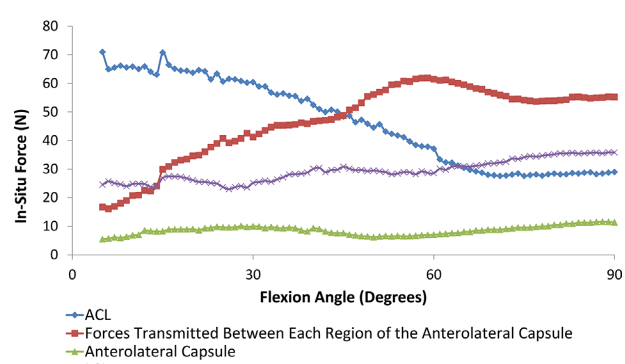

Figure 4. The in situ force in the ACL and the anterolateral structures throughout the range of flexion for the intact knee. (Newtons, mean).

Table 2. The In Situ Force in the ACL and the Anterolateral Structures at Discrete Flexion Angles for the Intact Knee

Flexion Angle (°)	ACL	Forces Transmitted Between Each Region of the Anterolateral Capsule	Anterolateral Capsule	LCL
5	71.0 ± 14.0	$16.7 \pm 7.1^{*}$	$5.4 \pm 1.6^{*,\#}$	$24.5 \pm 15.6^{*,+}$
15	70.7 ± 31.8	$29.9 \pm 14.5^{*}$	$8.2 \pm 3.2^{*,\#}$	$26.9 \pm 13.4^{*,+}$
30	60.4 ± 29.0	41.2 ± 19.3	$10.0 \pm 3.1^{*,\#}$	$25.1 \pm 12.1^{*,+}$
45	48.4 ± 26.3	48.8 ± 21.1	$7.5 \pm 4.4^{*,\#}$	$30.8 \pm 16.5^{*,+}$
60	37.1 ± 17.1	$61.4 \pm 16.2^{*}$	$7.0 \pm 3.7^{*,\#}$	$28.6 \pm 12.5^{*,+}$
75	27.6 ± 12.6	$54.1 \pm 14.7^{*}$	$9.5 \pm 5.6^{*,\#}$	$34.1 \pm 13.0^{+}$
90	29.0 ± 12.4	$55.2 \pm 18.4^{*}$	$11.4 \pm 6.9^{*,\#}$	$35.8 \pm 16.3^{+}$

Newtons, Mean ± standard deviation. Statistically significant differences ($p < 0.05$) are designated as follows: *denotes comparison to ACL, $^{\#}$denotes comparison to the forces transmitted between capsular regions and $^{+}$denotes comparison to anterolateral capsule.

Finally, in order to assess the role of the anterolateral capsule during the simulated pivot shift test, the in situ force in the anterolateral capsule was compared to each structure at 5°, 15°, 30°, 45°, 60°, 75°, and 90° of knee flexion. The in situ force in the anterolateral capsule was significantly lower than the in situ force in the ACL, the LCL, and the forces transmitted between each region of the anterolateral capsule at all flexion angles ($p < 0.05$).

DISCUSSION

This study demonstrated that the anterolateral structures of the knee play an increasingly important role in rotational stability with increasing flexion angle. Consistent with our hypothesis, our results confirmed that the ACL is the primary restraint to a simulated pivot shift test near full extension (5° and 15° of flexion), however as the flexion angle increases, the role of other structures in rotational stability increases. At 30° of flexion, the approximate flexion angle of the reduction event that occurs during the pivot shift test, no significant difference could be detected between the in situ force in the ACL and the forces transmitted between capsular regions. At higher flexion angles (60°, 75°, and 90° of flexion) the forces transmitted between each region of the anterolateral capsule became greater than the in situ force in the ACL.

The findings at low flexion angles are consistent with recently published kinematic data which showed that the ACL is the primary restraint to a simulated pivot shift test and that the anterolateral capsule plays a limited role at low flexion angles.[27,48] The role of the anterolateral capsule was evaluated during a simulated pivot shift test in response to a 5 Nm internal rotation torque and 10 Nm valgus torque applied to the knee at full extension.[27] Sectioning the anterolateral capsule in an ACL-deficient knee resulted in a small (2°) but significant increase in internal rotation leading to the conclusion that the anterolateral capsule has an effect on controlling rotational stability.[27]

A unique feature of the present study is that the loads were applied continuously to the knee during the simulated pivot shift test from full extension to 90° of flexion.[35] Thus, continuous data (Fig. 4) on the in situ forces in the soft tissue structures of the knee were obtained in response to the complex rotatory loads throughout the entire range of flexion. It is clear that the ACL is the primary stabilizer to the pivot shift at low flexion angles, which is critical for in vivo functional stability.[49] However, the fact that the role of the anterolateral capsule increases with increasing flexion angle highlights the importance of properly addressing injuries to secondary stabilizers when performing an ACL reconstruction.

An increased focus on the secondary stabilizers of the knee has led researchers to explore the peripheral structures, which resulted in the emergence of the anterolateral ligament. The anterolateral capsule was originally described by Vincent et al.,[28] but received more attention after it was anatomically described,[25] ultimately resulting in the so-called "anatomic anterolateral capsule" reconstruction. Although anatomic anterolateral capsule reconstructions are being used clinically,[50] little biomechanical or clinical data exists to justify the procedure. The concept of an "isometric graft" has been investigated and a procedure was proposed that does not theoretically result in excessive tightening or slacking during knee flexion.[51] However, the present study demonstrated that although the intact anterolateral capsule is an important rotatory stabilizer (especially at high flexion angles), this region primarily functioned as a sheet of tissue in response to the applied loading conditions and only transmits minimal load along its longitudinal direction.[52] Although the anterolateral capsule only carried small loads at all flexion angles, the role of the LCL did increase with increasing flexion angle and this ligament appears to become an important rotational stabilizer beyond 60° of flexion during a simulated pivot shift test.

This study had some limitations that should be considered. First, the iliotibial band had to be removed in order to visualize the anterolateral capsule and to enable the in situ forces to be determined. The iliotibial band has been reported to be an important restraint to anterior subluxation between 30° and 90° of flexion.[53] Although the present study was focused on examination of the passive knee structures rather than the active structures (iliotibial band), their findings should be considered when interpreting our results. In addition, the present study did not evaluate the role of the meniscus, which has previously been reported to contribute to rotational stability in combination with an ACL injury,[54,55] The anterolateral capsule, or an associated thickening in the described anatomical region, could not be identified in the majority of our specimens. Therefore, the region that would contain the capsular thickening was separated from the surrounding capsular structures. Although this limits the specificity of the study, the principle of superposition was utilized appropriately so that the in situ forces in the longitudinal fibers of the anterolateral capsule region (inclusive of the anterolateral capsule) could be determined. It should be noted that when applying the principle of superposition, variability in the manipulators position, and the control methodology could create uncertainty in the results despite the rigorous attempts to minimize the variability described in the methods section. However, for this study the average root mean square error between the desired and actual load targets was determined to be 0.2 Nm of internal rotation torque and 0.2 Nm of valgus rotation torque, therefore the impact should be minimal. Finally, the findings in this study are based on the simulated pivot shift and are not necessarily indicative of function under other loading conditions, including those experienced during the clinical pivot shift test and those experienced during activities of daily living.

In summary, this study demonstrated that the ACL is the primary rotatory stabilizer at low flexion angles during a simulated pivot shift test, where the majority of injuries occur, but the forces transmitted between capsular regions plays an important role as the flexion angle increases. This in turn raises important considerations for anterolateral ligament reconstruction or extra-articular tenodesis, which currently is performed for patients with "high grade" rotatory instability.[56,57] The contribution of the thickening in the anterolateral capsule to rotatory knee instability in this study was negligible. Furthermore, as demonstrated in this study, the anterolateral capsule will have an insignificant contribution to knee rotational stability in low flexion angles and the pivot shift test.

AUTHORS' CONTRIBUTION

All authors listed were involved in conceptualization of the project, interpreting data, and composing the manuscript. The robotic experimentation and data analysis was performed by Kevin Bell, Ata Azar, Sebastian Irarrazaval, and Daniel Guenther. The work submitted for publication has not been and will not be simultaneously submitted elsewhere.

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