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The Effect of Medial Versus Lateral Meniscectomy on the Stability of the Anterior Cruciate Ligament-Deficient Knee

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Background: The pivot shift is a dynamic test of knee stability that involves a pathologic, multiplanar motion path elicited by a combination of axial load and valgus force during a knee flexion from an extended position.

Purpose: To assess the stabilizing effect of the medial and lateral meniscus on anterior cruciate ligament-deficient (ACL-D) knees during the pivot shift examination.

Study Design: Controlled laboratory study.

Methods: A Lachman and a mechanized pivot shift test were performed on 16 fresh-frozen cadaveric hip-to-toe lower extremity specimens. The knee was tested intact, ACL-D, and after sectioning the medial meniscus (ACL/MM-D; n = 8), lateral meniscus (ACL/LM-D; n = 8), and both (ACL/LM/MM-D; n = 16). A navigation system recorded the resultant anterior tibial translations (ATTs). For statistical analysis an analysis of variance was used; significance was set at $P < .05$.

Results: The ATT significantly increased in the ACL-D knee after lateral meniscectomy (ACL/LM-D; $P < .05$) during the pivot shift maneuver. In the lateral compartment of the knee, ATT in the ACL-D knee increased by 6 mm after lateral meniscectomy during the pivot shift (16.6 ± 6.0 vs 10.5 ± 3.5 mm, $P < .01$ for ACL/LM out vs ACL out). Medial meniscectomy, conversely, had no significant effect on ATT in the ACL-D knee during pivot shift examination ($P > .05$). With standardized Lachman examination, however, ATT significantly increased after medial but not lateral meniscectomy compared with the ACL-D knee ($P < .001$).

Conclusion: Although the medial meniscus functions as a critical secondary stabilizer to anteriorly directed forces on the tibia during a Lachman examination, the lateral meniscus appears to be a more important restraint to anterior tibial translation during combined valgus and rotatory loads applied during a pivoting maneuver.

Clinical Relevance: This model may have implications in the evaluation of surgical reconstruction procedures in complex knee injuries.

Keywords: pivot shift; navigation; anterior cruciate ligament (ACL): double bundle

The anterior cruciate ligament (ACL) is the primary restraint to anterior tibial translation.[5,10] In cadaveric studies using a dynamic knee stiffness apparatus, Levy et al[17] showed that the medial meniscus is a secondary restraint to anterior-posterior displacement in the ACL-deficient knee during a simulated Lachman examination. On average, an additional 4 mm of anterior translation was observed after the medial meniscus was resected.

The lateral meniscus, unlike the medial meniscus, has no significant posterior wedge effect and has less firm capsular attachments to the tibial plateau.[16] Previous studies have shown that lateral meniscectomy in an ACL-deficient knee results in small but insignificant increases in anterior tibial translation during a Lachman test.[17] These studies, which assessed knee stability using a uniplanar anterior load, have resulted in the prevailing dogma that the medial meniscus is an important secondary passive restraint to anterior tibial translation.[16,17] Lateral meniscal injury may result in instability of the lateral compartment,[14,25] and the lateral meniscus is commonly injured concomitantly with ACL injury.[24]

The pivot shift is a dynamic test of knee stability that involves a pathologic, multiplanar motion path elicited by

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a combination of axial load and valgus force during knee flexion from an extended position. The presence of a positive pivot shift is predictive of osteoarthrosis of the knee, failure to return to previous level of sport, patient-reported instability, and poor subjective and objective outcome scores after ACL reconstruction.[3-6]

The emergence of computer navigation provides an opportunity to quantify the pivot shift in various knee conditions. We have previously developed a mechanized pivot shift tool to standardize the pivot shift examination and have quantified translations during pivot shift examination in various regions of the knee.[19,22] To our knowledge, there are no data on the effect of medial and lateral meniscectomy on the pivot shift examination in the ACL-deficient knee. Although it may be rare clinically, combined concomitant medial and lateral meniscus deficiency was used as a consistent model of complex knee instability in this study.

The objective was therefore to study the effect of sequential meniscectomy (lateral and medial) in the ACL-deficient knee kinematics during the pivot shift and other biomechanical tests of stability. Because translation in the lateral compartment was previously shown to most closely correlate to the clinical grade of the pivot shift,[15,22] our hypothesis was that anterior tibial translations during the pivot shift would be greater after lateral meniscectomy than after medial meniscectomy.

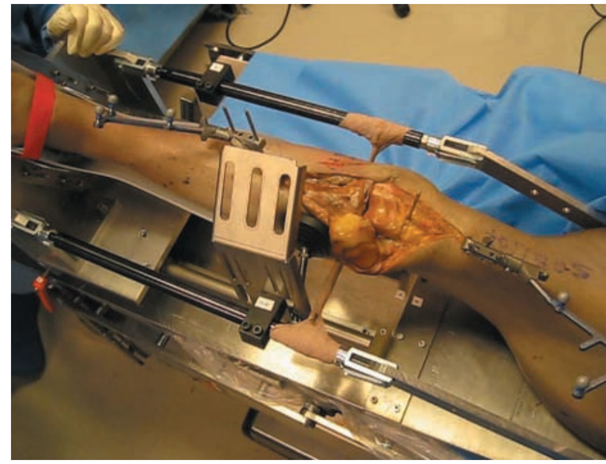

Figure 1. Left knee secured in mechanized pivot shift device. The leg holder holds the leg fixed in internal rotation and suspends the proximal tibia. There is no thigh support for the femur to allow subluxation posteriorly off the tibia. A bolster was mounted laterally to accentuate the valgus effect once the device is tilted to 45° (not imaged). The contralateral leg is abducted approximately 45° to increase the effect of the pivot shift.

METHODS

Ten fresh-frozen cadaveric hip-to-toe lower extremity specimens were used for this study (20 paired knees). Specimens were thawed for 48 hours at room temperature before testing. A testing cycle per extremity took, on average, 8 hours. Specimens were stored in a cold room overnight and the contralateral extremity was tested the following day.[18] During the testing procedure, room temperature was consistently kept at 22°C.[27]

Specimens were placed supine on an operating room table. A cross bar was mounted at the top of the table such that the pelvis was secured from moving in a proximal direction during the application of axial loads (Figure 1). Specimen position allowed for a free unrestricted range of motion at the hip and knee. Physical examination and a medial parapatellar arthrotomy of the knee were performed. Specimens were examined for alignment, deformities, ligamentous integrity, as well as the absence of significant meniscal and articular cartilage lesions.

The Praxim Surgetics surgical navigation system (Praxim/Medivision, Grenoble, France) with dedicated ACL software was used for kinematic data acquisition. A rigid body array was fixed to Steinman pins that were drilled in the distal femur and proximal tibia. Passive optical reflective markers were tracked by an infrared camera as described in previous reports.[2,7] Surface landmarks were recorded, intra-articular surface geometry was mapped, and a 3-dimensional model of the knee was created.[26] The knee was manually cycled from full extension to 90° of flexion. This represented the passive reference flexion/extension path from which the deviation was measured during each pivot shift examination.

The accuracy of the tracking system has been shown to be 1 mm/1°.[11,12] We have previously demonstrated a nearly perfect correlation between the navigated tracking system and an industrial robotic sensor.[22] Finally, we have recently demonstrated that the motion path, including the starting point, generated by the mechanized pivot shift has high repeatability.[19]

Instrumented laxity testing consisted of a Lachman test and pivot shift test. A 68-N Lachman test was performed with a spring scale attached to a 6.5-mm screw in the anterior tibia. Optical tracking of joint position allowed for consistent testing at 30° of knee flexion. Anterior knee translation was recorded by the navigation system during the instrumented Lachman examination. This biomechanical test setup has been shown to have adequate repeatability when compared with a robotic manipulator.[22]

A standardized navigated mechanized pivot shift maneuver was performed as described previously.[19] The mechanized pivot shifter was built to support and constrain the tibia of a whole lower extremity specimen while the femur was left unconstrained. The pivot shifter weighs approximately 70 lb and has a flat base that can be placed on an operating room table. Side brackets are mounted onto the base with a mechanical hinge. The center of rotation of the hinge is lined up at the level of the knee. A custom-made foot holder is attached at the lower end of the pivot shifter (Figure 1).

Application of forces and moments with the pivot shifter was achieved through built-in mechanisms. The foot holder

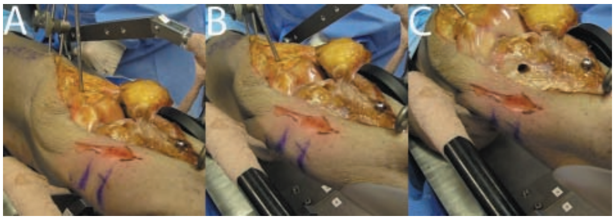

Figure 2. Femoral and tibial positions at different flexion angles. A, at full extension the tibiofemoral joint is reduced. B, at 30° of flexion the lateral femoral condyle shifts anteriorly. C, at 70° of flexion the lateral femoral condyle shifts completely anteriorly and rotates internally.

constrained the tibia in internal rotation or external rotation and allowed for application of axial compression loads to the knee joint. A side post positioned on the lateral aspect of the proximal tibia allowed for application of a valgus moment. Axial load on the limb was maintained throughout the pivot shift maneuver by securing the pelvis to the table and the foot to the foot holder. The motorized pivot shifter was able to range the knee from full extension to 100° of knee flexion through a motorized unit at the base of the device that moved the foot holder in a cranial direction (similar to a continuous passive motion unit). Because the femur was completely unconstrained it could reproducibly subluxate posteriorly with respect to the tibia after ACL transection. One full extension-flexion cycle took approximately 15 seconds, which allowed for ample time to observe the subluxation as well as reduction of the femorotibial joint (Figure 2).

The mechanized pivot shifter has been shown to reproducibly induce a positive pivot shift test in ACL-deficient knees with excellent repeatability compared with a manual examination. Magnitude of translation and rotation was thereby consistently lower than that achieved with a manual pivot shift examination.[19]

During the mechanized pivot shift, the navigation system recorded the 3-dimensional motion path of a tracked point at the center of the tibia, center of the medial tibial plateau, and center of the lateral tibial plateau. Motion of the tibial points was analyzed throughout a given motion path with respect to a tracked central point in the notch of the femur. The ACL-specific software of the navigation system allowed for comparison of the motion path during the pivot shift with the reference motion path of flexion-extension.[7,15,21] The navigation software used for the biomechanical testing in this study was a dedicated ACL navigation application designed by Praxim. In addition to navigated guidance for tunnel positioning, this application allows for tracking and quantification of knee kinematics during a stability examination. Maximum tibial translation during the pivot shift maneuver is reported as the difference between reference motion path and pivot shift motion path. The surgical navigation system enabled separate analysis of kinematics in the medial, lateral, and central compartments, respectively. Therefore, it was possible to test the hypothesis under study. The main advantage of soft tissue navigation is the ability to analyze kinematics during a dynamic test rather than during a “simulated pivot shift.”

The use of a surgical navigation system during clinical laxity examinations was shown to be reliable and repeatable. High intraclass correlation coefficients were recorded for the surgical navigation system in comparison with a robotic manipulator (intraclass correlation coefficient = 0.998).[22]

The knees were divided into 2 groups: a medial meniscectomy (MM) group and a lateral meniscectomy (LM) group. For each cadaveric specimen, 1 knee was randomly assigned to the MM group and the contralateral knee was assigned to the LM group. In all cases, a medial parapatellar arthrotomy was performed to vent the joint. Specimens were excluded for the following criteria: (1) previous cruciate ligament injury (by physical examination and inspection); (2) collateral ligament instability (by physical examination); (3) meniscal injury involving greater than one third of the meniscus; (4) signs of pre-existing degenerative joint disease, such as osteophytes and synovitic disease; (5) grade III and greater cartilage lesions; (6) deformities; and (7) previous knee surgery.

The testing protocol consisted of instrumented Lachman and mechanized pivot shift evaluation in the intact state and after complete ACL transection (Figure 3). The ACL was transected in the following sequence. In the first step of ACL transection, the ACL was exposed by carefully dissecting the synovial sheath from the ACL at 90° of flexion. The synovial tissue was removed between the ACL and the PCL. Starting with the femoral insertion, soft tissue lining the medial wall of the lateral femoral condyle was removed, exposing the lateral intercondylar ridge. At 120° of flexion the femoral insertion of the ACL was identified below the lateral intercondylar ridge. With use of a No. 15 blade, the anteromedial bundle was dissected from its femoral insertion followed by the posterolateral bundle. The center of the femoral insertion of the anteromedial bundle and the posterolateral bundle was marked with a methylene blue marker. With use of a Kocher clamp the ACL was retracted anteriorly. The posterolateral bundle was sharply dissected from its tibial insertion followed by the anteromedial bundle. An anterior drawer test now revealed no remaining fibers under tension.

In the MM group, a complete meniscectomy was performed after ACL transection (Figure 4A). This was performed with the knee at 15° of flexion and valgus stress followed by full flexion. A small peripheral rim and the deep medial collateral ligament were left intact. In the LM group, a complete lateral meniscectomy was performed after ACL transection (Figure 4B). This was performed by cutting and elevating the anterior horn of the lateral meniscus with a No. 15 scalpel. The anterior horn was clamped with a Kocher clamp and the body of the meniscus was resected at the meniscocapsular junction under axial tension on the Kocher clamp and with the knee at 90° of flexion and varus stress. With the knee in full flexion, the lateral meniscus was dislocated into the notch and the posterior horn was resected. The popliteus tendon was left intact. Instrumented testing was performed for the ACL/medial meniscus-deficient (MM group) knees and for the ACL/lateral meniscus-deficient (LM group)

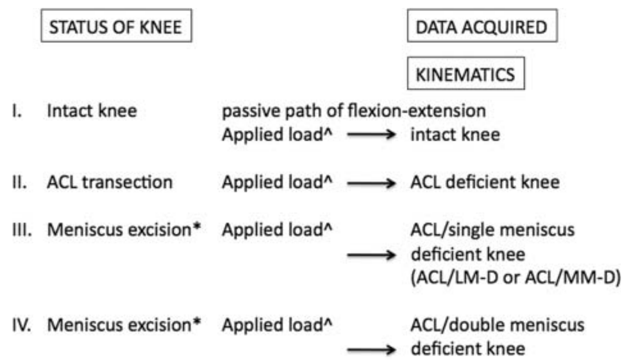

Figure 3. Experimental protocol and data that were acquired. *, the order of meniscectomy (medial vs lateral) was randomized. ^; three loading conditions were applied (68-N Lachman test, 68-N anterior drawer test, and pivot shift test).

knees. Extreme care was taken to avoid violation of the joint capsule on the medial or lateral compartment during meniscectomy. Finally, in both groups, the remaining meniscus was excised and testing was repeated in the ACL medial and lateral meniscus-deficient knees.

Statistical Analysis

Repeated measures analysis of variance with post hoc Tukey multiple comparison tests was used to compare the translations during the Lachman examination and for each tracked point during the pivot shift examination within each group (MM group and LM group). The study was powered to detect a difference (3 mm) in the Lachman test in the ACL-deficient versus ACL and medial meniscus-deficient state based on historical data (alpha 0.80). For the pivot shift manual grading, a Wilcoxon signed rank test was used to compare the nonparametric grades between the ACL-deficient and ACL and meniscus-deficient states. All statistical analysis was performed using GraphPad Prism (GraphPad Software, San Diego, California). Significance was set at $P < .05$.

RESULTS

Specimens

There were 6 female and 4 male specimens with an average age of 51 years (range, 35-62 years). Of the 10 cadavers, 2 were excluded because of degenerative changes in the knee. As such, 8 cadavers (16 knees) were used to provide 8 knees each in both the MM and the LM groups.

Lachman Testing

In both the MM and the LM groups, isolated transection of the ACL resulted in significant increased anterior translation during Lachman examination compared with the

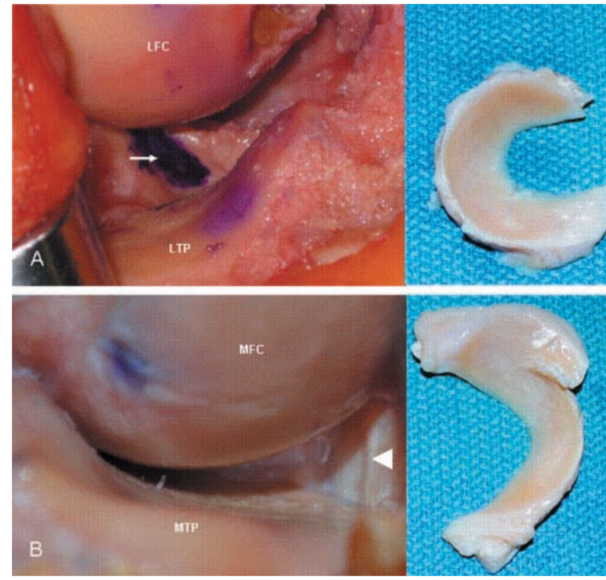

Figure 4. A, the lateral compartment after total meniscectomy. The intact popliteus tendon is seen (arrow). The macroscopic specimen is shown on the right. LFC, lateral femoral condyle; LTP, lateral tibial plateau. B, the medial compartment after total meniscectomy. The intact deep medial collateral ligament is seen (arrow head). The macroscopic specimen is shown on the right. MFC, medial femoral condyle; MTP, medial tibial plateau.

intact knee state (5.9 ± 3.1 vs 3.1 ± 1.1 mm, $P < .05$, for ACL-deficient vs intact in the MM group; 6.7 ± 2.4 vs 3.6 ± 1.8 mm, $P < .05$, for ACL-deficient vs intact in the LM group)

In the MM group, there was an average of 5.5 mm additional anterior translation after excision of the medial meniscus; this difference was statistically significant (11.4 ± 5.2 vs 5.9 ± 3.1 mm, $P < .001$, for ACL/MM-deficient vs ACL-deficient, respectively). Further resection of the lateral meniscus in the ACL/MM-deficient knee resulted in no significant change in anterior translation during Lachman examination (11.9.0 ± 2.9 vs 11.4 ± 5.2 mm, $P > 0.5$ for ACL/MM/LM-deficient vs ACL/MM-deficient, respectively). These data are summarized in Figure 5A.

In the LM group, additional excision of the lateral meniscus after ACL transection resulted in an average of 1.9 mm of increased anterior translation; this difference was not statistically significant (8.6 ± 2.8 vs 6.7 ± 2.4 mm, $P > .05$ for ACL/LM-deficient vs ACL-deficient, respectively). However, when excision of the medial meniscus was performed in the ACL/LM-deficient knees, there was a significant increase averaging 5.3 mm in anterior translation during Lachman testing (13.9 ± 2.7 vs 8.6 ± 2.8 mm, $P < .001$ for ACL/MM/LM-deficient vs ACL/LM-deficient). These results are summarized in Figure 5B.

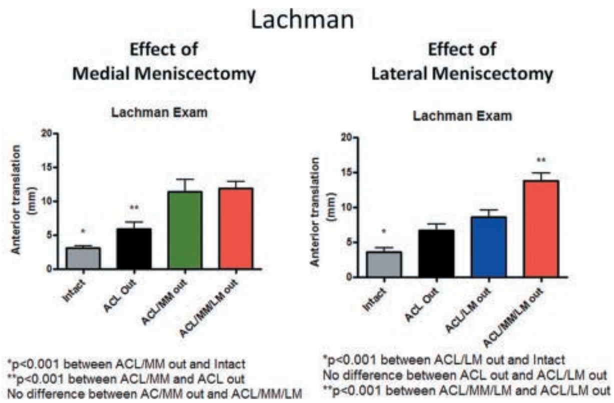

Figure 5. The effect of medial meniscectomy (MM, n = 8) and lateral meniscectomy (LM, n = 8) in response to a 68-N Lachman test. Anterior tibial translation for the intact knee, isolated ACL deficiency (ACL-D), ACL-single meniscectomy (ACL/LM-D or ACL/MM-D), and ACL-double meniscectomy (ACL/LM/MM-D) is shown. In the medial meniscectomy group there is a significant difference between ACL-D and ACL/MM-D ($P < .001$). In the lateral meniscectomy group there is a significant difference between ACL-D and ACL/LM/MM-D ($P < .001$). ACL out, ACL-deficient; ACL/MM out, ACL/MM-deficient; ACL/MM/LM out, ACL/MM/LM-deficient.

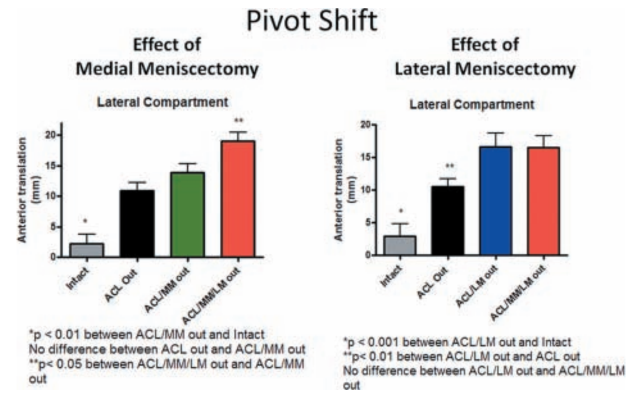

Figure 6. The effect of medial meniscectomy (MM; n = 8) and lateral meniscectomy (LM; n = 8) in response to pivot shift test. Anterior tibial translation in the lateral compartment for the intact knee, isolated ACL deficiency (ACL-D), ACL-single meniscectomy (ACL/LM-D or ACL/MM-D), and ACL-double meniscectomy (ACL/LM/MM-D) is shown. In the MM group there is a significant difference between ACL-D and ACL/LM/MM-D ($P < .05$). In the LM group there is a significant difference between ACL-D and ACL/LM-D ($P < .01$). ACL out, ACL-deficient; ACL/MM out, ACL/MM-deficient; ACL/MM/LM out, ACL/MM/LM-deficient.

Pivot Shift Examination

Lateral Compartment Translations. In both the MM and LM groups, isolated ACL transection resulted in significant increases in mean anterior translation of approximately 9 mm in the lateral compartment during pivot shift examination (10.9 ± 4.0 vs 2.2 ± 4.6 mm, $P < .001$, for ACL-deficient vs intact knee in MM group and 10.5 ± 3.5 vs 2.9 ± 5.4 mm, $P < .001$, for ACL-deficient vs intact knee in LM group).

In the MM group, medial meniscectomy after ACL transection resulted in no significant increases in anterior translation in the lateral compartment compared with the isolated ACL transection alone (13.9 ± 4.3 vs 10.0 ± 4.0 mm, $P > .05$ for ACL/MM out vs ACL-deficient). However, when excision of the lateral meniscus was performed in the ACL/MM-deficient knees, there was a significant increase in anterior translation in the lateral compartment during pivot shift examination (19.0 ± 4.6 vs 13.9 ± 4.3 mm, $P < .05$, for ACL/MM/LM-deficient vs ACL/MM-deficient) (Figure 6A).

Conversely, lateral meniscectomy after ACL transection resulted in a significant increase of approximately 6 mm of additional anterior translation in the lateral compartment compared with isolated ACL transection; this difference was statistically significant (16.6 ± 6.0 vs 10.5 ± 3.5 mm, $P < .01$, for ACL/LM-deficient vs ACL-deficient). Additional excision of the medial meniscus in the ACL/LM knees had no effect on translation in the lateral compartment during the pivot shift (16.5 ± 5.2 vs 16.6 ± 6.0 mm, $P > .05$ for ACL/MM/LM-deficient vs ACL/LM-deficient). These results are summarized in Figure 6B.

Central Point and Medial Compartment Translations. Isolated ACL transection did not significantly increase anterior translation in the center of the knee or the medial compartment compared with the intact knee in either group. In the MM group, medial meniscectomy after ACL transection resulted in no significant increases in anterior translation in the central region of the knee or the medial compartment compared with isolated ACL transection alone. Conversely, lateral meniscectomy after ACL transection resulted in significant increases in anterior translation in both the central region of the knee and the medial compartment compared with isolated ACL transection alone (11.4 ± 6.2 vs 5.9 ± 3.4 mm, $P < .01$, for ACL/LM-deficient vs ACL-deficient for central point and 6.0 ± 8.8 vs –0.7 ± 6.3 mm, $P < .05$, for ACL/LM-deficient vs ACL-deficient in medial compartment).

DISCUSSION

This study examined the effect of lateral meniscectomy versus medial meniscectomy on knee kinematics during the Lachman examination and the pivot shift in the ACL-deficient knee. In support of previous studies, we found the medial meniscus is an important secondary restraint to anterior tibial translation during the Lachman test. However, using computer-assisted navigation, we were able to objectively assess the effect of meniscectomy on anterior laxity during the pivot shift test and found that the lateral meniscus has a relatively more important secondary restraining role to the combined axial and rotatory loads. With the complex rotatory and axial loads of a pivoting maneuver, resection of the lateral meniscus resulted in significant increases in the translation of the lateral, central, and medial tibia compared with ACL deficiency alone. These results suggest that while the posterior horn of the medial meniscus has been recognized as the critical secondary stabilizer of the knee in the setting of ACL deficiency, the lateral meniscus is of tantamount importance and may play a more crucial role in conferring stability to the ACL-deficient knee that is subjected to the complex and combined rotatory loads of sports activities.

The results in this study support previous authors' findings that the medial meniscus is more important than the lateral meniscus in restraining uniplanar anterior loads on the tibia.[16,17] Using a standardized Lachman examination, we demonstrated that resection of only the medial and not the lateral meniscus resulted in significant increases in the anterior translation of the tibia. This finding is thought to be due to the firm capsular attachments of the posterior horn of the medial meniscus and associated "wedge effect." The clinical significance of this finding, however, appears unclear. It has been well established in the literature that significantly greater translations of the tibia occur in the lateral compartment with gait, running, and other activities of daily living.[16] The Lachman test is useful as a clinical test of ACL integrity but does not replicate the complex, combined rotatory and axial loads that are applied to the knee during sports activities. The pivot shift examination is a better test of the functional instability experienced by patients with ACL insufficiency leading to the symptoms of the knee "giving way."

The use of whole lower extremities in this study enabled application of a reproducible pivot shift, which cannot be done in midfemur-transected specimens. Computer navigation further enabled the study of motion paths independently in the medial and lateral compartments of the knee. The lateral compartment was previously shown to have a greater correlation to the grading of the pivot shift.[15,21] The importance of the lateral meniscus is therefore not entirely unexpected, based on previous work reported in the literature.[7,9,21] Furthermore, removal of the lateral meniscus may increase the incongruity of an already incongruent lateral compartment and facilitate the tibiofemoral subluxation that occurs with a pivoting maneuver.

The clinical relevance of these findings is significant. As a critical secondary stabilizer of the knee that is subjected to combined axial and rotatory loads, the lateral meniscus should be repaired and preserved whenever possible. Our study suggests that a concomitant partial meniscectomy for lateral meniscal injury at the time of ACL reconstruction may render the knee at greater risk for postoperative instability and recurrent ACL failure. In addition, this may explain the accelerated deterioration of the lateral compartment clinically after lateral meniscectomy, particularly in an ACL-deficient knee.[8] In this regard, in the setting of ACL deficiency or reconstruction, meniscal repair whenever possible or even lateral meniscus transplantation in the event of subtotal or total meniscal loss may be crucial to not only preserve the lateral compartment, but also to restore native kinematics to the knee joint.

Assessment of knee stability after combined medial and lateral meniscectomy after ACL transection has limited clinical relevance. The sequential cutting methods used in this study are well accepted for testing the restraints to tibiofemoral laxity, and much of our present understanding of the mechanical role of passive restraining structures has come from the use of sequential cutting studies. The 2 cutting protocols used in our study allowed for the menisci to be investigated in a manner that allowed quantitative data to be obtained on their individual contributions to resisting the range of translation forces and rotational moments applied.

A limitation of the study is the use of arthrotomy instead of arthroscopy. This was done to facilitate resection of menisci and digitization for navigation. Cadaveric laxity testing forms much of the basis of our understanding of the function of the knee. Previous studies assessing knee kinematics using the Praxim system have relied on manual pivot examination.[23] This has obvious limitations of interobserver error.[13] The mechanized pivot shifter is a validated tool to reproduce the aberrant motion path elicited by a pivot shift examination.[19] This tool has excellent repeatability for translations during the pivot shift maneuver and, in the setting of ACL deficiency, reliably induces a characteristic pathologic motion path that is reproduced with manual pivot shift testing. Specifically, in the sagittal plane, the tibia subluxates anterior to the femur during early flexion and then suddenly reduces at approximately 20° to 30° of flexion; this motion path results in a pathognomonic P-shaped curve that has previously been described clinically and in cadaveric studies in the setting of ACL deficiency.[7,15,21] This P-shaped curve in the sagittal plane was seen in all ACL-transected knees in this study during the mechanized maneuver. However, the magnitude of applied forces and moments during the pivot shift is unknown. Repeatability for rotations has not been shown to be robust using this device; as such, rotation data were not presented. In addition, the magnitude translations of the pivot shift are typically larger, although less reproducible, when the examination is performed manually when comparing the mechanized device.[20]

Future studies should attempt to identify the influence of partial meniscectomy on knee instability. It is important to recognize that our study does not conclude a more important or significant biomechanical role of the lateral compared with medial meniscus in the setting of ACL deficiency. Rather, we have identified novel and complementary roles that are both critical for the native kinematics of the knee joint.

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