Biomechanical Analysis of an Isolated Fibular (Lateral) Collateral Ligament Reconstruction Using an Autogenous Semitendinosus Graft

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Background: The fibular collateral ligament is the primary stabilizer to varus instability of the knee. Untreated fibular collateral ligament injuries can lead to residual knee instability and can increase the risk of concurrent cruciate ligament reconstruction graft failures. Anatomic reconstructions of the fibular collateral ligament have not been biomechanically validated.

Purpose: To describe an anatomic fibular collateral ligament reconstruction using an autogenous semitendinosus graft and to test the hypothesis that using this reconstruction technique to treat an isolated fibular collateral ligament injury will restore the knee to near normal stability.

Study Design: Controlled laboratory study.

Methods: Ten nonpaired, fresh-frozen cadaveric knees were biomechanically subjected to a 10 N·m varus moment and 5 N·m external and internal rotation torques at 0°, 15°, 30°, 60°, and 90° of knee flexion. Testing was performed with an intact and sectioned fibular collateral ligament, and also after an anatomic reconstruction of the fibular collateral ligament with an autogenous semitendinosus graft. Motion changes were assessed with a 6 degree of freedom electromagnetic motion analysis system.

Results: After sectioning, we found significant increases in varus rotation at 0°, 15°, 30°, 60°, and 90°, external rotation at 60° and 90°, and internal rotation at 0°, 15°, 30°, 60°, and 90° of knee flexion. After reconstruction, there were significant decreases in motion in varus rotation at 0°, 15°, 30°, 60°, and 90°, external rotation at 60° and 90°, and internal rotation at 0°, 15°, and 30° of knee flexion. In addition, we observed a full recovery of knee stability in varus rotation at 0°, 60°, and 90°, external rotation at 60° and 90°, and internal rotation at 0° and 30° of knee flexion.

Conclusion: An anatomic fibular collateral ligament reconstruction restores varus, external, and internal rotation to near normal stability in a knee with an isolated fibular collateral ligament injury.

Clinical Significance: An anatomic reconstruction of the fibular collateral ligament with an autogenous semitendinosus graft is a viable option to treat nonrepairable acute or chronic fibular collateral ligament tears in patients with varus instability.

Keywords: fibular collateral ligament; anatomic reconstruction; semitendinosus graft; biomechanics

It has been well documented that the fibular (lateral) collateral ligament (FCL) is the primary varus stabilizer of the knee.[8,10] Consequently, isolated FCL injuries can elicit abnormal varus knee instability that can lead to functional limitations, a varus thrust gait pattern, and the potential development of medial meniscal tears or medial compartment arthritis over time due to the increased compressive forces at the medial tibiofemoral compartment.[16,23,30] In addition, it has been demonstrated that varus instability, primarily due to a deficient FCL from an untreated posterolateral knee injury, causes a significant increase in force on both anterior cruciate (ACL) and posterior cruciate ligament (PCL) reconstruction grafts.[11,21,22] Therefore, a reconstruction technique to address nonrepairable acute or chronic isolated FCL tears is important to address these pathologic abnormalities.

Historically, isolated FCL injuries have been treated by direct repair,[2] augmentation with a strip of the common biceps tendon,[3,38] augmentation with a portion of the iliotibial band,[3] imbrication and advancement with a bone

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block,[7,13] or reconstruction using allograft tissue at nonanatomic attachment sites.[4,6,24,29] However, to our knowledge no anatomic approach to reconstructing nonrepairable isolated FCL injuries has been published. The importance here is that often a direct repair is not possible, and in the absence of a more complicated injury additionally involving the popliteus tendon and popliteofibular ligament, our previously described anatomic technique[19] to address reconstruction of these 3 structures is not indicated. Therefore, our hypothesis was that an anatomic reconstruction of an isolated FCL injury using an autogenous semitendinosus graft would restore the knee to near normal stability. An anatomic approach was considered based on previous studies for other knee ligaments that demonstrated that anatomic reconstructions better approximate normal knee biomechanics.[5,6,11,12]

MATERIALS AND METHODS

This study was performed using 10 nonpaired fresh-frozen cadaveric knees that had no evidence of prior injury, arthritis, or other abnormalities. The knees were stored at –20 C and thawed out overnight before biomechanical testing. The skin and superficial layers were dissected and the semitendinosus tendon harvested with a closed-ended hamstring stripper, cleaned of all muscular tissues, tubularized on each end with a No. 2 nonabsorbable suture to fit through a 7-mm tunnel, and kept moist in room temperature saline for the reconstruction.

Next, the proximal 10 cm of the femur was stripped of all soft tissues, and the marrow cavity was packed with polymethylmethacrylate (PMMA). The tibia and fibula were potted together with PMMA, and an intramedullary rod was placed for application of external loads. The knee was then mounted on the testing fixture with the femur fixed by an aluminum clamp. The orientation of the knee was with the femur lying horizontal and the tibia/fibula secured at the desired knee-testing angle with carbon fiber rods (Figure 1).

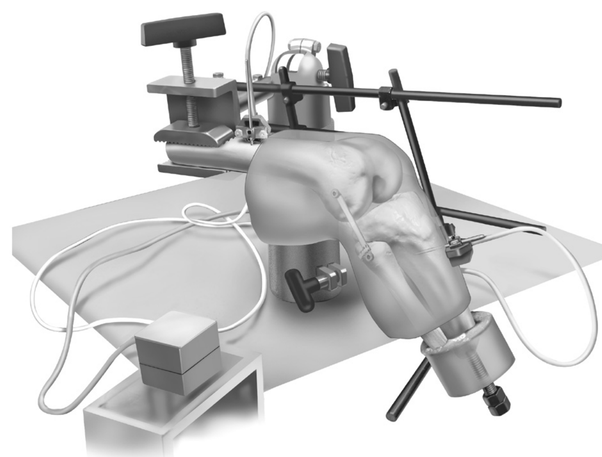

Figure 1. The biomechanical testing apparatus for the fibular collateral ligament reconstruction with an autogenous semitendinosus graft (anterolateral view, right knee).

Degree of Angulation Measurements

The position of the tibia with respect to the femur was measured using a 6 degree of freedom electromagnetic motion analysis system (Polhemus Fastrak; Polhemus Incorporated, Colchester, Vt) with sensors that were rigidly attached to the femur and tibia. To minimize any metallic interference, the global transmitter was mounted on Plexiglas, and no metal objects were allowed between this transmitter and the 2 sensors mounted to the knees. With use of a stylus, a 3-dimensional x, y, z coordinate system was established for the 2 sensors, which were firmly attached to the anterior cortex of both the femur and tibia. The bony landmarks used to establish the coordinate systems were the medial and lateral femoral epicondyles, the proximal shaft of the femur, and the distal shaft of the tibia. Information regarding the motion of these planes with respect to each other was collected from the Polhemus device and was integrated into Motion Monitor computer software (Innovative Sports Training, Chicago, Ill). Data involving the position changes between the established planes before and after an applied load were recorded. All experiments were performed at approximately 400 mm from the transmitter, which is within the reported range of 100 to 700 mm between the sensors and the transmitter for optimal accuracy.[1,27] To verify the Polhemus was operating within its reported accuracy during each trial, we measured points on a 3-dimensional grid with a known accuracy of 0.001 mm and compared this with the reading displayed through the computer software. We have previously demonstrated this to have an accuracy of 0.1 mm.[20] The accuracy of AC-tracking devices has been reported to be within 0.3 to 0.9 mm and 0.3° to 1.0°.[27]

Load Application and Anatomic Reconstruction

Varus moments were applied with a load cell (Interface, Scottsdale, Ariz). External and internal torques were applied with a torque wrench (Stanley-Proto, New Britain, Conn; manufacturer's reported accuracy, ±1%). The Polhemus device and the Motion Monitor software were used to ensure that all motions during testing were accurate. This was possible because movements were reported through the program on each isolated axis, allowing us to focus on varus or rotational torques and ignore any confounding motions. Immediate feedback via graphs was provided to verify proper data capture. Any test with irregular motions along our desired axis was repeated before any further testing continued. At all times, the specimens were kept moist with a saline spray.

The knees were tested under 3 conditions: FCL intact, FCL cut, and FCL reconstructed using an autogenous semitendinosus graft. We tested the knees at flexion angles of 0 , 15 , 30 , 60 , and 90 with the following applied loads: 10 N·m varus moment, and 5 N·m external and internal rotational torques.[21,22] To calculate the force applied in varus rotation testing, we took the desired moment (10 N·m) and divided this by the distance from the joint line to the point of force application in meters. Dividing the moment (N·m) by the distance (m) resulted in the required force to apply at that point to achieve the 10 N·m moment. Each knee was tested 3 times for each applied load at each flexion angle and the results averaged.

The knees were first tested in the intact state. After testing, the FCL was sectioned. Biomechanical testing was repeated to measure the degree of instability seen with an isolated tear of the FCL.

After biomechanical testing of abnormal motion limits for an isolated FCL tear was complete, an anatomical FCL reconstruction using an autogenous semitendinosus graft was performed. The anatomic femoral attachment site of the FCL, slightly proximal and posterior to the lateral epicondyle,[20] was isolated, and an eyelet pin was drilled proximomedially across the distal femur through the center of the FCL femoral attachment site. A 7-mm reamer was then reamed to a depth of 25 mm over the eyelet pin, and a 7-mm bioabsorbable screw tap was used to tap the tunnel. The previously tubularized semitendinosus graft was then passed into the tunnel by pulling its femoral passing sutures medially across the femur via the eyelet-passing pin, and the tendon was recessed 25 mm into the tunnel. A 7 mm × 23 mm bioabsorbable screw was placed at the superior aperture of the reconstruction tunnel to secure the graft in place (Figure 2). The strength of the femoral fixation was then qualitatively verified at this point by applying a secure manual lateral traction force.

The fixation tunnel for the graft in the fibular head and styloid was drilled next. The fibular attachment site of the FCL, in a depression on the lateral aspect of the fibular head,[20] was identified, and a guide pin was drilled through it using a cannulated ACL guide system. The guide pin exited the posteromedial aspect of the fibular styloid, distal to the attachment site of the popliteofibular ligament on the posteromedial aspect of the fibular head. The FCL graft was then passed distally along its normal course under the superficial layer of the iliotibial band and the lateral aponeurosis of the long head of the biceps femoris[35] and through the fibular tunnel, from lateral to medial. While an 88-N proximal traction force was applied to tension the graft, it was fixed in the fibular head tunnel with a 7 mm × 23 mm bioabsorbable screw while the knee was flexed to 30 , in neutral rotation, and with a valgus force applied to reduce any potential lateral compartment gapping (due to the sectioned FCL). Once its fibular fixation screw was in place, the graft was then routed anteriorly around the posterior aspect of the fibular head, medial (deep) through a small split in the anterior arm of the long head of the biceps femoris, and sutured to itself with No. 2 nonabsorbable sutures to serve as supplemental fixation (Figure 2). Biomechanical testing was then performed for the FCL reconstruction graft.

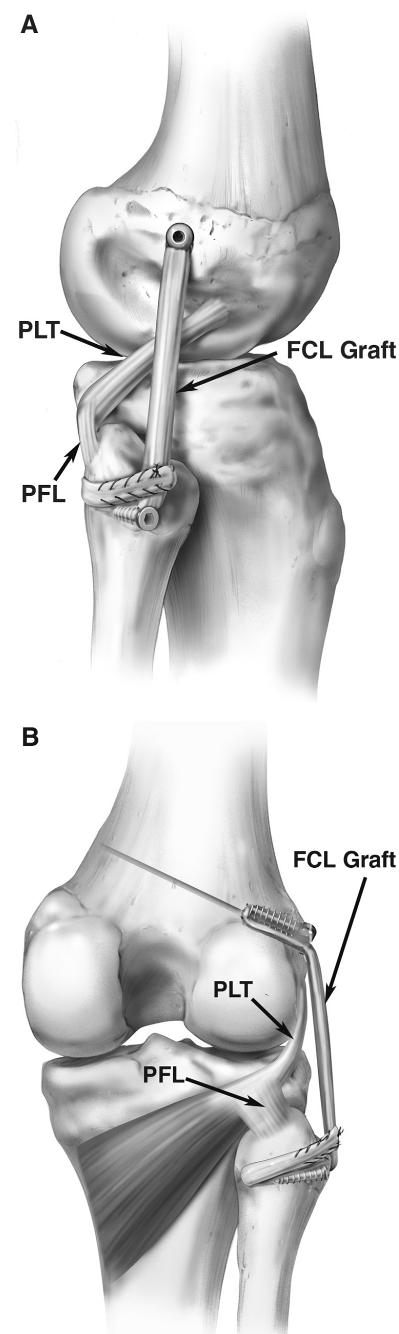

Figure 2. An isolated FCL reconstruction procedure demonstrating the reconstructed FCL using a semitendinosus graft. Also shown is an intact popliteus tendon and popliteofibular ligament. Note that the tunnel exiting the posteromedial margin of the fibular head is distal to the fibular attachment of the popliteofibular ligament. A) lateral view, right knee. B) posterior view, right knee. FCL graft, fibular collateral ligament reconstruction with an autogenous semitendinosus graft; PLT, popliteus tendon; PFL, popliteofibular ligament.

Pilot Studies

A pilot study was performed on 2 knees to determine the specific loading conditions and biomechanical forces to be included in the study. Pilot testing was performed at 0 , 15 , 30 , 60 , and 90 of knee flexion with the following applied loads: 5 N·m external and internal torques, 10 N·m varus and valgus moments, and 60-N anterior and posterior forces.[21,22] Data gathered during our pilot studies, and also previously reported results,[8,10,28,36] demonstrated no change in anterior, posterior, or valgus motions after isolated FCL injuries, so these applied loads were removed from the final biomechanical testing protocol. Our exclusion criteria for these loads were established by observing differences in rotation of less than 1 degree and in translation of less than 1 mm.

Statistical Analysis

An a priori power analysis using data from the pilot study revealed that 9 knees had a power of .85 to detect a difference of 0.5° of varus rotation with an alpha of .05. Statistical data analysis of each of the 3 motions was performed using repeated-measures analysis of variance. We compared the intact, sectioned, and reconstructed states of the knees at each flexion angle using the Bonferroni multiple comparisons test. The program SAS 9.1.3 (SAS Institute, Cary, NC) for Windows (Microsoft, Seattle, Wash) was used to run the statistical analysis. Statistical significance was defined for $P < .05$.

RESULTS

There were no graft fixation problems or evidence of graft slippage in any of the specimens. Average means for each testing condition are listed in Table 1.

Varus Data

We found statistically significant increases in varus rotation when comparing sectioned and intact knee conditions at 0° ($P < .0001$), 15° ($P < .0001$), 30° ($P < .0001$), 60° ($P < .0001$), and 90° ($P < .0001$) of knee flexion (Figure 3). In addition, we found statistically significant decreases in varus rotation when comparing the reconstructed to sectioned FCL knee conditions at 0° ($P < .0001$), 15° ($P < .0001$), 30° ($P < .0001$), 60° ($P < .0001$), and 90° ($P < .0001$) of knee flexion. When comparing the reconstructed to intact knee conditions, we found small but significant increases of 0.8° at 15° ($P < .0004$) and 0.7° at 30° ($P < .005$) of knee flexion. No significant differences were found between these 2 conditions at 0°, 60°, or 90° of knee flexion.

External Rotation Data

We found significant increases in external rotation when comparing the sectioned and intact FCL knee conditions at 60° ($P < .01$), and 90° ($P < .006$) of knee flexion. There were no significant differences in the intact versus sectioned states at 0°, 15°, and 30° of knee flexion. Comparing the reconstructed FCL and sectioned conditions, we also saw significant decreases in external rotation at 0° ($P < .0004$), 15° ($P < .02$), 60° ($P < .0002$), and 90° ($P < .0001$) of knee flexion. No significant difference was observed at 30° of knee flexion. When comparing the reconstructed FCL and the intact conditions, there was a small, but significant, 1.4° decrease in external rotation at 0° ($P < .0008$) of knee flexion, and no significant differences were seen at 15°, 30°, 60°, and 90° (Figure 4) of knee flexion.

Internal Rotation Data

We found significant increases in internal rotation when comparing sectioned and intact FCL knee conditions at 0° ($P < .02$), 15° ($P < .0001$), 30° ($P < .0001$), 60° ($P < .0001$), and 90° ($P < .0001$) of knee flexion. Comparing the reconstructed FCL and sectioned conditions, we saw statistically

TABLE 1
Average Degree Changes After an Applied Load in Each Testing Condition for Varus Rotation, External Rotation, and Internal Rotation

Testing State	Intact	Sectioned	Reconstructed
Varus Rotation			
0°	3.7° ± 1.8°	5.2° ± 2.0°[a]	3.9° ± 2.0°[b]
15°	5.0° ± 2.5°	8.0° ± 3.3°[a]	5.9° ± 3.2°[b,c]
30°	5.6° ± 2.3°	8.9° ± 3.6°[a]	6.3° ± 3.2°[b,c]
60°	5.4° ± 1.2°	8.0° ± 1.9°[a]	6.0° ± 1.7°[b]
90°	5.4° ± 1.1°	6.7° ± 1.2°[a]	5.1° ± 1.1°[b]
External Rotation			
0°	11.8° ± 3.6°	11.8° ± 2.5°	10.4° ± 4.2°[b,c]
15°	14.8° ± 3.8°	15.6° ± 3.7°	14.4° ± 4.7°[b]
30°	14.8° ± 3.9°	15.7° ± 3.8°	14.4° ± 4.2°
60°	15.2° ± 3.7°	16.1° ± 3.7°[a]	14.9° ± 4.1°[b]
90°	17.0° ± 4.5°	17.7° ± 5.2°[a]	16.6° ± 5.1°[b]
Internal Rotation			
0°	11.1° ± 2.6°	11.9° ± 3.8°[a]	10.4° ± 2.4°[b]
15°	15.0° ± 3.2°	17.1° ± 4.6°[a]	15.8° ± 3.9°[b,c]
30°	17.5° ± 5.7°	18.8° ± 6.2°[a]	17.6° ± 6.0°[b]
60°	15.3° ± 6.1°	16.5° ± 6.2°[a]	16.1° ± 6.7°[c]
90°	12.5° ± 3.2°	14.2° ± 4.0°[a]	13.9° ± 3.9°[c]

[a]Sectioned significantly different from intact.
[b]Reconstructed significantly different from sectioned.
[c]Reconstructed significantly different from intact.

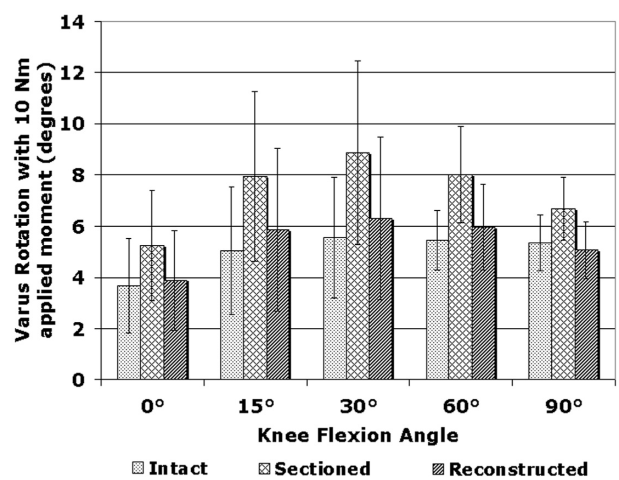

Figure 3. Angulation change in varus rotation with an applied moment of 10 N·m for intact, sectioned, and reconstructed FCL knee conditions at each flexion angle.

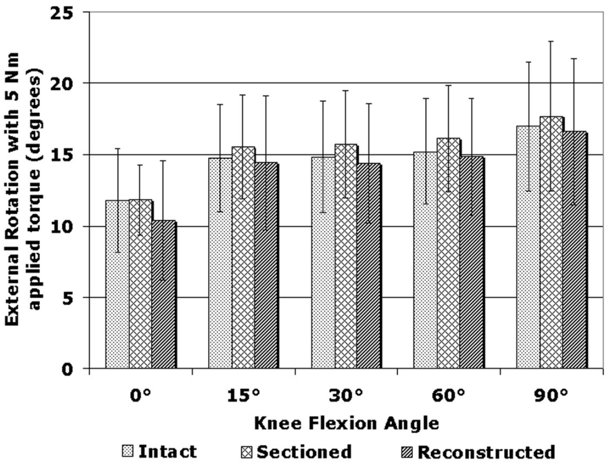

Figure 4. Angulation change in external rotation with an applied torque of 5 N·m for intact, sectioned, and reconstructed FCL knee conditions at each flexion angle.

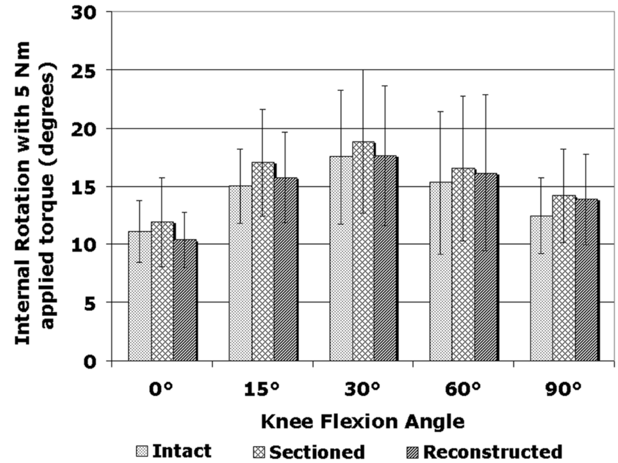

Figure 5. Angulation change in internal rotation with an applied torque of 5 N·m for intact, sectioned, and reconstructed FCL knee conditions at each flexion angle.

significant decreases in internal rotation at 0° ($P < .0001$), 15° ($P < .0001$), and 30° ($P < .0003$) of knee flexion, and there were no significant differences at 60° and 90° of knee flexion. Lastly, when comparing the FCL reconstruction to the intact state, we found a significant increase in internal rotation of 0.7° at 15° ($P < .03$) of knee flexion, 0.8° at 60° ($P < .01$) of knee flexion, and 1.4° at 90° ($P < .0001$) of knee flexion, and there were no significant differences at 0° and 30° (Figure 5) of knee flexion.

DISCUSSION

Isolated FCL injuries compose an important subset of posterolateral knee injuries that can be symptomatic and cause functional limitations; however, current reported treatment options only describe FCL repairs or reconstructions that do not place the FCL graft at its anatomic attachment sites.[2-4,6,7,13,24,31,38] An extensive literature search yielded no published biomechanically validated surgical techniques for anatomic reconstructions of FCL injuries. Our study reports on a technique that reconstructs the FCL using a semitendinosus graft that courses between drill holes positioned at the anatomic attachment sites of the FCL on the femur and the lateral aspect of the fibular head. The FCL graft passes along its native course between these 2 attachment sites, medial to both the superficial layer of the iliotibial band and the lateral aponeurosis of the long head of the biceps femoris.[35] We chose to study an anatomic FCL reconstruction because previous studies have reported that anatomic ligament reconstructions more closely approximate normal knee biomechanics.[5,6,11,12,19]

An autogenous semitendinosus graft was used as the reconstruction graft for this procedure because of its larger size, increased strength,[32] and decreased chance of saphenous nerve irritation during harvest[14,39] compared with a gracilis graft. In addition, since the length of the FCL has been noted to average approximately 70 mm,[18,20] the semitendinosus graft has more utility than the much shorter patellar tendon graft with its average length of 48.6 mm.[17]

We chose to tension the FCL graft at 30° of flexion. This flexion angle was chosen partly because this is the angle at which the greatest amount of varus instability is created by FCL sectioning.[8,10] Additionally, 30° is the angle at which the greatest amount of increased force is seen on an ACL reconstruction graft with isolated FCL sectioning.[22]

In general, the results of this study indicate that our anatomic FCL reconstruction technique to treat isolated FCL injuries significantly improves knee stability for varus, external, and internal rotations compared with the sectioned state. For varus rotation, we observed significant increases in instability after FCL sectioning at all flexion angles. The FCL reconstruction significantly decreased this instability at all knee flexion angles and additionally provided a full recovery of the varus instability at 0°, 60°, and 90°. However, at 15° and 30° of knee flexion, a small increase of 0.8° and 0.7°, respectively, was observed between the reconstructed and intact state. We do not believe that this difference would be important clinically considering the large amount of varus instability that was recovered at these 2 flexion angles. Furthermore, isolated FCL sectioning created small but significant amounts of increased external rotation at higher degrees of knee flexion (60° and 90°), which was fully recovered after reconstruction.

Our results for internal rotation showed small but significant increases in internal rotation at all knee flexion angles after FCL sectioning. In addition, the FCL reconstruction significantly decreased the observed instability at 0°, 15°, and 30°, providing full recovery at 0° and 30° of knee flexion. However, our reconstruction did not recover the instability observed at 60° and 90° of knee flexion. We do not believe this observation was important clinically because of the minor differences observed in internal rotation between each of the tested knee conditions.

In addition to validating the use of an autogenous semitendinosus graft for an anatomic FCL reconstruction, our study also provided additional information on the biomechanics of the FCL in controlling abnormal motion about the knee. It is generally accepted that the FCL is the primary varus stabilizer of the knee,[8-10,25,28,34,36] and that varus rotation is not increased with sectioning of other posterolateral structures or cruciate ligaments as long as the FCL remains intact.[10,28] The varus rotation instability changes we observed (Figure 3) for isolated sectioning of the FCL were similar to those previously reported with the greatest amount of instability seen at 30° of knee flexion.[8,10,22,28,36]

Published biomechanical studies on the primary stabilizing role of the FCL on external rotation suggest that the FCL has its greatest stabilizing effects at knee flexion angles of 30° and higher.[8,10,15,28,36,37] These reports correlate with our results where we found that sectioning the FCL resulted in significant increases in external rotation at higher angles of knee flexion. In addition, the amount of increased external rotation that we observed with FCL sectioning was relatively small, which also correlates with these previous studies.[8,10,15,28,36,37]

Previously reported studies also indicate that the FCL plays a small but significant primary role in stabilizing internal rotation about the knee.[26,28,33,37] While all reported studies agree that the FCL and posterolateral structures only contribute to small changes as a primary stabilizer for internal rotation, there appears to be some discrepancy at which flexion angles these effects are most important. Our results showed that sectioning the FCL increases internal rotation at all knee flexion angles, which would suggest that the FCL plays an important primary role in stabilizing internal rotation throughout the entire range of flexion angles. Conversely, Markolf et al[26] noted that the FCL and posterolateral corner structures are important as primary stabilizers of internal rotation at 60° and 90°, and Nielsen et al also noted that the most important effects of the FCL to preventing increased internal rotation are at higher flexion angles.[28] However, the amount of increased internal rotation observed with FCL sectioning across all studies has been small, with high standard deviations, which made achieving significance difficult.[26,28,33,37]

Varus instability caused by isolated FCL injuries has been demonstrated to significantly increase the forces on ACL and PCL grafts, and neglected FCL injuries increase the risk of failure of these reconstructions.[21,22] Since FCL and posterolateral injuries rarely occur in isolation and most commonly occur concurrently with ACL and/or PCL tears,[23] proper recognition and treatment of FCL injuries is critical to the success of cruciate ligament reconstruction(s). Anatomic repair or reconstruction of FCL or other posterolateral knee injuries is recommended at the time of ACL or PCL reconstructions to reduce the risk of cruciate ligament graft failure.[11,21,22]

In conclusion, our results validate that an anatomic FCL reconstruction using an autogenous semitendinosus graft can restore near normal stability to knees with an isolated FCL injury. Prospective outcomes studies to assess subjective and objective results in patients with an isolated FCL reconstruction are recommended.

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