# Analysis of the Static Function of the Popliteus Tendon and Evaluation of an Anatomic Reconstruction

## The ''Fifth Ligament'' of the Knee

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**Background:** The popliteus tendon has important dynamic and static stabilizing functions at the knee. Evaluation of its static role as the ''fifth ligament'' of the knee and a subsequent analysis of a popliteus tendon reconstruction has not been performed.

**Hypothesis:** In vitro knee stability can be restored to a popliteus tendon–deficient knee with an anatomic popliteus tendon reconstruction.

**Study Design:** Controlled laboratory study.

**Methods:** Eleven nonpaired cadaveric knees were tested under the following popliteus tendon states: intact, sectioned, and reconstructed using an autogenous semitendinosus graft. Each knee was subjected to 10-N·m varus moments, 5-N·m external and internal torques, and 88-N anterior and posterior loads at flexion angles of 0°, 20°, 30°, 60°, and 90°. A 6 degrees of freedom electromagnetic motion tracking system was used to assess motion changes of the tibia with respect to the femur.

**Results:** Significant increases in external rotation and small but significant increases in internal rotation, varus angulation, and anterior translation motion were found after sectioning the popliteus tendon compared to the intact state. Significant decreases in external rotation were found in the reconstructed state compared with the sectioned state at knee flexion angles of 20°, 30°, 60°, and 90°. Comparing the reconstructed state to the intact state, there were no significant differences at knee flexion angles of 0° and 20°, but significant decreases of external rotation were found at knee flexion angles of 30°, 60°, and 90°. Additionally, there were small but significant differences between the reconstructed and intact state with respect to varus angulation at knee flexion angles of 20°, 30°, and 60°; anterior translation at 20° and 30°; and internal rotation at all flexion angles.

**Conclusion:** The popliteus tendon has important primary stabilization roles at the knee. The authors also found that an anatomic popliteus tendon reconstruction significantly reduced the increase in external rotation that occurred with sectioning the popliteus tendon; however, differences seen with respect to internal rotation, varus angulation, and anterior translation were not restored.

**Clinical Significance:** The popliteus tendon functions essentially as the fifth major ligament of the knee. An anatomic popliteus tendon reconstruction can restore external rotation stability to knees with popliteus tendon injury.

**Keywords:** popliteus tendon; anatomic reconstruction; semitendinosus graft; biomechanics

The popliteus tendon, a component of the stabilizing structures of the posterolateral knee, has been reported to have both static and dynamic functions with respect to knee stability.[†] The popliteus tendon has been described as a primary restraint to external rotation in the knee,[2,10] yet its role in knee stability regarding internal rotation, translation, and varus motion has not been well defined in previous biomechanics studies.

Popliteus injuries are found in up to 68% of patients operated on for posterolateral instability,[10,18] and they frequently occur with injuries to other structures in the knee, notably the posterior cruciate ligament (PCL).[4,5,15] In an imaging study of 24 popliteus tendon injuries, 8.3% were isolated popliteus injuries, 16.7% occurred with anterior

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The authors declared that they had no conflicts of interests in their authorship and publication of this contribution.

†References 3, 6, 11, 16, 17, 20, 24, 26.

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: 10.1177/0363546509349493

cruciate ligament tears, 29.2% occurred with posterior ligament tears, and the rest occurred with meniscal and collateral ligament injuries.[4] Combined PCL and popliteus tendon injuries are problematic because restraints to posterior tibial translation and external tibial rotation are both compromised.[17] A popliteus tendon reconstruction technique that could address this deficit in external rotation stability may be beneficial in the restoration of knee motion after an injury.

Surgical treatment of popliteus tendon injuries are varied and based on the nature of the injury. Often, direct repair is not possible in high-energy injuries where the popliteus tendon has been avulsed at the musculotendinous junction or has undergone plastic deformation.[6] An isolated popliteus reconstruction may be used in cases of posterolateral knee injuries with a primary external rotation instability pattern where varus rotation is minimally affected.[31]

The purpose of our study was to analyze the static, ligament-like function of the popliteus tendon and biomechanically evaluate a surgical reconstruction technique for popliteus tendon injury based on its native anatomy and static function. Our hypothesis was that an anatomic reconstruction of a popliteus tendon injury using an autogenous semitendinosus graft would restore passive knee motion limits to near normal values.

## MATERIALS AND METHODS

### Specimen Preparation

This study was performed using 11 nonpaired fresh-frozen cadaveric knees that had no evidence of prior injury, arthritis, or other abnormalities; the knees were a mean age of 64 years (range, 43-76 years). The knees were stored at −20°C and thawed overnight before testing.

The femur was severed 20 cm proximal and the tibia was severed 13 cm distal to the knee joint. The tibia marrow cavity was reamed, and a threaded fiberglass rod was fixed in position parallel to the long axis of the tibia with screws. The tibia and fibula were then secured in a pot filled with polymethylmethacrylate. The specimen was secured in a previously described customized testing apparatus[9,12,13,34] with the femur fixed horizontally at the proximal end and anchored in position with a pin while allowing for uninhibited motion of the tibia at flexion angles. The lower portion of the testing apparatus was set to a flexion angle between 0° and 90° by securing screws at the appropriate angle for testing.

### External Force Application

Varus, anterior, and posterior external loads were applied with a Model SM S-type load cell (Interface, Scottsdale, Arizona) with a manufacturer-reported nonrepeatability error of ±0.01%.[13] External and internal torques were applied via a Model TS12 shaft-style reaction torque transducer (Interface) with a manufacturer-reported nonrepeatability error of ±0.02%.[13] Motion values were recorded through Motion Monitor software (Innovative Sport Training, Chicago, Illinois) and transferred to a computer for data processing.

Knees were tested at flexion angles of 0°, 20°, 30°, 60°, and 90°. Five-N·m external and internal torques, 10-N·m varus moments, and 88-N anterior and posterior forces, as used in previous studies to simulate clinical testing,[8,9] were applied 3 times at each flexion angle with the knee returned to a neutral position between all testing trials. Data from each trial were averaged for final results. The specified experimental settings were applied to knees in the following states: popliteus tendon intact, popliteus tendon cut, and popliteus tendon reconstructed using an autogenous semitendinosus graft.

### Angulation and Displacement Measurements

Quantification of tibia movement with respect to the femur was measured with a 6 degrees of freedom electromagnetic motion-analysis system (Polhemus Fastrak, Polhemus Inc, Colchester, Vermont) using sensors attached to the anterior femur and tibia.[1] The manufacturer-reported accuracy of this device is within 0.15° and 0.76 mm, and previous validation of the motion analysis and data collection has been performed.[15] Receivers for the tracking device were placed at the anterior midfemur, and 2 on the medial tibia at approximately the level of the tibial tubercle. Before load application, the neutral position, with the femur securely anchored in the testing apparatus[9,12,13,34] and no outside forces applied to the tibia, of each specimen at each flexion angle was established for testing by recording the position of sensors with the knee at rest to provide a 0 reference point for motion in all testing states. Landmarks—including the lateral and medial epicondyles on the femur and the medial, lateral, and anterior tibial plateau—were marked and tracked with the Polhemus digitizing stylus relative to the tibial sensors. Experiments were performed approximately 300 mm from the system transmitter, which was within the manufacturer-reported range of accuracy (100-700 mm) for the Polhemus system.[8,27]

### Data Analysis

Data were acquired during testing via the Polhemus device, which was coordinated with Motion Monitor computer software. Data were collected continuously during external load application via voltage measurements collected from the S-type load cell or shaft-style reaction torque transducer. The recorded voltages of the load cells and torque transducers from each test were imported into MATLAB R2006b analysis software (MathWorks Inc, Natick, Massachusetts). Voltages from the load cell were converted to forces via the load cell's force-voltage ratio, defined using linear analysis. All positional data points within 2 seconds of the digital mark, where the testing load reached its predetermined load, were extracted, while positional data outside of this range, where the load was under or over its target value, were excluded from further processing. The output was averaged among these points and compared with the voltage determining the target load. Data points were filtered at the end of the range until the average voltage measurement demonstrated the load was within 2% of its target; therefore, only positional data for the correct predetermined load value were used. The data were then averaged to produce a single reading for the loading cycle. This process was repeated for each of the 3 loading attempts.

## Popliteus Tendon Reconstruction Technique

The reconstruction process began with harvesting the semitendinosus tendon by making a vertical incision over the pes anserine attachment. The semitendinosus tendon was harvested with a hamstring stripper. A tendon graft length of at least 16 cm, determined by the measurement of grafts used for testing that ranged from 12.0 to 14.3 cm, was sufficient to insert into the femoral tunnel, pass along the course of the native tendon, and extend completely through the tibial tunnel. The tendon was cleaned of all muscular tissues and tubularized on each end with nonabsorbable sutures to fit through a 7-mm–diameter tunnel.

This study used the surgical approach to the posterolateral knee as previously described by Terry and LaPrade.[33] With the knee at approximately 60° of flexion, a curved incision was made starting distally between Gerdy's tubercle and the fibular head and extending parallel to the femur, approximately 6 cm proximal to the lateral epicondyle. A posterior-based skin flap was developed along the incision by reflecting the skin and subcutaneous tissues posteriorly from the superficial layer of the iliotibial band and the long and short heads of the biceps femoris.

Blunt dissection between the lateral gastrocnemius and the soleus muscles provided access to the popliteus musculotendinous junction. A second fascial incision split the iliotibial band, extending proximally from Gerdy's tubercle, to access the femoral attachment of the popliteus tendon. The femoral attachment site of the popliteus tendon on the proximal portion of the anterior fifth of the popliteal sulcus of the femur was exposed by a vertical arthrotomy through the midthird lateral capsular ligament. The fibular collateral ligament femoral attachment, which was posterior and proximal to the popliteus tendon with an average distance of 18.5 mm between their attachment sites, was avoided.[21,22]

With the popliteus tendon femoral attachment identified, a femoral anterior cruciate ligament guide (Arthrex, Naples, Florida) was used to drill a guide pin with eyelet from the femoral insertion of the popliteus tendon across the femur to the anteromedial knee, proximal and anterior to the adductor tubercle. A 25-mm–deep tunnel was then reamed over the guide pin with a 7-mm reamer.

Landmarks for the tibial tunnel were identified, including the musculotendinous junction of the popliteus tendon on the posterior tibia and the flat area on the anterior tibia just distal and medial to Gerdy's tubercle (Figure 1). A guide pin with eyelet was drilled between those 2 sites, and a 7-mm reamer was used to create a transtibial tunnel.

Approximately 25 mm of the tendon graft was recessed into the femoral tunnel by threading the passing sutures at the end of the graft through the eyelet at the end of the guide pin and pulling the pin through the medial femur.

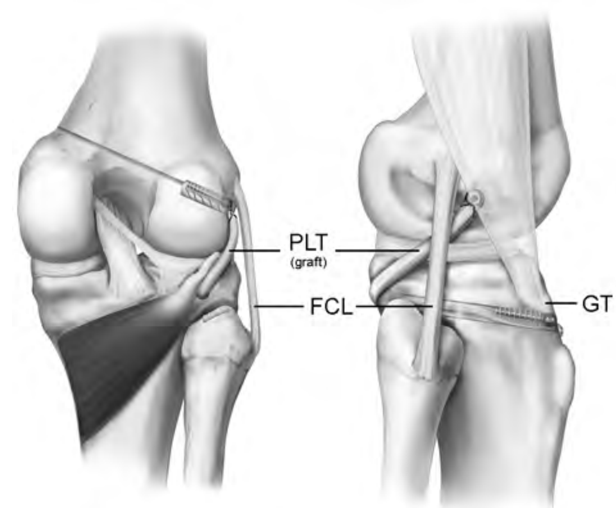


**Figure 1.** Posterior and lateral views of an isolated anatomic popliteus tendon reconstruction using a semitendinosus graft. The femoral attachment site is identified at the proximal portion of the anterior fifth of the popliteal sulcus. Landmarks for the tibial tunnel, including the musculotendinous junction of the popliteus tendon on the posterior tibia and the flat area on the anterior tibia just distal and medial to Gerdy's tubercle (GT), are shown in the figure. PLT, popliteus tendon reconstruction graft; FCL, fibular collateral ligament.

The femoral attachment of the graft was fixed into place using a 7-mm × 23-mm bioabsorbable screw. The semitendinosus graft was then passed along the anatomic path of the popliteus tendon down the popliteal hiatus, and the passing suture of the free end of the graft passed through the tibial tunnel from posterior to anterior to pull the graft into the tunnel. The graft was then secured in the tibial tunnel with a 7-mm × 23-mm bioabsorbable screw in the anterior tibia while an anterior traction force was applied to the graft with the knee at 60° of knee flexion and in neutral rotation.

## Pilot Study

A pilot study was performed on 1 knee to determine the initial setup, testing procedures, and specific forces and moments included in the biomechanics study. Pilot testing was performed at 0°, 20°, 30°, 60°, and 90° of knee flexion with applied loads of 5-N·m external and internal torques, 10-N·m varus and valgus moments, and 88-N anterior and posterior forces. Increased motion after popliteus tendon sectioning was detected for all applied loads except for the valgus moments; therefore, valgus loads were not included.

## Statistical Data Analysis

Statistical data analysis for each of the motions investigated was performed using SAS 9.1.3 software (SAS Institute Inc, Cary, North Carolina). Intact, sectioned, and reconstructed states of the popliteus tendon at each flexion angle were

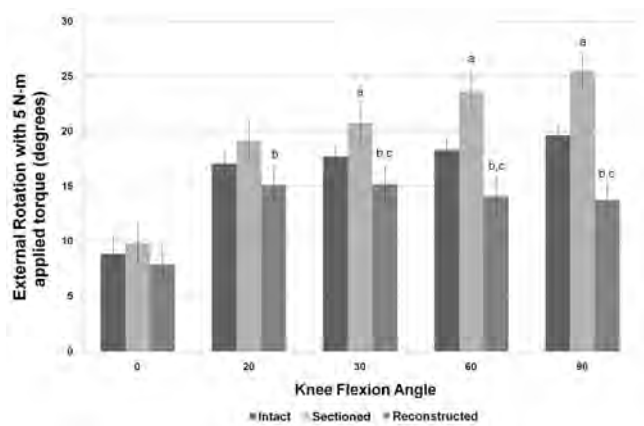


**Figure 2.** Change in external rotation with an applied 5-N·m torque for the intact, sectioned, and reconstructed popliteus tendon states at each flexion angle. Statistical significance is noted in the figure as: a, sectioned significantly different from intact; b, reconstructed significantly different from sectioned; and c, reconstructed significantly different from intact.

compared using a 2-way analysis of variance, and the means were compared post hoc using Tukey-adjusted $P$ values. Differences between intact, sectioned, and reconstructed states at varying degrees of knee flexion were considered significant at $P < .05$.

## RESULTS

### Angulation and Displacement of the Knee Joint

The results from biomechanical testing are outlined below and averages for all testing conditions are presented in Table 1. Graft failure or slippage was not seen during testing.

### External Rotation

Significant increases in external rotation after sectioning the popliteus tendon were found at flexion angles of 30° (3.0°; $P < .04$), 60° (5.3°; $P < .01$), and 90° (5.9°; $P < .01$) (Figure 2) with an applied external rotation torque. Additionally, significant decreases in external rotation were found in the reconstructed state compared with the sectioned state at knee flexion angles of 20° ($P < .001$), 30° ($P < .0001$), 60° ($P < .0001$), and 90° ($P < .0001$). Comparing the reconstructed state to the intact state, there were no significant differences at knee flexion angles of 0° and 20°. Significant decreases of external rotation of the reconstructed knee compared with the intact states were found at knee flexion angles of 30° (2.5°; $P < .05$), 60° (4.2°; $P < .005$), and 90° (5.9°; $P < .001$).

### Internal Rotation

Small, but significant, increases in internal rotation after sectioning the popliteus tendon were found at knee flexion angles of 0° (1.3°; $P < .01$), 20° (1.3°; $P < .002$), 30° (1.4°; $P < .002$), 60° (2.6°; $P < .001$), and 90° (2.8°; $P < .01$) with an applied internal rotation torque. Comparing the reconstructed state to the intact state, small yet significant increases of internal rotation of the reconstructed knee compared with the intact states were found at knee flexion angles of 0° (1.0°; $P < .03$), 20° (1.0°; $P < .02$), 30° (1.4°; $P < .03$), 60° (2.1°; $P < .004$), and 90° (2.4°; $P < .02$).

### Varus Angulation

Small, but significant, increases in varus angulation after sectioning the popliteus tendon were found at knee flexion angles of 20° (1.6°; $P < .01$), 30° (1.6°; $P < .01$), and 60° (1.7°; $P < .02$) with an applied varus load. Comparing the reconstructed state with the intact state, small but significant increases in varus angulation remained at knee flexion angles 20° (1.3°; $P < .03$), 30° (1.6°; $P < .01$), and 60° (2.4°; $P < .003$). No significant increases in varus angulation were seen at 0° and 90°.

### Posterior Translation

With an applied posterior load, no significant increases in posterior translation after sectioning the popliteus tendon were found at flexion angles of 0° ($P = .06$), 20° ($P = .8$), 30° ($P = .2$), 60° ($P = 1.0$), and 90° ($P = .8$). Comparing the reconstructed state with the intact state, there were no significant differences at flexion angles of 0° ($P = .3$), 20° ($P = 1.0$), 30° ($P = .4$), 60° ($P = .9$), and 90° ($P = .8$).

### Anterior Translation

With an applied anterior load, significant increases in anterior translation after sectioning the popliteus tendon were found of 1.5 mm at 0° ($P < .02$), 2.6 mm at 20° ($P < .04$), and 2.6 mm at 30° ($P < .01$) of knee flexion. Comparing the reconstructed state with the intact state, there were no significant differences at flexion angles of 0°, 60°, and 90°. Significant increases in anterior translation remained for the reconstructed knee of 2.4 mm at 20° ($P < .05$) and 2.4 mm at 30° ($P < .04$) of knee flexion compared with the intact knee state.

## DISCUSSION

The results of this study demonstrate that the popliteus tendon is a primary stabilizer to external rotation and has small but significant primary stabilization roles with respect to internal rotation, varus angulation, and anterior translation. Although the popliteus tendon functions dynamically as a tendon, these results are evidence of the ligament-like role of the popliteus tendon in providing static function about the knee. Thus, in effect, the popliteus tendon functions as the fifth major ligament of the knee. The anatomic popliteus tendon reconstruction technique that we described and tested significantly reduced

TABLE 1
Comparison of Rotational and Translational Changes With Application of Externally Applied Loads for Each Testing State[a]

| | Knee Flexion | Intact | Sectioned | Reconstructed |
|---|---|---|---|---|
| External rotation with 5-N·m applied torque, deg | 0° | 8.8 ± 1.5 | 9.8 ± 1.8 | 7.9 ± 1.6 |
| | 20° | 17.1 ± 1.2 | 19.2 ± 1.7 | 15.1 ± 1.7 |
| | 30° | 17.7 ± 1.0 | 20.7 ± 1.8[b] | 15.2 ± 1.6[b] |
| | 60° | 18.3 ± 1.0 | 23.6 ± 1.8[b] | 14.1 ± 1.7[b] |
| | 90° | 19.6 ± 0.9 | 25.5 ± 1.6[b] | 13.8 ± 1.4[b] |
| Internal rotation with 5-N·m applied torque, deg | 0° | 7.7 ± 1.3 | 9.0 ± 1.4[b] | 8.8 ± 1.4[b] |
| | 20° | 15.3 ± 1.6 | 16.6 ± 1.7[b] | 16.2 ± 1.7[b] |
| | 30° | 17.0 ± 1.7 | 18.5 ± 1.8[b] | 18.0 ± 1.8[b] |
| | 60° | 17.1 ± 1.8 | 19.8 ± 1.9[b] | 19.2 ± 1.9[b] |
| | 90° | 15.7 ± 1.9 | 18.5 ± 2.1[b] | 18.2 ± 1.9[b] |
| Varus angulation with 10-N·m applied moment, deg | 0° | 2.1 ± 0.5 | 2.7 ± 0.9 | 2.8 ± 0.8 |
| | 20° | 4.5 ± 1.1 | 6.1 ± 1.2[b] | 5.8 ± 1.1[b] |
| | 30° | 5.2 ± 0.8 | 6.9 ± 1.1[b] | 6.8 ± 0.9[b] |
| | 60° | 5.0 ± 0.6 | 6.7 ± 1.2[b] | 7.4 ± 0.9[b] |
| | 90° | 5.8 ± 0.8 | 7.1 ± 1.2 | 6.5 ± 0.9 |
| Posterior translation with 88-N posterior load, mm | 0° | 5.1 ± 1.1 | 6.8 ± 1.4 | 6.1 ± 1.2 |
| | 20° | 6.4 ± 1.3 | 7.2 ± 1.7 | 6.3 ± 1.8 |
| | 30° | 5.5 ± 1.4 | 7.4 ± 1.7 | 6.7 ± 1.6 |
| | 60° | 5.8 ± 1.5 | 5.9 ± 1.7 | 5.3 ± 1.5 |
| | 90° | 6.4 ± 1.4 | 5.2 ± 1.8 | 5.3 ± 1.6 |
| Anterior translation with 88-N anterior load, mm | 0° | 3.4 ± 0.7 | 4.9 ± 0.7[b] | 4.5 ± 0.7 |
| | 20° | 3.9 ± 1.1 | 6.4 ± 0.8[b] | 6.3 ± 0.8[b] |
| | 30° | 3.8 ± 0.9 | 6.4 ± 0.7[b] | 6.1 ± 0.7[b] |
| | 60° | 5.4 ± 1.1 | 6.7 ± 1.3 | 7.0 ± 1.0 |
| | 90° | 5.4 ± 1.2 | 6.7 ± 1.5 | 6.5 ± 1.3 |

[a]Mean ± standard error of the mean.
[b]Significant difference from the intact state.

external rotation laxity found in the sectioned state, which replicated a popliteus tendon injury.

Injuries to the popliteus tendon are commonly found in cases of posterolateral instability,[10] and various surgical treatments have been described including direct repair,[28,32] augmentation with iliotibial band or biceps tendon, recess procedures, reconstruction with patellar tendon autografts or allograft,[35] and Achilles tendon allograft.[7,21,35] However a review of the literature found no previous studies that biomechanically validate an anatomic popliteus tendon reconstruction technique.

An autogenous semitendinosus graft was used for the reconstruction because of its size, strength, and low chance of saphenous nerve irritation during harvest.[8,29,36] The semitendinosus graft, when compared with a shorter patellar tendon graft,[8] better accommodates a popliteus tendon reconstruction because of its longer length. The length of the popliteus tendon from its musculotendinous junction to the femoral attachment has been reported to be 5.45 cm,[22] approximately 0.6 cm longer than the average patellar tendon length of 4.86 ± 0.52 cm.[19] Therefore, using a patellar tendon graft to reconstruct the popliteus tendon may result in a nonanatomic graft length in most knees. Our study found that a tendon graft length of ≥16 cm was needed for the popliteus tendon reconstruction, including the tibial and femoral tunnel lengths.

Failure to recognize injuries to posterolateral structures, such as the popliteus tendon, have been implicated as a cause of posterior cruciate graft failure.[6,17,23,30] A study investigating PCL reconstruction found sectioning of the posterolateral structures resulted in a doubling of the forces on the PCL graft, increasing the risk of graft failure.[17] Our study found significant increases in external rotation of between 3.0° and 5.9° for the sectioned state as compared with the intact state. The increases in external rotation seen with sectioning in our study suggest that the popliteus tendon is an important primary restraint to external rotation at the knee. Therefore, its repair may have a role in the prevention of graft failure with concurrent PCL injury by decreasing forces on a PCL reconstruction graft. Our reconstruction technique did result in significant decreases in external rotation laxity compared with the sectioned state, establishing an ability to restore its ligament-like function to the knee. However, testing of the reconstructed state compared with the intact state showed minor overconstraint at higher flexion angles, which is outlined further in the limitations of this study.

We found small, but significant, motion differences between the intact and sectioned states for varus, internal rotation, and anterior translation near extension, demonstrating that the popliteus tendon also has a role in preventing these knee motions. Several previous posterolateral sectioning studies have reported that the fibular collateral ligament is the primary stabilizer of the knee to varus translation.[11,14,23] We are not aware of previous studies that have found the popliteus tendon to have a primary stabilizing role in preventing increases in knee varus motion. The small increases in internal rotation that were found for the sectioned state compared with the intact state at all knee flexion angles ranged between 1.3° and 2.8°. We also found increases in anterior translation near extension of between 1.5 and 2.6 mm in the sectioned state compared with the intact state. This finding may help to explain why there can be a Lachman test with a perceived increase in anterior translation with a solid end point in patients with posterolateral knee injuries and an intact anterior cruciate ligament, as previously described with injuries to the PCL.[25] In a comparison of the reconstructed state to the intact state, the secondary functions of the popliteus tendon, including prevention of varus angulation, anterior translation, and internal rotation, were not restored for all flexion angles; this is also discussed further in the limitations of this study.

One limitation of this study was that the slight differences in decreased external rotation and the lack of significant restoration of internal rotation seen between the reconstructed state and the intact state could have resulted from difficulty in determining the neutral point of the knee when performing the popliteus reconstruction without the remainder of the extremity present. The graft may have been inadvertently secured in slight internal rotation, causing the mild overconstraint of external rotation at higher flexion angles. Clinically, it would be recommended to secure the grafts with the tibia in neutral rotation to minimize overconstraint of the knee in external rotation. Because the focus for our study was on the popliteus tendon reconstruction, the popliteofibular ligament was not repaired, which may have also contributed to minor motion differences between the reconstructed and intact states. Further studies including a concurrent repair or reconstruction of the popliteofibular ligament may be indicated pending the results of clinical outcomes studies. Additionally, although our reconstruction attempts to mimic the anatomic path of the popliteus tendon by securing the graft at the musculotendinous junction, an intact popliteus tendon is continuous with the popliteus muscle, which extends distally on the posterior tibia; this may also account for the minor residual motion differences between the intact and reconstructed states for varus, internal rotation, and anterior translation near extension. We also acknowledge that this was a static in vitro study of the popliteus tendon and the dynamic interactions that normally occur in vivo were not detectable. Prospective clinical studies of this anatomic popliteus tendon reconstruction are currently under way to more fully evaluate this reconstruction technique.

In summary, our study results indicate that the major ligament-like role of the popliteus tendon within the knee is as a primary stabilizer to external rotation with a minor primary stabilizing role with regard to internal rotation, varus angulation, and anterior translation near extension. Our anatomic popliteus tendon reconstruction technique using an autogenous semitendinosus graft primarily restores external rotation stability to the knee without restoration of secondary changes in anterior translation, varus angulation, and internal rotation, which has clinical importance in the possible prevention of concurrent PCL reconstruction graft failures.

## ACKNOWLEDGMENT

The authors acknowledge Bryan Armitage, MD, MSc, and Benjamin R. Coobs, MD, biomechanics testing advisors; Conrad Lindquist, laboratory engineer; and Paul Lender, statistician, for their contributions to the project. This project was supported by the Sports Medicine Research Fund of the Minnesota Medical Foundation.

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