Mechanical Properties of the Posterolateral Structures of the Knee

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Background: The individual biomechanical strength properties of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon have not been well elucidated by previous studies. To define the necessary strength requirements for a posterolateral knee reconstruction, these properties for the main individual structures of the posterolateral knee need to be defined.

Hypothesis: The biomechanical failure properties of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon can be determined by cadaveric testing.

Study Design: Descriptive laboratory study.

Methods: Each structure was individually isolated in 8 fresh-frozen, nonpaired cadaveric knees and loaded to failure at more than 100%/s.

Results: The mean ultimate tensile strength of the fibular collateral ligament was 295 N, the popliteofibular ligament was 298 N, and the popliteus tendon was 700 N. The mean cross-sectional areas of these same structures at their midpoints were 11.9 mm^2, 17.1 mm^2, and 21.9 mm^2, respectively. Although the stiffness of the fibular collateral ligament (33.5 N/m) was similar to that of the popliteofibular ligament (28.6 N/m), the popliteus tendon was significantly stiffer than both (83.7 N/m).

Conclusion: The popliteofibular ligament, fibular collateral ligament, and popliteus tendon can resist fairly large loads before failure. Knowledge of the strengths of the main native posterolateral knee stabilizers will assist with reconstructive graft choices for these structures.

Keywords: fibular collateral ligament; popliteofibular ligament; popliteus tendon; biomechanics

Although posterolateral knee injuries[16] are less common than injuries to the ACL or PCL and are infrequently found as isolated injuries,[2,7-9,13,26,41] recently, injuries to the posterolateral knee structures have been more commonly diagnosed than they were in the recent past.[17,19-21,26] It has also been shown that posterolateral knee injuries alter forces in knees after cruciate ligament graft reconstructions,[14,24,25] and it has been recommended that posterolateral knee reconstructions be performed concurrently in knees with these combined ligament injuries. There have been many different proposed surgical techniques to reconstruct the posterolateral knee structures.[1,5,6,18,22,28,40] The goals of these reconstructions have been to reconstruct the posterolateral knee structures to provide stability to the knee and ensure a good clinical outcome. A primary goal of any surgical reconstruction should be to duplicate the biomechanical properties and function of the most frequently injured structures. Sectioning studies have identified the fibular collateral ligament, popliteus tendon, and popliteofibular ligament as the main static stabilizers of the posterolateral knee.[10-12,30,41] However, their mechanical properties have not been well characterized. Therefore, the purpose of this study was to determine the structural properties of these individual posterolateral knee structures to assist with the selection of reconstruction graft choices for anatomical posterolateral knee reconstruction techniques.[22,23]

MATERIALS AND METHODS

Specimen Preparation

Eight fresh-frozen, nonpaired cadaveric knee specimens with a mean age of 57.5 years (range, 40-77 years) were used in this study. In addition, 2 cadaveric pilot knees were used to ensure that a standardized surgical dissec-

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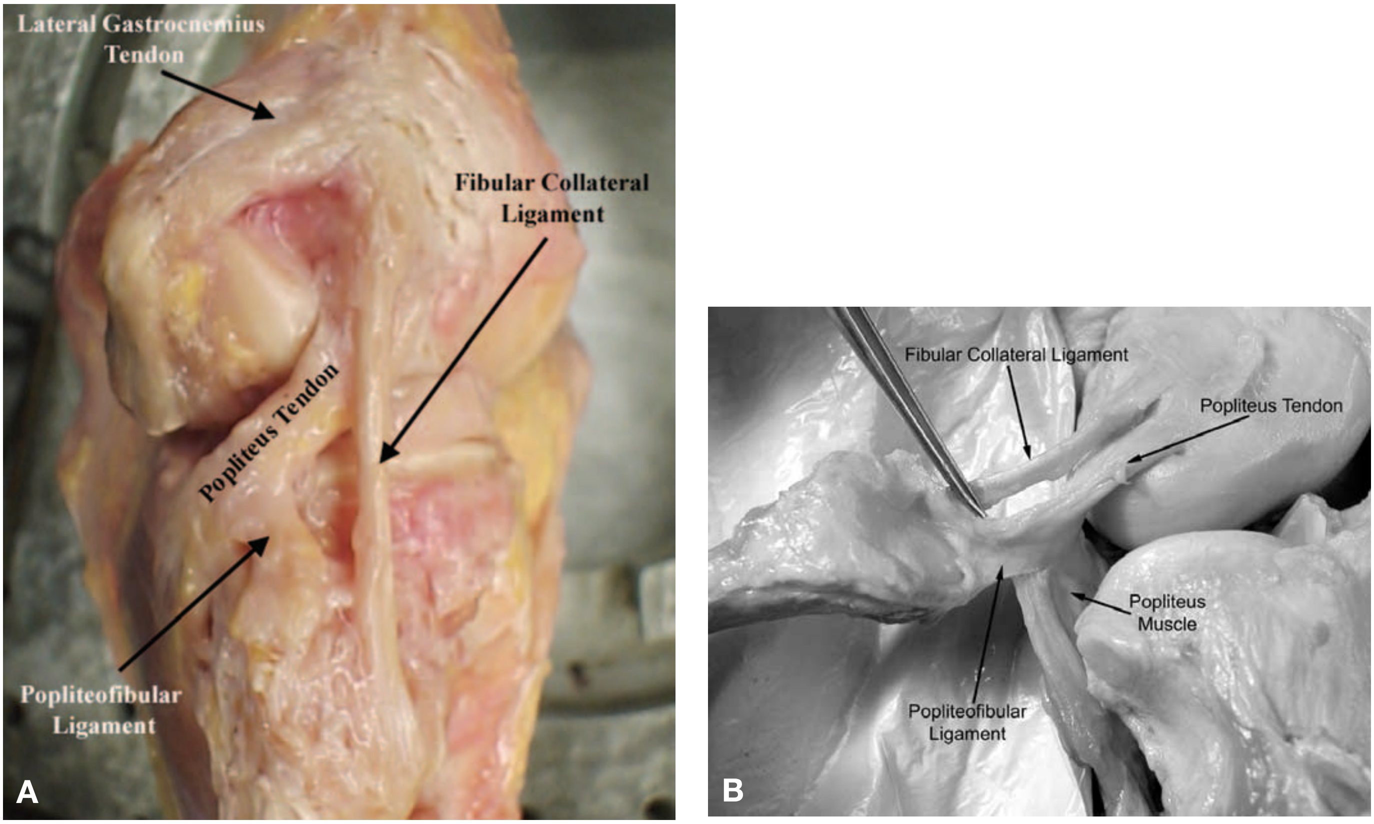

Figure 1. A, relationship between the normal fibular collateral ligament, popliteofibular ligament, and popliteus tendon in a right knee (from *Am J Sports Med*. 2003;31:856, Figure 1). B, the isolated fibular collateral ligament, popliteofibular ligament, and popliteus tendon (right knee) used in this study.

tion and potting technique was used. The specimens were maintained at –20°C and thawed at room temperature just before testing. Throughout the dissection and measurements, all soft tissues were kept moist with normal saline. Each specimen included a minimum of 20 cm of bone and soft tissue on each side of the knee.

Once the specimens were thawed, the skin and subcutaneous adipose tissues were removed en bloc to facilitate further dissection. The iliotibial band and its multiple layers[36,38] were detached from the Gerdy tubercle from distal to proximal. Next, the multiple attachments of the long and short heads of the biceps femoris were carefully removed from distal to proximal.[37] This removal allowed for visualization of the fibular collateral ligament and popliteofibular ligament. Careful dissection of the soft tissue attachments of the popliteus complex to the lateral meniscus and fibular head and styloid[34,38] was also performed by an inside-out technique,[30] and the proximal tibiofibular joint was disrupted from distal to proximal. This technique allowed for isolation of the popliteofibular ligament along its course from the popliteus musculotendinous junction to the posteromedial aspect of the fibular head and styloid.[23,34] The proximal fibula was then stripped of all soft tissue attachments from proximal to distal, with the exception of the attachment sites of the fibular collateral ligament on the fibular head and the popliteofibular ligament on the fibular styloid. The attachments of the long and short heads of the biceps femoris and the fabellofibular ligament were carefully dissected away from the fibular collateral ligament and fibular head and styloid. Similarly, the soft tissue structures and the meniscofemoral portion of the midthird lateral capsule were removed from the lateral femoral condyle, with the exception of the attachment sites of the fibular collateral ligament and popliteus tendon (Figure 1). The popliteus tendon was separated from its popliteomeniscal fascicle's attachment of the lateral meniscus and the attachment of the popliteal aponeurosis to the lateral meniscus. At this point, the only remaining structures attached to the popliteus tendon were the popliteofibular ligament and its distal muscle belly. The muscle belly was separated from the tibia and removed en bloc to clamp it into the soft tissue specimen grips.

So that we could test the fibular collateral ligament (Figure 2) and popliteofibular ligament individually, the fibular head was split longitudinally with a small oscillating saw between the attachment sites. The fibular collateral ligament and popliteus tendon femoral attachments were also separated with large bony margins off the lateral femoral condyle. All bone plugs were then potted using bone cement. Once each specimen had been divided into bone-ligament-bone or bone-ligament/tendon complexes, the specimens were placed into potted or soft tissue specimen grips designed for a materials testing machine (Material Test Systems, Eden Prairie, Minn). The speci-

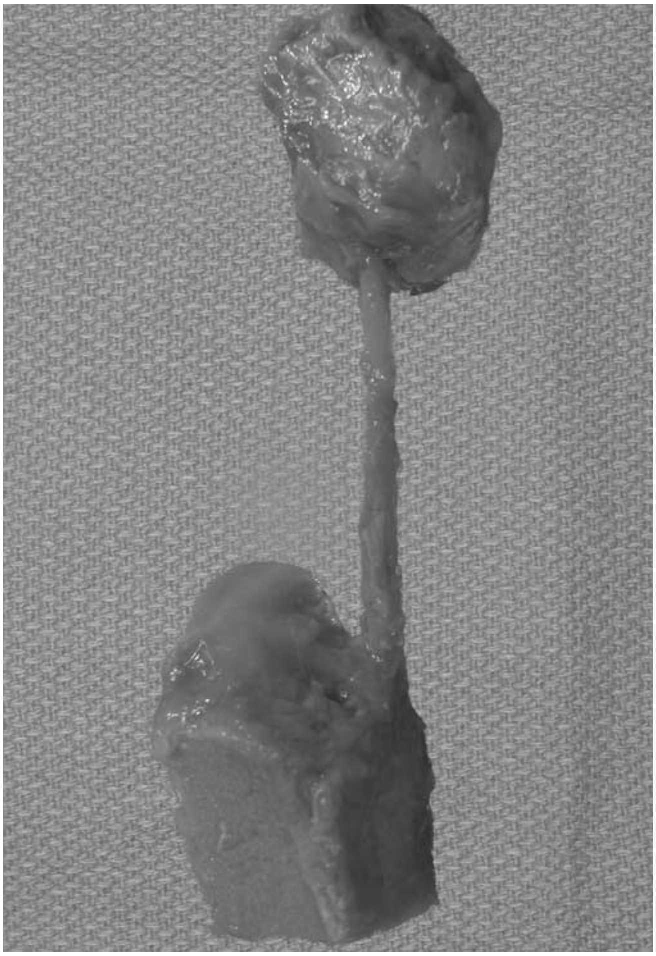

Figure 2. An isolated fibular collateral ligament with bone blocks (left knee).

men grips for the musculotendinous junction of the popliteus tendon were placed up to the edge of both structures. The grips were placed so that testing could be performed on one structure, and the structure not being tested was wrapped and kept moist at all times in saline-soaked gauze.

Anatomical Measurements

Before mechanical testing was performed, measurements of the lengths of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon were made to the midpoint of their attachment sites using a micrometer, according to previous descriptions of the attachment sites of these structures.[22,23,27,34,38] Cross-sectional area was measured by using a constant pressure micrometer[29,39] at the midpoint of the attachment sites. Three measurements were taken for each specimen, and the results were averaged.

Mechanical Testing

Each prepared construct was mounted on the Material Test Systems machine. The specimen holders were aligned to apply tensile force along the axis of each of the structures (fibular collateral ligament, popliteofibular ligament, popliteus tendon) tested. Testing of the popliteus complex structures was performed by first testing the popliteofibular ligament, while the popliteus tendon and its attachments were wrapped in a moist, saline-soaked gauze. Once testing was completed on the popliteofibular ligament, testing on the popliteus tendon was performed. Before tensile testing was performed, several preconditioning cycles were performed by slowly cycling the specimens from an unloaded state to the linear portion of their load deformation curve and back to zero load. Each specimen was then rapidly loaded to failure at more than 100%/s to obtain the ultimate tensile strength. Force displacement graphs were recorded, and mechanical properties were calculated. Each specimen was also examined for the location and type of failure.

Differences between the biomechanical properties of the fibular collateral ligament, popliteofibular ligament, and popliteus tendon were tested using the Student paired 2-tailed t test with unequal variance. Statistical significance was determined at $P < .05$.

RESULTS

The fibular collateral ligament, popliteofibular ligament, and popliteus musculotendinous complex (popliteus tendon and its musculotendinous junction) were identified in all 8 specimens. Biomechanical testing results are summarized in Tables 1 and 2.

Fibular Collateral Ligament

The mean length of the fibular collateral ligament was 57.8 ± 5.5 mm. The mean cross-sectional area of the fibular collateral ligament was 11.9 ± 2.9 mm^2. Its cross-sectional area was 66% that of the popliteofibular ligament and 54% that of the popliteus tendon (Table 1). The ultimate tensile load of the fibular collateral ligament averaged 295 ± 96 N. The fibular collateral ligament failed at midsubstance in all 8 specimens (Table 2).

Popliteofibular Ligament

The mean length of the popliteofibular ligament was 14.7 ± 2.5 mm. The mean cross-sectional area of the popliteofibular ligament was 17.9 ± 1.9 mm^2. The strain on the popliteofibular ligament was 400% greater than that on the fibular collateral ligament and 237% greater than that on the popliteus tendon (Table 1). The ultimate tensile load of the popliteofibular ligament averaged 298.5 ± 144.1 N. Mechanisms of failure for the popliteofibular ligament included midsubstance tears in 4 specimens, tears at the musculotendinous-grip junction in 3 cases, and 1 bony avulsion of the fibula (Table 2).

Popliteus Tendon

The mean length of the popliteus tendon was 34.3 ± 5.5 mm. The mean cross-sectional area of the popliteus tendon

TABLE 1
Mean Failure Properties (±SD) of the Fibular Collateral Ligament, Popliteofibular Ligament, and Popliteus Tendon of the Posterolateral Knee

Structure	Ultimate Tensile Load, N	Stiffness, N/mm	Maximum Stress, mPa	Strain, %	Modulus, mPa	Cross-sectional Area, mm^2
Fibular collateral ligament	295 ± 96	33.5 ± 13.4	26.9 ± 11.7	0.16 ± 0.05	183.5 ± 110.7	11.9 ± 2.9
Popliteofibular ligament	298.5 ± 144.1	28.6 ± 13.6	12.8 ± 6.0	0.64 ± 0.40	24.8 ± 14.5	17.9 ± 1.9
Popliteus tendon	700.3 ± 231.7	83.7 ± 24.3	32.0 ± 13.1	0.27 ± 0.18	130.9 ± 37.0	21.9 ± 3.9

TABLE 2
Ultimate Tensile Loads and Failure Locations for Structural Testing of Posterolateral Knee Structures[a]

			Structure					
			FCL		PFL		PLT	
Specimen	Age, y	Sex	UTL, N	Failure Location	UTL, N	Failure Location	UTL, N	Failure Location
1	52	Male	330.9	Midsubstance	269.0	At grips	693.3	Midsubstance
2	48	Female	188.8	Midsubstance	242.4	Midsubstance	503.9	Midsubstance
3	62	Male	417.1	Midsubstance	167.9	Midsubstance	749.1	Midsubstance
4	66	Male	229.9	Midsubstance	169.4	Midsubstance	475.7	Midsubstance
5	40	Male	381.9	Midsubstance	586.9	Midsubstance	1170.0	At grips
6	58	Male	305.2	Midsubstance	239.7	At grips	772.0	At grips
7	77	Female	150.1	Midsubstance	271.8	Fibular bony avulsion	764.7	Midsubstance
8	57	Male	358.4	Midsubstance	441.0	At grips	468.7	Femoral bony avulsion

[a]FCL, fibular collateral ligament; PFL, popliteofibular ligament; PLT, popliteus tendon; UTL, ultimate tensile load.

was 21.9 ± 3.9 mm^2. The ultimate tensile load of the popliteus tendon averaged 700.3 ± 231.7 N. Its ultimate tensile load was 237% that of the fibular collateral ligament and 234% that of the popliteofibular ligament (Table 1). Mechanisms of failure of the popliteus tendon included midsubstance tears in 5 specimens (of which 3 were close to the femur), 1 femoral bony avulsion, and 2 musculotendinous failures in the Material Test Systems machine soft tissue grips (Table 2).

STATISTICAL ANALYSIS

The mean load to failure for the popliteus tendon was significantly higher than those of the fibular collateral ligament ($P < .001$) and popliteofibular ligament ($P < .001$). There was no difference between the failure loads of the fibular collateral ligament and the popliteofibular ligament.

The mean strain at failure was significantly higher for the popliteofibular ligament compared to both the fibular collateral ligament ($P < .01$) and popliteus tendon ($P < .03$). There was no difference in the strain at failure between the fibular collateral ligament and the popliteus tendon.

The mean stiffness of the popliteus tendon was significantly higher than that of either the fibular collateral ligament ($P < .0003$) or the popliteofibular ligament ($P < .0002$). No significant difference was demonstrated between the mean stiffness of the fibular collateral ligament and that of the popliteofibular ligament.

DISCUSSION

Previously, the individual failure characteristics of the native fibular collateral ligament, popliteofibular ligament, and popliteus tendon had not been well defined. Many biomechanical studies have documented the importance of these 3 specific individual posterolateral knee structures to knee stability.[10-12,30,41]

Two recent studies that attempted to address the tensile strengths of the native posterolateral corner structures yielded very different results and did not separately test all 3 main stabilizers.[30,35] This lack of testing has made it difficult to compare the biomechanical properties of these 3 native structures. Maynard et al[30] examined the tensile strength of the lateral (fibular) collateral ligament, the popliteofibular ligament, and the popliteus muscle. In this particular study, each of these structures was not tested individually. Both the fibular collateral ligament and the popliteofibular ligament were simultaneously stretched to failure along the axis of the fibular collateral ligament. Their failure rates were reported sequentially, with mean tensile strengths of the fibular collateral ligament and popliteofibular ligament of 750 N and 425 N, respectively. However, because these structures were not individually tested, the data obtained cannot be viewed as representative of the strength of the individual ligaments without further verification. In fact, these strengths differed significantly from those in a more recent study that reported individual tensile strengths of the fibular collateral ligament and popliteofibular ligament of 309 N and 180 N, respectively.[35] These authors did not individually test the popliteus tendon in this study (A. Amis, personal communication, 2003). In addition, the load to failure of these 2 studies differed significantly (100%/s[30] vs 200 mm/min[35]). Because it is generally desired to have a rapid load to failure (≥100% of the ligament length per second) to simulate the rapid loading observed in a structure at the time of injury, it was unknown if these slower applied testing loads in the study by Sugita and Amis[35] would accurately predict the tensile strengths of the tested structures. Our study found similar ultimate tensile strengths to those found by Sugita and Amis[35] for the fibular collateral ligament (295 N) and slightly higher results for the popliteofibular ligament (298 N). We note that the popliteofibular ligament is difficult to test biomechanically because of its attachment at the musculotendinous junction of the popliteus tendon. In fact, 3 of our specimens failed at this location (Table 2), and it is possible we underestimated its true overall strength. In addition, as noted in Table 1, although the popliteofibular ligament has similar ultimate tensile strength properties to those of the fibular collateral ligament, its thin, sheetlike anatomy is reflected in different overall biomechanical properties than the cordlike fibular collateral ligament with its parallel bundled collagen fibrils (and the popliteus tendon with its similarly oriented collagen bundles). In addition, the smaller modulus values observed for the popliteofibular ligament may reflect the difficulty of fixation of this structure in the soft tissue grips during biomechanical testing. Our study also found the popliteus tendon to be stronger (700 N) than either of these 2 structures. However, it is important to understand that the relatively advanced age of the specimens in this study may lead to an underestimation of the strength of these structures in young patients. Although it is recognized that the popliteus tendon is a dynamic stabilizer of the knee, it has also been demonstrated in several biomechanical studies that it is a very important primary static stabilizer to external rotation and posterolateral rotation motions.[10,12,22,27,31]

Although it is clear that the failure properties found for these 3 structures indicate they can resist fairly large loads before failure, they are not as strong as the native ACL or PCL.[33,43] We believe that there are 2 possible implications from this finding. The first is that multiple structures provide both primary and secondary varus and external rotation stability within the posterolateral corner of the knee. This implication would help to explain the large discrepancy between our current study and the study of Maynard et al,[30] which tested the failure strengths as a group. The second may be that these structures are not inherently well developed to resist loads individually and that the primary and secondary restraint roles of these structures are closely related.[4] Reconstruction grafts must be strong enough to take up the loads caused by torn or stretched secondary stabilizers. These findings may imply that it is important to consider having posterolateral knee reconstruction grafts that are not only strong enough for the primary biomechanical role of the structure being replaced but also strong enough to take up the secondary loading role to stabilize that structure against abnormal knee motion caused by a posterolateral corner injury.

Based on the failure properties found for these 3 important posterolateral knee structures, and recognizing the limitations of testing cadaveric tissues, recommendations for the minimum replacement reconstruction grafts for these structures can be proposed. Based on previously published studies and the soft tissue lengths needed to replicate the normal course of these structures, a single-looped semitendinosus tendon (maximum failure load, 1216 N),[32] a central quadriceps tendon (maximum failure load, 1075 N),[15] or a portion of an Achilles tendon allograft (maximum failure load, 3055 N) (R.F. LaPrade, unpublished data, 1996) would appear to be suitable autogenous or allograft reconstruction grafts. Although the gracilis (maximum load, 838 N)[32] and tubularized superficial layer of the iliotibial band (maximum load [16-mm width], 628 N)[32] may also be suitable grafts, it is recommended that until the ultimate tensile strengths of these posterolateral structures are identified in younger cadaveric donors, caution should be taken in using these latter tissues as reconstruction grafts, especially for the iliotibial band, may have a deleterious effect on lateral stability of the knee if a large strip were used as an autograft. In addition, caution must also be taken when using local tissues, such as a portion of the common tendon of the biceps femoris or a small central slip of the iliotibial band,[1,3,42] to augment an intrasubstance stretch injury or tear of these structures in acute injuries because, to our knowledge, the biomechanical properties of these structures have not been defined.

In conclusion, the structural properties of the main posterolateral knee static stabilizers indicate they have an important role in stabilizing the knee. It is recommended that the strengths of grafts chosen for posterolateral knee reconstructions meet or exceed these findings.

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