Biomechanical Evaluation of the Medial Stabilizers of the Patella

Matthew D. LaPrade,* BS, Samantha L. Kallenbach,* BS, Zachary S. Aman,* BA, Gilbert Moatshe,*†‡ MD, Hunter W. Storaci,* MS, Travis Lee Turnbull,* PhD, Elizabeth A. Arendt,§ MD, Jorge Chahla,* MD, PhD, and Robert F. LaPrade,*||¶ MD, PhD
Investigation performed at the Department of BioMedical Engineering, Steadman Philippon Research Institute, Vail, Colorado, USA

Background: Quantification of the biomechanical properties of each individual medial patellar ligament will facilitate an understanding of injury patterns and enhance anatomic reconstruction techniques by improving the selection of grafts possessing appropriate biomechanical properties for each ligament.

Purpose: To determine the ultimate failure load, stiffness, and mechanism of failure of the medial patellofemoral ligament (MPFL), medial patellotibial ligament (MPTL), and medial patellomeniscal ligament (MPML) to assist with selection of graft tissue for anatomic reconstructions.

Study Design: Descriptive laboratory study.

Methods: Twenty-two nonpaired, fresh-frozen cadaveric knees were dissected free of all soft tissue structures except for the MPFL, MPTL, and MPML. Two specimens were ultimately excluded because their medial structure fibers were lacerated during dissection. The patella was obliquely cut to test the MPFL and the MPTL-MPML complex separately. To ensure that the common patellar insertion of the MPTL and MPML was not compromised during testing, only one each of the MPML and MPTL were tested per specimen (n = 10 each). Specimens were secured in a dynamic tensile testing machine, and the ultimate load, stiffness, and mechanism of failure of each ligament (MPFL = 20, MPML = 10, and MPTL = 10) were recorded.

Results: The mean ± SD ultimate load of the MPFL (178 ± 46 N) was not significantly greater than that of the MPTL (147 ± 80 N; $P = .706$) but was significantly greater than that of the MPML (105 ± 62 N; $P = .001$). The mean ultimate load of the MPTL was not significantly different from that of the MPML ($P = .210$). Of the 20 MPFLs tested, 16 failed by midsubstance rupture and 4 by bony avulsion on the femur. Of the 10 MPTLs tested, 9 failed by midsubstance rupture and 1 by bony avulsion on the patella. Finally, of the 10 MPMLs tested, all 10 failed by midsubstance rupture. No significant difference was found in mean stiffness between the MPFL (23 ± 6 N/mm^2) and the MPTL (31 ± 21 N/mm^2; $P = .169$), but a significant difference was found between the MPFL and the MPML (14 ± 8 N/mm^2; $P = .003$) and between the MPTL and MPML ($P = .028$).

Conclusion: The MPFL and MPTL had comparable ultimate loads and stiffness, while the MPML had lower failure loads and stiffness. Midsubstance failure was the most common type of failure; therefore, reconstruction grafts should meet or exceed the values reported herein.

Clinical Relevance: For an anatomic medial-sided knee reconstruction, the individual biomechanical contributions of the medial patellar ligamentous structures (MPFL, MPTL, and MPML) need to be characterized to facilitate an optimal reconstruction design.

Keywords: medial patellar stabilizers; biomechanics; patellofemoral; medial patellar ligaments

Lateral patellar dislocations are the second leading cause of traumatic knee hemarthroses, and recurrent patellar dislocations often require surgery.[2] The medial knee structures responsible for stabilization of the patellofemoral joint are the medial patellofemoral ligament (MPFL), the medial patellotibial ligament (MPTL), and the medial patellomeniscal ligament (MPML). Although the MPFL has been identified as the main medial patellar restraint, new evidence suggests that the MPTL and MPML might also play an important role in medial patellar stability.[20,25] Consequently, injury to these ligaments can lead to altered patellofemoral joint contact forces, patellar instability, and joint degeneration,[18,20] highlighting the need for appropriate anatomic surgical management to restore joint kinematics.

The optimal treatment algorithm for addressing lateral patellar instability needs to be further refined.[5,8,9] The biomechanical properties and function of the individual medial ligaments attaching to the patella must be determined to restore the native kinematics of the patella. In this regard, we were motivated to determine whether

The American Journal of Sports Medicine
1–8
DOI: 10.1177/0363546518758654

further quantification of the biomechanical properties of each individual ligament of the medial side of the patellofemoral joint would help to explain injury patterns and advance reconstruction techniques by improving the selection of appropriate grafts for each ligament.

Although an extensive body of literature on anatomic and biomechanical characteristics of the MPFL has been published,[5,7,22,24,25] limited data exist for the MPTL and MPML.[13] Therefore, the purpose of this study was to determine the ultimate load, stiffness, and mechanism of failure of the MPFL, MPTL, and MPML to ultimately assist with the selection of grafts for anatomic reconstruction. It was hypothesized that consistent biomechanical properties would be found for each structure.

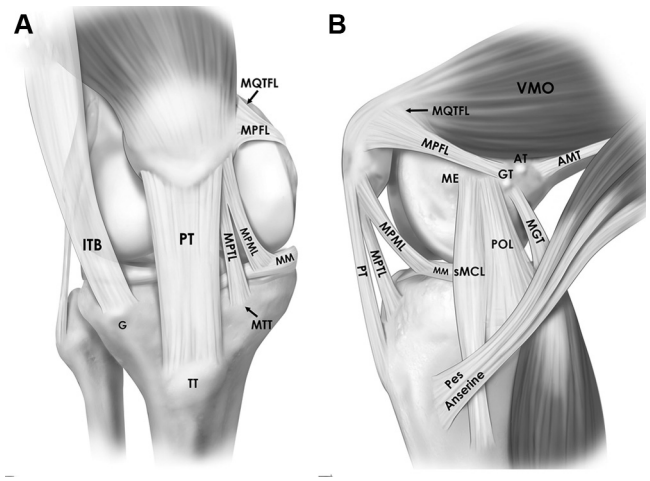

Figure 1. (A) Anterior view depicting the insertions and orientations of the medial patellar ligaments on the right knee. (B) Medial view of a right knee in flexion. AMT, adductor magnus tendon; AT, adductor tubercle; G, Gerdy's tubercle; GT, gastrocnemius tubercle; ITB, iliotibial band; ME, medial epicondyle; MGT, medial gastrocnemius tendon; MM, medial meniscus; MPFL, medial patellofemoral ligament; MPML, medial patellomeniscal ligament; MPTL, medial patellotibial ligament; MQTFL, medial quadriceps tendon femoral ligament; MTT, medial tibial tubercle; POL, posterior oblique ligament; PT, patellar tendon; sMCL, superficial medial collateral ligament; TT, tibial tubercle; VMO, vastus medialis oblique. (Reprinted with permission from Kruckeberg BM, Chahla J, Moatshe G, et al. Quantitative and qualitative analysis of the medial patellar ligaments: an anatomic and radiographic study. *Am J Sports Med*. 2018;46(1):153-162.[17])

METHODS

Specimen Preparation

Twenty-two male, nonpaired, fresh-frozen cadaveric knees (mean ± SD age, 56.4 ± 12.4 years; body mass index, 25.29 ± 5.54 kg/m^2) with no history of knee injury, prior surgery, or gross anatomic abnormality were used for this study. All fine dissections were carried out by an orthopaedic physician (J.C.). The medial structure fibers of 2 specimens were lacerated during dissection, leading to their exclusion. This led to a total count of n = 20, n = 10, and n = 10 for the MPFL, MPTL, and MPML, respectively. The cadaveric specimens used in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. The use of cadaveric specimens is exempt at our institution, so institutional review board approval was not required. Specimens were maintained at –20°C and thawed at room temperature for 24 hours before testing. After dissection of the subcutaneous tissues, the MPFL, MPTL, MPML, and medial quadriceps tendon femoral ligament (MQTFL) were identified by a combined outside-in and inside-out anatomic dissection similar to a previously published method[5] (Figures 1 and 2).

The MPFL was identified deep to the distal edge of the vastus medialis oblique (VMO) and subsequently dissected out. The MPFL fibers were then followed to the femoral, patellar, and quadriceps tendon attachments. Next, the MQTFL fibers were resected to isolate the MPFL fibers. The MPFL was dissected using both inside-out and outside-in techniques. For the inside-out dissection of the MPTL and MPML, a lateral arthrotomy was performed, Hoffa's fat pad was removed, and the patella was reflected medially. The synovium and the capsule on the anteromedial aspect of the knee were dissected, and the MPTL and MPML were identified by first exposing their common attachments to the patella and then following their fibers distally to their tibial and meniscal attachments, respectively. The soft tissues surrounding the MPTL and MPML were resected, leaving their attachments intact. A high risk of damaging these ligaments is present when dissecting from outside in; therefore, the inside-out technique was chosen. Pilot studies were performed on cadaver knees to determine the best means to pot the specimens. During the pilot studies, we observed that the MPTL and MPML were occasionally damaged by routine placement of the medial parapatellar arthroscopic portal (this frequency increased if portals were created in a transverse fashion).

To allow for individual testing of the MPFL and the MPTL-MPML complex, the patella was split obliquely starting from the midpoint between the most distal aspect

¶Address correspondence to Robert F. LaPrade, MD, PhD, Steadman Philippon Research Institute, 181 W. Meadow Drive, Suite 1000, Vail, CO 81657, USA (email: rlaprade@thesteadmanclinic.com).

*Steadman Philippon Research Institute, Vail, Colorado, USA.

†Oslo University Hospital and University of Oslo, Oslo, Norway.

‡Norwegian School of Sports Sciences, Oslo Sports Trauma Research Center, Oslo, Norway.

§Department of Orthopaedic Surgery, University of Minnesota Minneapolis, Minnesota, USA.

‖The Steadman Clinic, Vail, Colorado, USA.

One or more of the authors has declared the following potential conflict of interest or source of funding: R.F.L. receives royalties and is a paid consultant for Smith and Nephew, Arthrex, and Ossur. E.A.A. is a consultant for Smith & Nephew.

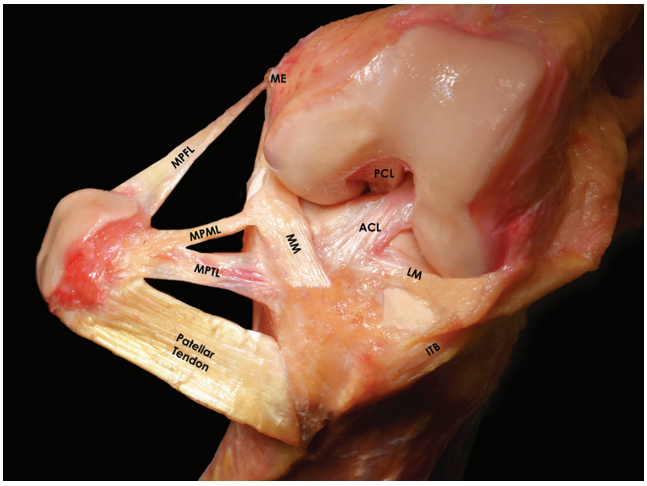

Figure 2. Everted view of the patella after a completed dissection showing the origin and insertions of the MPFL, MPML, and MPTL (left knee). ACL, anterior cruciate ligament; ITB, iliotibial band; LM, lateral meniscus; ME, medial epicondyle; MM, medial meniscus; MPFL, medial patellofemoral ligament; MPML, medial patellomeniscal ligament; MPTL, medial patellotibial ligament; PCL, posterior cruciate ligament.

of the MPFL attachment and the most proximal insertion of the MPTL-MPML complex (Figure 2). Three 3.18-cm-long screws were inserted into each half of the patella to act as anchors for subsequent potting. The hemisected patellas were individually potted in a cylindrical mold with poly(methyl methacrylate) (PMMA; Fricke Dental International). The MPTL patellar bone block was potted in a smaller mold than those of the MPFL and MPML to prevent impingement upon the femoral condyles during testing. Additionally, the femur and tibia of each specimen were potted and served as rigid fixation points during testing.

Anatomic Measurements

Before mechanical testing, a digital caliper (manufacturer-reported accuracy of ±0.02 mm) (Fowler High Precision) was used to obtain the initial length of each specimen as well as the width and thickness at the 2 insertion points and the midpoint of each ligament. These width and thickness measurements were used to calculate an average cross-sectional area for each specimen. The lengths of the MPFL and the MPTL were measured between the centers of bony insertions, while the MPML length was measured from the center of the insertion on the patella to the center of the insertion on the medial meniscus. All measurements were conducted by the same examiner (M.D.L.).

Mechanical Testing

For each knee, random selection was used for the testing order for the MPFL versus the MPTL-MPML complex and for selection of either the MPTL or MPML for testing. For testing of the MPTL-MPML complex ligaments, the selected ligament was left intact, while the other ligament was sectioned at its most distal attachment to avoid injury to its common patellar attachment site. The potted patellar side of each ligament was rigidly mounted to the actuator of a dynamic testing machine (Instron ElectroPuls E10000; Instron Systems). Measurement error of the testing machine was certified by Instron to be less than ±0.01 mm and less than ±1 N. For MPFL and MPML testing, both the femur and tibia were positioned horizontally and rigidly secured to the base of the testing machine. To test the MPML, an 11-mm staple (Arthrex) was used to fix the anterior horn of the meniscus to the tibial plateau to isolate the mechanical properties of the ligament by avoiding extraneous meniscus motion; this format is similar to a previously published technique (Figure 3B).[3] For MPTL testing, the tibia was rigidly attached to the base of the testing machine in a vertical orientation, and the femur was freely, maximally flexed. Each ligament was oriented during setup to be pulled to failure in line with its fibers by use of the native physiological vector (Figure 3) through a combination of rotating the patellar side in the actuator fixture and aligning and rotating the femur or tibia in fixtures attached to the base of the testing machine. Before being pulled to failure, specimens were cyclically loaded from 2 to 10 N at 0.1 Hz for 10 cycles. After preconditioning, specimens were loaded to failure

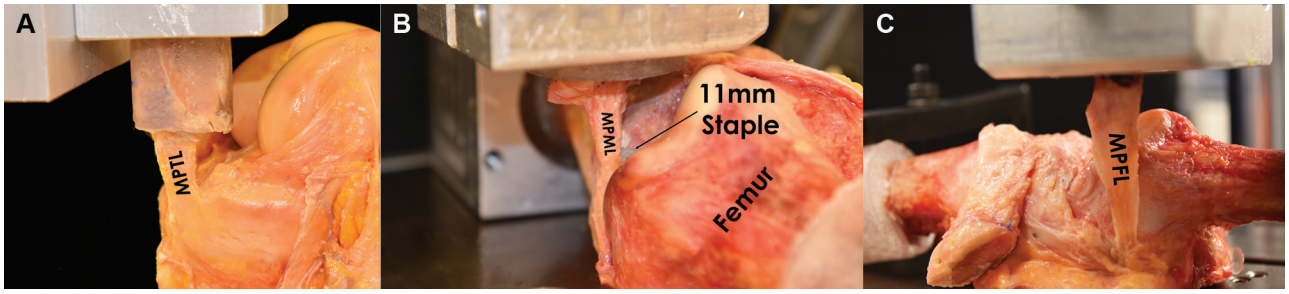

Figure 3. Photographs demonstrating the experimental setup for the different ligaments. Both the tibia and the patella were potted. (A) The medial patellomeniscal ligament (MPML) was cut to isolate the medial patellotibial ligament (MPTL), which was then loaded in the direction of the fibers. (B) To test the MPML, an 11-mm staple was placed on the meniscus, just medial to the MPML attachment on the medial meniscus to secure the meniscus to the tibia before testing. (C) The patella and the femur were potted, and the direction of pull was in line with the fibers to test the medial patellofemoral ligament (MPFL).

TABLE 1
Failure Load, Stiffness, Failure Stress, and Modulus of the MPFL, MPTL, and MPML[a]

Structure	Failure Load, N	Stiffness, N/mm	Failure Stress, MPa	Modulus, MPa	Length, mm	Cross-sectional Area, mm^2
MPFL	178 ± 46 (91-270)	23 ± 6 (8-34)	5 ± 2 (2-9)	41 ± 19 (13-87)	69.5 ± 7.1 (53-79)	43.1 ± 13.8 (14.8-68.8)
MPTL	147 ± 80 (23-279)	31 ± 21 (6-75)	4 ± 2 (2-7)	35 ± 17 (23-47)	44.6 ± 8.8 (29-60)	34.8 ± 16.6 (25.5-79.5)
MPML	105 ± 62 (35-233)	14 ± 8 (5-30)	2 ± 1 (1-4)	14 ± 8 (5-32)	53.4 ± 10.7 (38-72)	55.3 ± 18.4 (10.5-63.8)

[a]Values are reported as mean ± SD (range). MPFL, medial patellofemoral ligament; MPML, medial patellomeniscal ligament; MPTL, medial patellotibial ligament.

at a rate of 25 mm/min, during which the load and actuator displacement were continuously recorded at 500 Hz (WaveMatrix software; Instron).

Data Analysis

Failure load was classified and detected algorithmically as a reduction of 5% or more from the local instantaneous peak load. Stiffness was calculated through use of a linear least squares regression fit with a sliding window of 1000 data points to find the maximum slope of the force-displacement curve. The location and mechanism of failure in each ligament were visually confirmed and recorded.

Statistical Analysis

Summary statistics were reported in terms of mean and SD. The average cross-sectional area was determined by computing the mean cross-sectional area at the 3 different measurement points for each specimen. Continuous measurement data were not observed to be skewed or overdispersed; thus, parametric testing methods were used. Independent *t* tests were used to compare biomechanical characteristics of MPTL versus MPML, and paired *t* tests were used for comparisons involving MPFL. All biomechanical analyses, statistical analyses, and graphics were produced by use of software written in Python 3.4 (The Python Foundation with the packages NumPy, Pandas, Matplotlib).[15,19,26,29]

RESULTS

Anatomic Measurements

The MPFL, MPTL, and MPML were identified in all specimens. The mean ± SD specimen lengths for the MPFL, MPTL, and MPML were 69.5 ± 7.11 mm, 44.6 ± 8.82 mm, and 53.4 ± 10.7 mm, respectively. The mean ± SD cross-sectional areas for the same ligaments were 43.1 ± 13.8 mm^2, 34.8 ± 16.6 mm^2, and 55.3 ± 18.5 mm^2, respectively.

Failure Method and Location

Of the 20 MPFLs tested, 16 failed by midsubstance rupture and 4 by bony avulsion on the femur. Of the 10 MPTLs tested, 9 failed by midsubstance rupture and 1 by bony avulsion on the patella. Of the 10 MPMLs tested, all 10 failed by midsubstance rupture.

Mechanical Properties

The mean failure load for the MPFL, MPTL, and MPML was 178 N, 147 N, and 105 N, respectively. No significant difference was found for the mean failure load between the MPFL and MPTL (147 N; $P = .706$) or between the MPTL and the MPML ($P = .210$). However, a significant difference was noted in the mean failure load between the MPFL (178 N) and MPML (105 N; $P = .001$). The mean stiffness of the MPFL, MPTL and MPML was 23 N/mm, 31 N/mm, and 14 N/mm, respectively. No significant difference was found in mean stiffness between the MPFL and the MPTL ($P = .169$). A significant difference was found in mean stiffness between the MPFL (23 N/mm^2) and the MPML (14 N/mm^2; $P = .003$) and between the MPTL (31 N/mm^2) and MPML ($P = .028$). The mechanical properties of the ligaments are summarized in Table 1 and displayed in Figures 4 and 5.

DISCUSSION

The most important finding of this study was that the MPFL and MPTL had similar mean stiffness, modulus, failure stress, and failure load, which indicated that the MPTL may also have an important functional role for medial patellar stabilization. In addition, the mechanical properties of the MPML indicate a potentially important role in providing patellar stability. The most common type of failure observed among the tested MPFL, MPTL, and MPML specimens entailed midsubstance tears. Our findings are consistent with the concept that the MPFL is the strongest of the medially located patellar stabilizers; our data also support that the MPTL has mechanical properties similar to those of the MPFL.

The MPFL mean failure load in the current study (178 N) was comparable to the values reported by Burks et al,[4] Criscenti et al,[6] Herbort et al,[11] and Mountney et al.[21] In contrast, a recently published study by Hinckel et al[13] identified a much lower failure load (Table 2).

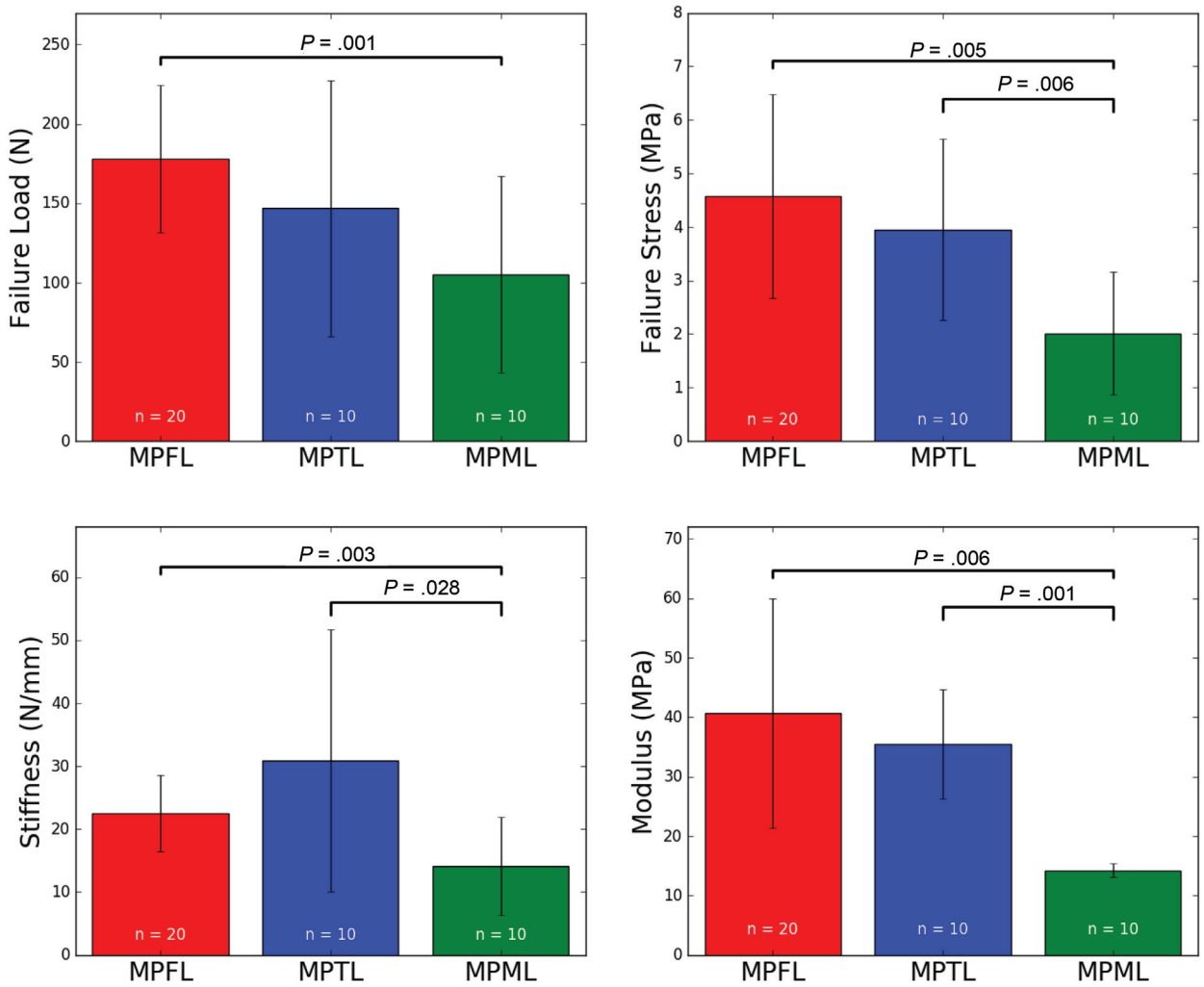

Figure 4. Mean failure load (N), failure stress (MPa), stiffness (N/mm), and modulus (MPa) for the medial patellofemoral ligament (MPFL), medial patellotibial ligament (MPTL), and medial patellomeniscal ligament (MPML).

In the present study, the mean failure loads of the MPTL and MPML were 147 N and 105 N, respectively, suggesting that these ligaments serve a functional role in patellar stability and tracking. Most of the literature related to the medial-sided patellar ligamentous restraints deals with the MPFL,[4,7,22,24,25] and few studies have investigated the MPTL and MPML.[10,12,14,16,24,27,30] A cadaveric study[25] that evaluated the role of the medial patellar ligaments in patellar tracking from 0° to 90° of flexion reported that the MPFL was the primary medial stabilizer of the patella in the first 30° of flexion, while the MPTL-MPML complex (not tested in isolation) had an increased role in restriction of lateral translation, patellar tilt, and patellar rotation at higher knee flexion angles. Of note, imaging studies have reported that the MPTL is torn in most primary lateral patellar dislocations,[28] which highlights the potential clinical importance of the distal, medial-sided ligaments that attach to the patella (MPTL-MPML complex).

The recent study by Hinckel et al[13] evaluated the force and deformation of the MPFL and MPTL (the MPML was not biomechanically studied). In that study, in contrast with our findings, the MPFL and the MPTL had a lower force energy at maximal tensile strength of 72.0 and 85.5 N, respectively. Additionally, while we found no significant difference in stiffness between the MPFL and MPTL, Hinckel et al[13] reported a lower stiffness (P = .024) for the MPFL than the MPTL. These discrepancies compared with our study could originate from the older ages of their donors (67.4 years in the Hinckel et al[13] study vs 56.4 years in our study), which may explain the differences in the biomechanical properties of the native medial patellar restraints. Furthermore, the testing setup, donor sex, and dissection techniques could explain some of the differences.

In our study, 4 of 20 (20%) MPFLs failed by bony avulsions from the femur. This finding stands in contrast to clinical studies, which have reported that the MPFL is often torn midsubstance or from the patella. One possible explanation is the bone quality of the cadavers. Most of the cadavers used in the present study were older than the typical patient with lateral patellar instability, and

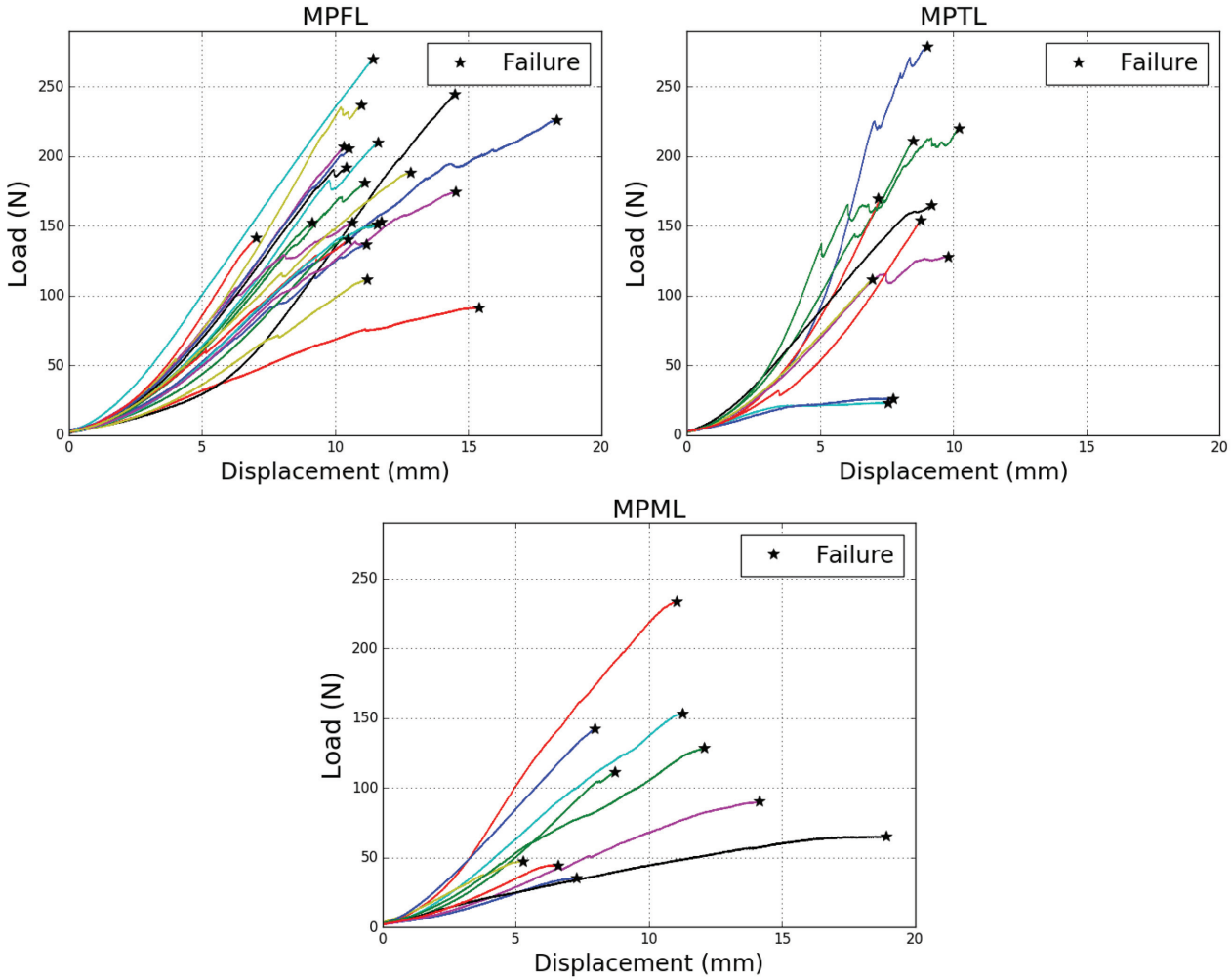

Figure 5. Force versus displacement curves of each specimen for the medial patellofemoral ligament (MPFL), medial patellotibial ligament (MPTL), and medial patellomeniscal ligament (MPML).

some might have had poorer bone quality. In much younger patients, ligaments can be stronger than the bone; hence, bony avulsions are common in that age group.

Interestingly, we found no significant difference between the failure load of the MPTL and MPML; however, a significant difference was noted in the failure stress of the MPTL and MPML. This finding suggests that the anatomic size of these ligaments was not the only factor determining their strength (eg, the MPMLs were of comparable size to the MPTLs, but when their size was factored into the failure analysis, they were not as strong). The role of the medial-sided patellar ligaments continues to evolve. When testing the role of these ligaments in lateral patellar dislocation, most testing formats have used straight lateral translation,[6,11,13] ignoring the probable superior and superior-lateral forces on the patella in vivo. Indeed, the anatomic position of the MPTL-MPML suggests a role in resisting a more superior directed force. In addition, the relatively low stiffness of all the medial-sided patellar ligaments suggests a certain degree of elasticity before failure is common for the patellofemoral joint. However, in the face of the dysplastic patellofemoral anatomy typically associated with lateral patellar dislocations,[28] the optimal goal may be to reconstruct with a ligament stronger than the native ligaments. Nonetheless, the surgeon must avoid overconstraining patellar mobility and increasing the patellofemoral contact pressures because these can cause pain and inferior results. In the present study, the ultimate loads of the MPFL and MPTL were 178 N and 147 N, respectively. When reconstructing these ligaments, surgeons should use grafts that have similar properties. Noyes et al[23] reported that a single-looped semitendinosus tendon had an ultimate load of 1216 N, while gracilis tendon had an ultimate load of 838 N. Both the semitendinosus tendon and gracilis tendon graft have higher failure loads; however, gracilis tendon would be the graft of choice for reconstruction of either the MPFL or MPTL because of its mechanical properties and availability. The next step would be to biomechanically evaluate the dynamic role of these ligaments under normal and pathologic conditions.

TABLE 2
Comparison of the Present Study to Previous Literature Regarding Biomechanical Properties of the Medial Patellofemoral Ligament

Study	Year	Knees Tested, n	Failure Load, Mean ± SD, N	Stiffness, Mean ± SD, N/mm
Current investigation	2017	20	178 ± 46	23 ± 6
Hinckel et al[13]	2017	9	72.0 ± 32.5	8.0 ± 1.9
Criscenti et al[6]	2016	12	145 ± 68	42.5 ± 10.2
Herbort et al[11]	2014	13	167.8 ± 80.0	29.4 ± 9.7
Mountney et al[21]	2005	10	208 ± 90	Not reported
Burks et al[4]	1998	10	209 ± 55	17.5

The synergistic roles of all 3 ligaments may be necessary in cases of increasing degrees of anatomic trochlear dysplasia.

The awareness of the MPFL and its role in patellofemoral stability is relatively recent; however, MPFL reconstructions for lateral patellar instability are now standard of care in surgery for patellar stabilization after a trial of nonoperative treatment.[1] The anatomic features of the MPTL and MPML have only been more recently defined, and further study is necessary to determine when repairs or reconstructions of these distomedial patellar stabilizers may be required. Our study has helped to further define the biomechanical properties of the MPTL and MPML. In addition, while conducting pilot studies on cadaver knees, we found that the MPTL and MPML were occasionally damaged by routine placement of the medial parapatellar arthroscopic portal (this increases if portals are created in a transverse fashion). Future studies could quantify the incidence and significance of iatrogenic MPTL-MPML damage.

We acknowledge some limitations in this study. The synergistic action of these ligaments in vivo cannot be replicated when they are tested individually. The specimens used in this study were older than the average patient who usually has lateral patellar instability, and this could have affected the biomechanical properties and the failure modes in this study. The sample size may not be sufficient to detect all anatomic differences that exist in vivo. The sample sizes for the MPTL and MPML tests were smaller than the sample size for the MPFL tests; however, to the best of our knowledge, the sample sizes for each ligament were among the highest compared with all other published biomechanical tests on the medial patellar stabilizers.[4-7,11,13,14,16,21,22] Nonpaired knees were used in this study, which could introduce a bias in comparison of the MPTL and MPML. In addition, only male cadavers were used; therefore, the applicability of these findings in younger females may be limited. It is important to view these ligament properties relative to each other, rather than as absolute values.

CONCLUSION

The MPFL and MPTL have comparable ultimate loads and stiffness, while the MPML had lower failure loads and stiffness. Midsubstance failure was the most common failure method; therefore, reconstruction grafts should meet or exceed the values reported herein.

ACKNOWLEDGMENT

The authors thank Grant Dornan, MS, for providing statistical analysis consultation.

REFERENCES

1. Arendt EA, Donell ST, Sillanpää PJ, Feller JA. The management of lateral patellar dislocation: state of the art. *J ISAKOS Jt Disord Orthop Sports Med*. 2017;2(4):205-212.
2. Arendt EA, Fithian DC, Cohen E. Current concepts of lateral patella dislocation. *Clin Sports Med*. 2002;21(3):499-519.
3. Bhatia S, Civitarese DM, Turnbull TL, et al. A novel repair method for radial tears of the medial meniscus: biomechanical comparison of transtibial 2-tunnel and double horizontal mattress suture techniques under cyclic loading. *Am J Sports Med*. 2016;44(3):639-645.
4. Burks RT, Desio SM, Bachus KN, Tyson L, Springer K. Biomechanical evaluation of lateral patellar dislocations. *Am J Knee Surg*. 1998; 11(1):24-31.
5. Conlan T, Garth WP, Lemons JE. Evaluation of the medial soft-tissue restraints of the extensor mechanism of the knee. *J Bone Joint Surg Am*. 1993;75(5):682-693.
6. Criscenti G, De Maria C, Sebastiani E, et al. Material and structural tensile properties of the human medial patello-femoral ligament. *J Mech Behav Biomed Mater*. 2016;54:141-148.
7. Desio SM, Burks RT, Bachus KN. Soft tissue restraints to lateral patellar translation in the human knee. *Am J Sports Med*. 1998; 26(1):59-65.
8. Dragoo JL, Nguyen M, Gatewood CT, Taunton JD, Young S. Medial patellofemoral ligament repair versus reconstruction for recurrent patellar instability: two-year results of an algorithm-based approach. *Orthop J Sports Med*. 2017;5(3):2325967116689465.
9. Duerr RA, Chauhan A, Frank DA, DeMeo PJ, Akhavan S. An algorithm for diagnosing and treating primary and recurrent patellar instability. *JBJS Rev*. 2016;4(9):01874474-201609000-00003.
10. Ebied AM, El-Kholy W. Reconstruction of the medial patello-femoral and patello-tibial ligaments for treatment of patellar instability. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(5):926-932.
11. Herbort M, Hoser C, Domnick C, et al. MPFL reconstruction using a quadriceps tendon graft, part 1: biomechanical properties of quadriceps tendon MPFL reconstruction in comparison to the intact MPFL. A human cadaveric study. *Knee*. 2014;21(6):1169-1174.
12. Hinckel BB, Gobbi RG, Bonadio MB, Demange MK, Pécora JR, Camanho GL. Reconstruction of medial patellofemoral ligament

using quadriceps tendon combined with reconstruction of medial patellotibial ligament using patellar tendon: initial experience. *Rev Bras Ortop*. 2016;51(1):75-82.
13. Hinckel BB, Gobbi RG, Demange MK, et al. Medial patellofemoral ligament, medial patellotibial ligament, and medial patellomeniscal ligament: anatomic, histologic, radiographic, and biomechanical study. *Arthroscopy*. 2017;33(10):1862-1873.
14. Hinckel BB, Gobbi RG, Kaleka CC, Camanho GL, Arendt EA. Medial patellotibial ligament and medial patellomeniscal ligament: anatomy, imaging, biomechanics, and clinical review [published online March 13, 2017]. *Knee Surg Sports Traumatol Arthrosc*. doi:10.1007/s00167-017-4469-y
15. Hunter J. *Matplotlib: A 2D Plotting Library*. Wilmington, DE: Python Software Foundation; 2012.
16. Kaleka CC, Aihara LJ, Rodrigues A, de Medeiros SF, de Oliveira VM, de Paula Leite Cury R. Cadaveric study of the secondary medial patellar restraints: patellotibial and patellomeniscal ligaments. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(1):144-151.
17. Kruckeberg BM, Chahla J, Moatshe G, et al. Quantitative and qualitative analysis of the medial patellar ligaments: an anatomic and radiographic study. *Am J Sports Med*. 2018;46(1):153-162.
18. Mäenpää H, Lehto MU. Patellofemoral osteoarthritis after patellar dislocation. *Clin Orthop*. 1997;339:156-162.
19. McKinney W. *Pandas: Python Data Analysis Library*. Wilmington, DE: Python Software Foundation; 2017.
20. Mehta VM, Inoue M, Nomura E, Fithian DC. An algorithm guiding the evaluation and treatment of acute primary patellar dislocations. *Sports Med Arthrosc Rev*. 2007;15(2):78-81.
21. Mountney J, Senavongse W, Amis AA, Thomas NP. Tensile strength of the medial patellofemoral ligament before and after repair or reconstruction. *J Bone Joint Surg Br*. 2005;87(1):36-40.
22. Nomura E, Horiuchi Y, Kihara M. Medial patellofemoral ligament restraint in lateral patellar translation and reconstruction. *Knee*. 2000;7(2):121-127.
23. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am*. 1984;66(3):344-352.
24. Panagiotopoulos E, Strzelczyk P, Herrmann M, Scuderi G. Cadaveric study on static medial patellar stabilizers: the dynamizing role of the vastus medialis obliquus on medial patellofemoral ligament. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(1):7-12.
25. Philippot R, Boyer B, Testa R, Farizon F, Moyen B. The role of the medial ligamentous structures on patellar tracking during knee flexion. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(2):331-336.
26. Python Software Foundation. *Python: A Programming Language That Lets You Work Quickly and Integrate Systems More Effectively*. Wilmington, DE: Python Software Foundation; 2017.
27. Sobhy MH, Mahran MA, Kamel EM. Midterm results of combined patellofemoral and patellotibial ligaments reconstruction in recurrent patellar dislocation. *Eur J Orthop Surg Traumatol Orthop Traumatol*. 2013;23(4):465-470.
28. Tompkins MA, Rohr SR, Agel J, Arendt EA. Anatomic patellar instability risk factors in primary lateral patellar dislocations do not predict injury patterns: an MRI-based study [published online February 28, 2017]. *Knee Surg Sports Traumatol Arthrosc*. doi:10.1007/s00167-017-4464-3
29. Van der Walt S, Colbert S, Varoquaux G. *The NumPy Array: A Structure for Efficient Numerical Computation*. Wilmington, DE: Python Software Foundation; 2017.
30. Zaffagnini S, Grassi A, Marcheggiani Muccioli GM, et al. Medial patellotibial ligament (MPTL) reconstruction for patellar instability. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(10):2491-2498.