Original Article

Anterior Mobility of the Posterior Horn of the Lateral Meniscus Is Associated With Abnormal Magnetic Resonance Imaging Findings of Anteroinferior Popliteomeniscal Fascicle and Posterosuperior Popliteomeniscal Fascicle as Well as a Clinical History of Catching or Locking Symptoms

Jun Suganuma, M.D., and Ryuta Mochizuki, M.D.

Purpose: To identify predictors of anterior mobility of the posterior horn of the lateral meniscus (PHLM) among patient demographics (age, sex), clinical characteristics (a history of catching or locking symptoms [CLS], body mass index, alignment of limb), and magnetic resonance imaging (MRI) findings of 4 restraints: anteroinferior popliteomeniscal fascicle (aiPMF), posterosuperior popliteomeniscal fascicle (psPMF), posteroinferior popliteomeniscal fascicle (piPMF), and meniscofibular ligament (MFibL). **Methods:** Between October 2010 and December 2014, patients who underwent arthroscopic measurement of mobility of the PHLM were identified. The Sakai classification was used to classify aiPMF and psPMF on MRI into the following 3 types: type A, the fascicle was depicted with obvious continuity and with a low-intensity band; type B, depicted with continuity but with an ambiguous intensity structure; and type C, depicted with discontinuity or not visible. Magnetic resonance images of the piPMF and MFibL were evaluated as presence or absence. The mobility of the PHLM was measured arthroscopically at traction forces of 10 and 20 N. **Results:** A total of 73 patients (47 men, mean age 41.8 ± 19.3 years) were included. Multivariate regression analyses revealed aiPMF type C and psPMF types B and C to be independent factors associated with mobility at both traction forces, and CLS was an independent factor at a traction force of 20 N. Compared with that of type A, the increased mobility of aiPMF type C was 5.0 mm ($P = .019$) and 5.6 mm ($P = .011$) at 10 and 20 N, respectively; the increased mobility of psPMF type B was 2.5 mm ($P = .007$) and 3.5 mm ($P = .0003$), respectively; and the increased mobility of psPMF type C was 3.3 mm ($P = .021$) and 3.6 mm ($P = .014$), respectively. The increased mobility associated with CLS was 3.5 mm at 20 N ($P = .022$). **Conclusions:** Anterior displacement of the PHLM induced by an external traction force at 90° of flexion of the knee joint was associated with abnormal MRI findings of the anteroinferior popliteomeniscal fascicle and posterosuperior popliteomeniscal fascicle, as well as a history of catching or locking symptoms. **Clinical Relevance:** Understanding signs and symptoms and associated pathology in patients with symptomatic anterior mobility of the posterior horn of the lateral meniscus may help guide best treatment.

Hypermobility of the posterior horn of the lateral meniscus (PHLM) has been described as a cause of knee pain,[1] a catching sensation, and recurrent subluxation of the lateral meniscus (RSLM),[2-11] and it is treated for these symptoms. Several methods of surgical intervention have been reported, including meniscal repair with the PHLM sutured to the posterior capsule,[2,3,12,13] thermal shrinkage of the posterolateral corner,[5,6] and repair or reconstruction of damaged popliteomeniscal fascicles (PMFs).[1,10,14-17] However, there are some cases in which the symptoms recur over time.[2,6,10,12,13]

The following structures have been described as having a role in guiding and restraining the movement

---

From the Department of Orthopedic Surgery, Hiratsuka City Hospital, Hiratsuka, Japan (J.S.); Yamabiko Hiratsuka Clinic for Orthopedic and Rheumatic Disease, Hiratsuka, Japan (J.S.); and Department of Orthopedic Surgery, Isehara Kyodo Hospital, Isehara, Japan (R.M.).

Received October 25, 2023; accepted February 24, 2024.

Address correspondence to Jun Suganuma, M.D., Department of Orthopedic Surgery, Hiratsuka City Hospital, 1-19-1 Minamihara, Hiratsuka, Kanagawa 254-0065, Japan. E-mail: junsugar@wa2.so-net.ne.jp

2666-061X/231510
https://doi.org/10.1016/j.asmr.2024.100922

of the lateral meniscus (LM): anterior and posterior meniscofemoral ligaments,[18-20] posterior meniscotibial ligament,[21,22] posteroinferior PMF (piPMF),[21,22] meniscofibular ligament (MFibL),[23,24] posterosuperior PMF (psPMF),[25-28] anteroinferior PMF (aiPMF),[25-28] and lateral meniscotibial ligament.[21,22] Although recent studies have precisely explained the structure of the restraints of the PHLM,[21,22] there have been no biomechanical studies investigating how much each structure restrains the mobility of the PHLM and what restraint is the most important to the PHLM, except for the study by Simonian et al.[27] in cadavers that showed that disruption of the aiPMF and psPMF resulted in increased mobility.

Although hypermobility of the PHLM can be diagnosed easily on arthroscopy,[9,13,14] it is not easy to determine which restraint is malfunctioning and how much a particular defective restraint contributes to the hypermobility. Thus, when symptoms caused by hypermobility of the PHLM emerge, it is difficult to know which restraints should be treated or what other treatment should be chosen. We therefore measured the mobility of the PHLM on arthroscopy at 90° of flexion of the knee joint to evaluate associations between its mobility and patient demographics, clinical characteristics, and magnetic resonance imaging (MRI) findings of the restraints. When selecting the patient demographics to study, we chose age and sex because age is reported to be associated with abnormal aiPMF and psPMF on MRI,[28] and women are reported to be more predisposed to RSLM than men.[9] When selecting clinical characteristics, we chose a history of catching or locking symptoms (CLS), body mass index (BMI), and limb alignment because there are reports indicating associations between BMI and meniscus extrusion,[29] as well as between limb alignment and meniscal tears.[30] In selecting the restraints to study, we chose 4 structures that seemed to be anatomically the most effective for controlling the mobility of the PHLM: aiPMF, psPMF, piPMF, and MFibL. The reason we did not select the meniscofemoral ligament or the posterior meniscotibial ligament is that the former induces anterior displacement of the PHLM throughout knee flexion,[19] and the latter is close to the tibial insertion site of the PHLM.[21,22] Furthermore, the posterior capsular ligament was also not selected because it becomes slack at 90° of flexion of the knee joint, while the lateral meniscotibial ligament is located too anteriorly to control the anterior mobility of the PHLM.[21,22]

When symptoms caused by hypermobility of the PHLM emerge, it is difficult to know which restraints should be treated. This study identifies predictors of anterior mobility of the PHLM among patient demographics (age, sex), clinical characteristics (CLS, BMI, alignment of limb), and MRI findings of 4 restraints (aiPMF, psPMF, piPMF, MFibL). We hypothesized that aiPMF, psPMF, and other risk factors would be associated with anterior mobility of the PHLM.

Methods

Institutional review board approval was obtained before starting this prospective study for arthroscopic measurements of the mobility of the PHLM. The inclusion criteria were (1) a visit to our knee joint clinic between October 2010 and December 2014 with a complaint of knee pain, including the lateral compartment, and the need to undergo diagnostic arthroscopy and/or surgical treatment; (2) anteroposterior and lateral radiographs of the knee joint; (3) proton density-weighted (PDW) MRI data, including coronal and sagittal images of the knee joint and anteromedial to posterolateral 45° oblique coronal images of the aiPMF and psPMF;[31] and (4) videos of arthroscopy of the knee joint. Patients with any of the following were excluded: knee joints with previous surgical treatment; anteroposterior or varus-valgus instability; open epiphyseal lines on radiographs; osteoarthritis of grade ≥ 2 in the lateral compartment on radiographic examination according to the Kellgren-Lawrence grading system; a tear or anomaly of the LM on MRI, except for the aiPMF, psPMF, piPMF, and MFibL; and abnormal morphology of the LM on arthroscopy, except for the 4 evaluated restraints.

The study population consisted of 2 groups of knee joints (Fig 1). Group A consisted of joints with no history of catching or locking symptoms. The final diagnoses in this group were based on clinical, MRI, and arthroscopic findings. Group A was subclassified into the following 2 subgroups to investigate whether the location of knee pain influenced the anterior displacement of the PHLM. Knee joints whose dominant pain was not located in the lateral compartment were assigned to group A1, and those whose dominant pain was in the lateral compartment were assigned to group A2. Group B consisted of joints with a history of mechanical locking episodes and pain on the lateral joint line, with these being diagnosed as RSLM.[9] Group B consisted of patients with RSLM, and group A was recruited as a control group. BMI and limb alignment were measured in all patients. Measurement of limb alignment was performed on a physical examination before any other examinations by the same orthopedist (J.S.). Patients were placed in the supine position on an examination table with their hips and knees extended. In patients with genu varum, the left-right distance between the medial margins of the knee joints was measured using a ruler. In patients with genu valgum, the left-right distance between the medial malleoli of the tibias was measured using a ruler. The limb alignments were classified into 3 groups. In group 1, which indicated valgus alignment, the distance between the medial malleoli was >3.0 cm; in group 2, which indicated

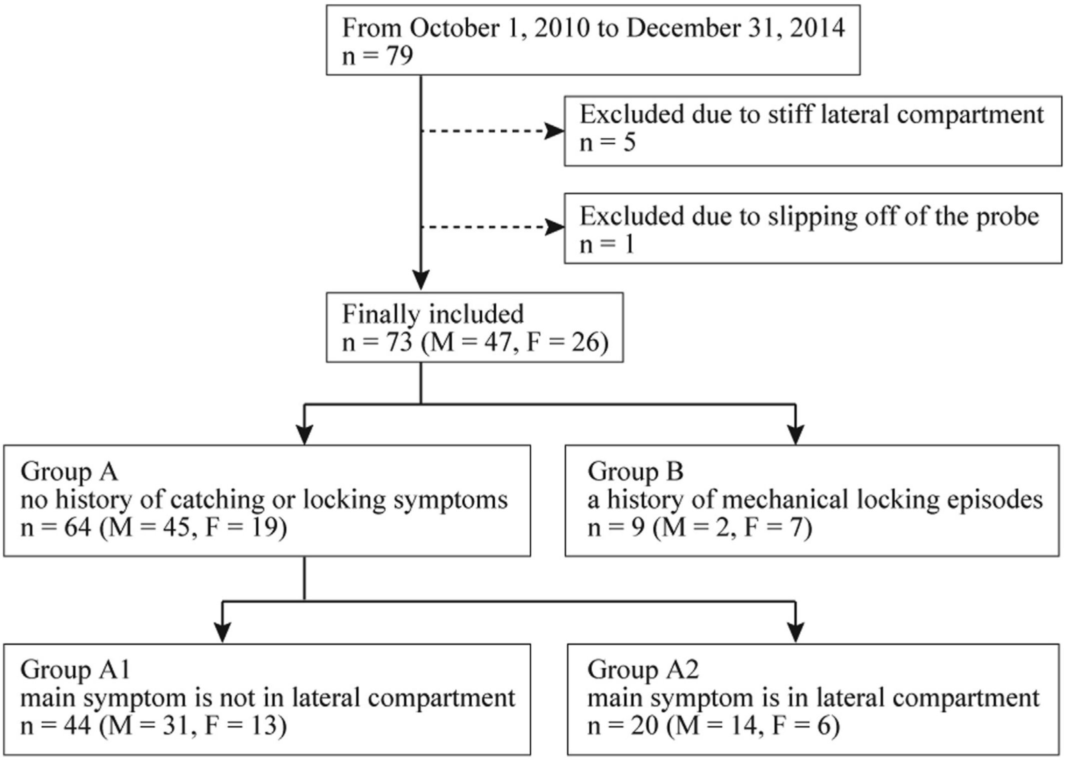

Fig 1. Flowchart depicting patient selection and classification. (F, female; M, male.)

intermediate alignment, limb alignment did not meet the criteria for either group 1 or 3; and in group 3, which indicated varus alignment, the distance between the medial margins of the knee joints was >3.0 cm.

MRI of the aiPMF, psPMF, piPMF, and MFibL was examined. MRI depicting the popliteus tendon (PT) at the level of the LM was used to evaluate the aiPMF and psPMF. MRI of the aiPMF and psPMF was classified according to the Sakai classification[31] into the following 3 groups: type A, the fascicle was depicted with obvious continuity and with a low-intensity band; type B, the fascicle was depicted with continuity but with ambiguous intensity structure; and type C, the fascicle was depicted with discontinuity or was not visible in any of the images. MRI of the piPMF and MFibL was assessed according to presence or absence (pre/ab). The piPMF was considered present if a structure was visualized running between the inferior margin of the posterior third of the LM and the PT located distal to the tibial plateau.[21] The MFibL was considered present if a curvilinear or straight hypointense structure anterior to the PT was visualized running between the inferior margin of the posterior third of the LM and the apex of the fibular head.[32] When the MFibL or piPMF was unrecognized, ambiguous, or interrupted, it was considered absent.

Measurement of Mobility of the PHLM

The arthroscopic force displacement (FD) measuring instrument for assessing the mobility of the PHLM consisted of 4 parts: a probe, a probe holder, a connecting cable, and the FD measuring unit (F-S Master; Imada). The first 3 parts were specially made for the present study by Teijin Nakashima Medical (Okayama, Japan) to facilitate accurate measurement (Fig 2). The F-S Master measuring unit consisted of a load cell, a load cell sliding device, a digital analyzer, and software that depicted an FD curve on a computer. The force measurement error, including the device's internal resistance, was less than 0.05 N according to the manufacturer.

First, an ordinary arthroscopic examination was performed through the anteromedial and anterolateral portals using a 30° arthroscope. The hip joint was then flexed to 45°, the knee joint was flexed to 90°, and the leg was circumducted externally. The proximal tibia was fixed to the operating table to prevent anteroposterior movement of the tibial condyle during the measurement. The hook of a probe was placed on the femoral peripheral rim of the PHLM just medial to the hiatal portion (or psPMF) through the anterolateral portal (Fig 3). The probe holder was fixed to the tibial condyle using a fixation belt, and the basal part of the probe was then fixed to the probe holder. One end of the connecting cable was fixed to the probe holder, and the other end was fixed to a load cell on a sliding device on a tripod (Fig 2). The probe could be moved forward or backward along its long axis by rotating the sterilized handle. The data measured by the load cell

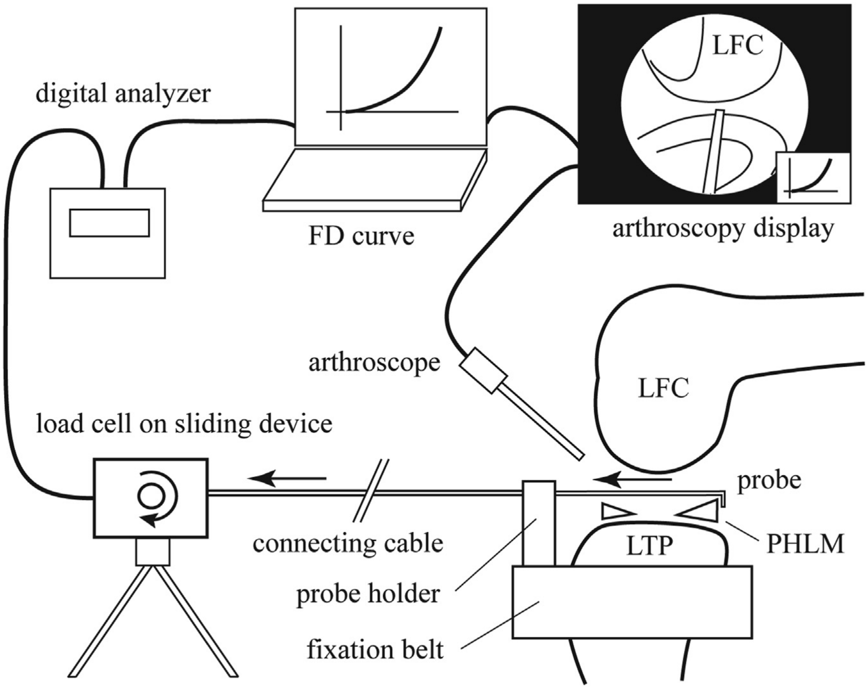

Fig 2. Diagram showing how to measure the mobility of the PHLM. The arthroscopic views and FD curve were examined simultaneously on the display during the measurement. (FD, force displacement; LFC, lateral femoral condyle; LTP, lateral tibial plateau; PHLM, posterior horn of the lateral meniscus.)

and sliding device were sent through a digital analyzer to a computer, where an FD curve was depicted and recorded.

The mobility of the PHLM was measured by the same orthopedist (J.S.). First, the probe was pulled until a 20.0-N traction force was reached, and then the probe was pushed back until it reached the initial position in the joint. A safe traction force with respect to the restraints was selected according to a study by Gupte et al.[33] that found a mean load to failure of the anterior meniscofemoral ligament (mean cross-sectional area is 14.7 mm^2) of 300.5 N, and 20 N is one-fifteenth of this force. The probe was moved at a speed of approximately 2.0 to 3.5 mm/s. The same measurement was repeated 3 times. When apparent undulations or notches were depicted on the FD curve, indicating that the probe had touched the articular cartilage, the data were discarded, and the position of the probe was adjusted. However, small notches depicted in the data in cases with a history of locking symptoms were accepted because slight contact between the highly deformed LM and the articular cartilage during traction could not be avoided. The FD curves always showed hysteresis, and therefore, the FD curves obtained when the PHLM was pulled anteriorly were used for measurement (Fig 4). The anterior displacement (in millimeters) of the PHLM at traction forces of 10.0 and 20.0 N was

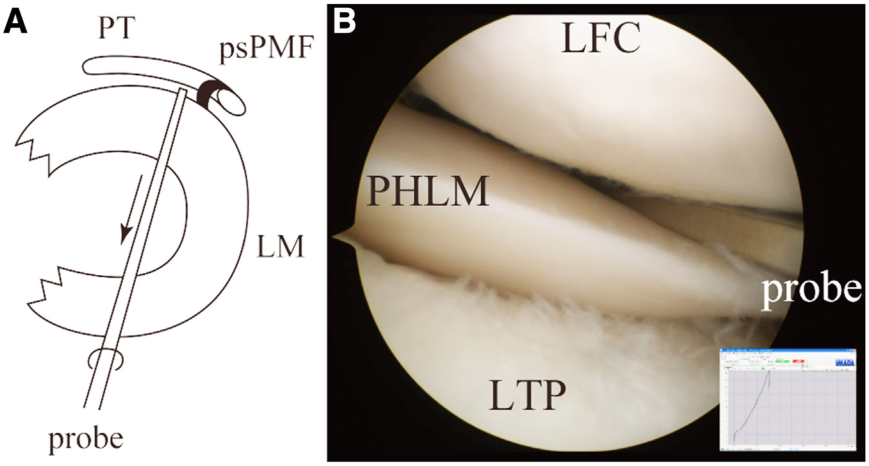

Fig 3. Applying a traction force to the PHLM using a probe. A 30° arthroscope and a probe were introduced through anteromedial and anterolateral portals, respectively, with the knee joint flexed at 90° and an image of the left knee being used. (A) Diagram showing how to adjust the probe onto the PHLM of the left knee joint. The tip of the probe was placed on the femoral peripheral rim of the PHLM just medial to the psPMF. (B) The force displacement curve depicted at bottom right shows the traction force starting to decrease after reaching 20 N. (LFC, lateral femoral condyle; LM, lateral meniscus; LTP, lateral tibial plateau; PHLM, posterior horn of the lateral meniscus; PT, popliteus tendon; psPMF, posterosuperior popliteomeniscal fascicle.)

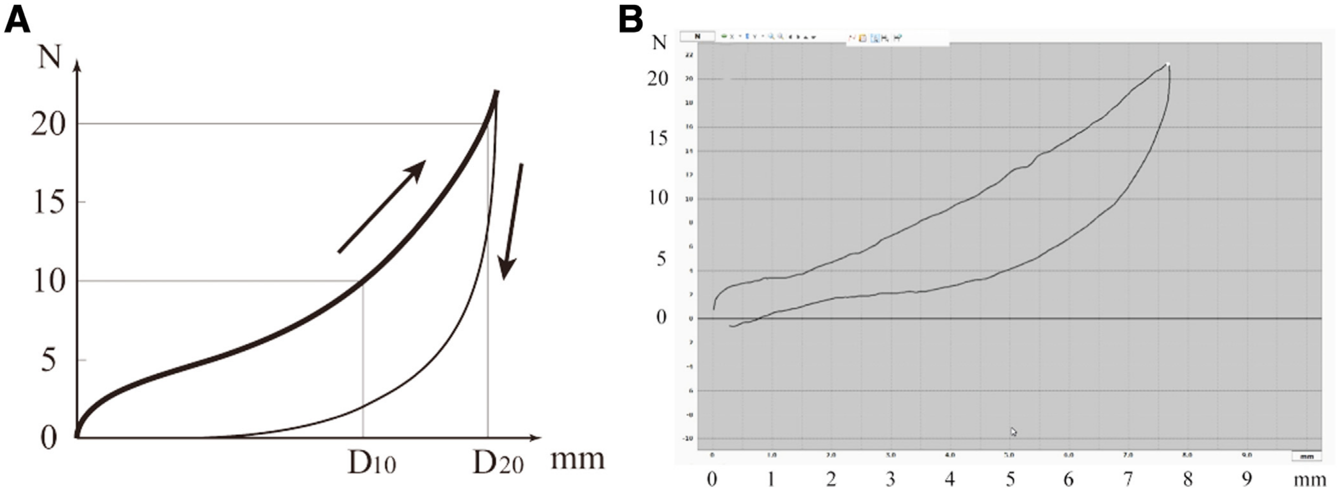

Fig 4. FD curve. (A) Diagram illustrating measurement of displacement of the PHLM on the FD curve at traction forces of 10 and 20 N. FD curves when the PHLM was pulled anteriorly were used for measurement. The anterior displacement of the PHLM at traction forces of 10.0 and 20.0 N was calculated from the FD curve and recorded as D10 and D20, respectively. (B) An actual FD curve as shown on a computer display. (FD, force displacement; PHLM, posterior horn of the lateral meniscus.)

calculated from the third FD curve and recorded as D10 and D20, respectively. The reason we used 10 and 20 N was that we wished to compare our results with those of a previous study that used 10 N,[27] and we expected to discover a hidden risk factor when using 20 N. The reason we used the third FD curve is that we measured meniscal mobility 5 times in a pilot study using a traction force of 20 N and found that the mobility increased slightly until the third measurement and that almost no increase occurred after that. Therefore, we decided to use the third FD curve for the measurement. The standard deviations and standard errors of the third to fifth repeated measurements were 0.13 mm and 0.07 mm, respectively, at 10 N, and 0.15 mm and 0.09 mm at 20 N.

Statistical Analysis

All statistical analyses were performed with IBM SPSS Statistics, Version 20.0 (IBM), with a *P* value of .05 indicating statistical significance.

Interobserver and intraobserver errors in determining the type of aiPMF and psPMF and the pre/ab status of the piPMF and MFibL on MRI were calculated with κ statistics using all knee joints. To determine interobserver error, 3 PMFs and MFibLs were classified independently by 2 examiners (J.S., R.M.) blinded to the patients' names. To determine intraobserver error, 3 PMFs and MFibL were classified twice by the same examiner (J.S.) with an interval of 1 month between measurements.

After categorizing several discrete variables to ensure effective statistical analysis, the final variables considered as risk factors included age, sex, CLS, BMI, alignment of limb (groups 1, 2, and 3), aiPMF type (A, B, and C), psPMF type (A, B, and C), piPMF (pre/ab), and MFibL (pre/ab). The mean and standard deviation were calculated to characterize continuous variables, and percentages were calculated for discrete variables. Unpaired *t* tests were used to compare the mean values of age, BMI, and anterior displacement of the PHLM between groups A1 and A2, as well as between groups A and B. The χ^2 test or Fisher exact test was applied to compare proportions of joints according to sex, CLS, limb alignment groups, types, and pre/ab status of ligaments between groups A1 and A2, as well as between groups A and B. To identify potential predictors of anterior mobility of the PHLM at 10- and 20-N traction force, univariate regression analysis was used to examine demographic and clinical characteristics and MRI findings. Multivariate regression analysis was then used to assess and select the best combination of significant factors in the univariate analysis. The results of the regression analyses are presented as mobility in millimeters (regression coefficient) with accompanying 95% confidence intervals.

Results

Seventy-nine patients underwent arthroscopic measurement of mobility of the PHLM during the above-mentioned period. Of these, 6 were excluded because it was not possible to complete the measurement. Five of these patients had a stiff lateral compartment with insufficient space for the measurement, whereas the PHLM of the other patient showed high mobility, and a probe slipped off the PHLM during measurement. Therefore, 73 patients (47 men and 26 women) with a mean (SD) age of 41.8 (19.3) years (range, 14-83 years) were ultimately enrolled (Fig 1). Group A included 64 patients/64 knees (45 men and 19 women; mean [SD]

Table 1. Patient Demographics, Clinical Characteristics, MRI Findings, and Anterior Displacement of the PHLM

	Group A					
Predictor and Anterior Displacement	Group A1	Group A2	P Value*	Total	Group B	P Value†
Age, mean ± SD, y	42.3 ± 19.7	41.5 ± 18.3	.88	42.0 ± 19.1	39.9 ± 21.3	.75
Sex			.97			.0048
Male	31 (48)	14 (22)		45 (62)	2 (3)	
Female	13 (20)	6 (9)		19 (26)	7 (10)	
CLS	0 (0)	0 (0)		0 (0)	9 (100)	<.0001
BMI, mean ± SD	21.8 ± 2.2	21.6 ± 1.3	.59	21.8 ± 1.9	22.2 ± 3.2	.59
Alignment of legs			.22			.062
Group 1 (valgus)	2 (3)	0 (0)		2 (3)	2 (3)	
Group 2	27 (42)	9 (14)		36 (49)	4 (5)	
Group 3 (varus)	15 (23)	11 (17)		26 (36)	3 (4)	
aiPMF			.25			<.0001
Type A	34 (53)	13 (20)		47 (64)	2 (3)	
Type B	10 (16)	6 (9)		16 (22)	4 (5)	
Type C	0 (0)	1 (2)		1 (1)	3 (4)	
psPMF			.26			<.0001
Type A	24 (38)	13 (20)		37 (51)	0 (0)	
Type B	17 (27)	4 (6)		21 (29)	3 (4)	
Type C	3 (5)	3 (5)		6 (8)	6 (8)	
piPMF			.80			.042
Presence	14 (22)	7 (11)		21 (29)	0 (0)	
Absence	30 (47)	13 (20)		43 (59)	9 (12)	
MFibL			.53			.090
Presence	10 (16)	6 (9)		16 (22)	0 (0)	
Absence	34 (53)	14 (22)		48 (66)	9 (12)	
Anterior displacement of the PHLM, mean ± SD, mm						
D10	6.2 ± 3.1	5.8 ± 2.8	.64	6.0 ± 3.0	10.7 ± 6.9	.0005
D20	10.5 ± 3.7	10.0 ± 3.6	.63	10.3 ± 3.6	18.4 ± 5.1	<.0001

NOTE. Values are presented as number (%) unless otherwise indicated. Types A, B, and C indicate Sakai classifications of the popliteomeniscal fascicle.

aiPMF, anteroinferior popliteomeniscal fascicle; BMI, body mass index; CLS, a history of catching or locking symptoms; D10, anterior displacement at a traction force of 10.0 N; D20, anterior displacement at a traction force of 20.0 N; MFibL, meniscofibular ligament; MRI, magnetic resonance imaging; PHLM, posterior horn of the lateral meniscus; piPMF, posteroinferior popliteomeniscal fascicle; psPMF, posterosuperior popliteomeniscal fascicle.

*P value between group A1 and group A2.

†P value between group A and group B.

age 42.0 [19.1] years; age range, 14-83 years). The final diagnoses in this group included isolated medial meniscal tear (14 joints); patellofemoral disorder, including bipartite patella (9 joints); grade 2 or 3 unicompartmental medial osteoarthritis with medial meniscal degeneration or tear (21 joints); synovitis, especially at the posterolateral corner (5 joints); and persistent pain of unknown cause at the posterolateral corner (15 joints). Group A1 included 31 men and 13 women, and group A2 included 14 men and 6 women. Group B included 9 patients/9 knees (2 men and 7 women; mean [SD] age [21.3] years; age range, 16-70 years).

The interobserver errors for the aiPMF, psPMF, piPMF, and MFibL were 0.68, 0.70, 0.63, and 0.41, respectively, while the intraobserver errors were 0.74, 0.75, 0.68, and 0.46, respectively. Both the inter- and intraobserver reliability measures for aiPMF, psPMF, and piPMF showed substantial agreement while those for MFibL showed moderate agreement.

The patient demographics, clinical characteristics, MRI findings, and anterior displacement of the PHLM are shown in Table 1. There were no significant differences in patient demographics, clinical characteristics, MRI findings, or anterior displacement of the PHLM between groups A1 and A2. To the contrary, when groups A and B were compared, we found significant differences in the mean values of D10 and D20, with the values being significantly higher in group B than in group A (P = .0005 and P < .0001, respectively). A significant difference was found in the distribution of the knee joints according to sex, with females predominating in group B (P = .0048). The distributions of joints also showed significant between-group differences according to aiPMF and psPMF, with type C predominating in group B (P < .0001), and according to piPMF, with it being present in significantly less subjects in group B (P = .042). However, there were no significant differences in the mean values of age or BMI between groups A and B, or in the

Table 2. Linear Regression Analyses of Associations of D10 and D20 With Independent Variables Including Demographic and Morphologic Factors on MRI

	D10 (Adjusted R^2 = .348)		D20 (Adjusted R^2 = .514)	
Predictor	R Coeff (95% CI), *P* Value (Univariate Analysis)	R Coeff (95% CI), *P* Value (Multivariate Analysis)	R Coeff (95% CI), *P* Value (Univariate Analysis)	R Coeff (95% CI), *P* Value (Multivariate Analysis)
Intercept		3.7 (2.2 to 5.2), <.0001		8.0 (6.5 to 9.5), <.0001
Age	−0.013 (−0.061 to 0.035), .60		0.012 (−0.045 to 0.069), .68	
Sex				
Male	Reference	Reference	Reference	Reference
Female	2.1 (0.22 to 3.95), .029	0.9 (−0.8 to 2.5), .31	2.7 (0.45 to 4.84), .019	0.7 (−1.1 to 2.4), .45
CLS	4.7 (2.1 to 7.3), .0005	0.3 (−2.6 to 3.2), .84	8.1 (5.3 to 10.8), <.0001	3.5 (0.5 to 6.5), .022
BMI	−0.12 (−0.56 to 0.32), .60		0.07 (−0.5 to 0.6), .80	
Alignment of legs				
Group 1 (valgus)	1.4 (−2.7 to 5.5), .49		4.5 (−2.2 to 9.2), .06	
Group 2	Reference		Reference	
Group 3 (varus)	−0.11 (−2.0 to 1.8), .91		0.2 (−2.0 to 2.4), .84	
aiPMF				
Type A	Reference	Reference	Reference	Reference
Type B	1.9 (0.08 to 3.8), .041	1.2 (−0.6 to 2.9), .18	3.1 (1.0 to 5.2), .0043	1.8 (−0.02 to 3.6), .053
Type C	7.9 (4.2 to 11.5), <.0001	5.0 (0.8 to 9.2), .019	10.4 (6.3 to 14.5), <.0001	5.6 (1.3 to 9.9), .011
psPMF				
Type A	Reference	Reference	Reference	Reference
Type B	3.1 (1.4 to 4.8), .0006	2.5 (0.7 to 4.3), .007	4.4 (2.5 to 6.3), <.0001	3.5 (1.7 to 5.4), .0003
Type C	5.8 (3.7 to 8.0), <.0001	3.3 (0.5 to 6.1), .021	7.6 (5.2 to 10.0), <.0001	3.6 (0.7 to 6.4), .014
piPMF				
Presence	Reference	Reference	Reference	Reference
Absence	2.7 (0.8 to 4.7), .0063	0.8 (−1.0 to 2.6), .37	3.0 (0.7 to 5.3), .011	0.15 (−1.7 to 2.0), .87
MFibL				
Presence	Reference		Reference	
Absence	0.18 (−2.0 to 2.4), .87		0.45 (−2.2 to 3.1), .73	

NOTE. Types A, B, and C indicate Sakai classifications of the popliteomeniscal fascicle.

aiPMF, anteroinferior popliteomeniscal fascicle; BMI, body mass index; CI, confidence interval; CLS, a history of catching or locking symptoms; D10, anterior displacement at a traction force of 10.0 N; D20, anterior displacement at a traction force of 20.0 N; MFibL, meniscofibular ligament; MRI, magnetic resonance imaging; piPMF, posteroinferior popliteomeniscal fascicle; psPMF, posterosuperior popliteomeniscal fascicle; R Coeff, regression coefficient; R^2, coefficient of determination.

distribution of knee joints according to limb alignment or presence of MFibL.

Results of the univariate and multivariate analyses are shown in Table 2. The univariate analysis showed that age, BMI, limb alignment, and MFibL were not associated with D10 or D20. However, female sex was associated with D10 and D20, with regression coefficients of 2.1 and 2.7 for traction forces of 10 and 20 N, respectively, indicating that women showed higher anterior displacement than men by 2.1 and 2.7 mm at 10 and 20 N, respectively. CLS was associated with D10 and D20, with CLS inducing 4.7 and 8.1 mm of anterior displacement, respectively. Type B and C aiPMF were associated with D10 and D20, with type B inducing 1.9 and 3.1 mm of anterior displacement compared with type A at traction forces of 10 and 20 N, respectively, and type C inducing 7.9 and 10.4 mm of anterior displacement. Type B and C psPMF were also associated with D10 and D20, with type B inducing 3.1 and 4.4 mm of anterior displacement compared with type A at traction forces of 10 and 20 N, respectively, and type C inducing 5.8 and 7.6 mm of anterior displacement. Furthermore, absence of piPMF was associated with D10 and D20, with it inducing 2.7 and 3.0 mm of anterior displacement at traction forces of 10 and 20 N, respectively.

After statistical analysis with univariate regression, 5 of the 9 independent variables were identified as potential predictors with $P < .05$ at a 10- and 20-N traction force: sex, CLS, aiPMF, psPMF, and piPMF. Multivariate regression analysis, including these 5 potential predictors, revealed that aiPMF and psPMF were associated with D10 and D20, and CLS was associated with D20. That is, aiPMF type C and psPMF types B and C were independent factors associated with anterior mobility of the PHLM at both traction forces, and CLS was an independent factor at a traction force of 20 N. For aiPMF, the increased mobility of type C in comparison with type A was 5.0 mm at 10 N ($P = .019$) and 5.6 mm at 20 N ($P = .011$). For psPMF, in comparison with type A, the increased mobility of type B was 2.5 mm at 10 N ($P = .007$) and 3.5 mm at 20 N ($P = .0003$), and the increased mobility of type C was 3.3 mm at 10 N ($P = .021$) and 3.6 mm at 20 N ($P = .014$). CLS was responsible for increased mobility of 3.5 mm at 20 N ($P = .022$).

The setup of instruments that did not require sterilization was made before surgery and took approximately 10 minutes. The setup of sterilized instruments and measurement of the mobility of the LM were made during surgery and took approximately 15 minutes. There were no adverse events associated with arthroscopic measurement of mobility after surgery.

Discussion

The amount of anterior displacement of the PHLM induced by external traction forces of 10 and 20 N at 90° of flexion of the knee joint was associated with aiPMF type C and psPMF types B and C. Furthermore, CLS was also associated with anterior displacement at a 20-N traction force.

The 9 parameters of age, sex, CLS, BMI, alignment of legs, aiPMF, psPMF, piPMF, and MFibL were examined as potential factors affecting the mobility of the PHLM in regression analysis. Anatomically, the aiPMF runs distally from around the inferior margin of the PHLM to the PT, and the psPMF runs proximally from the superior margin of the PHLM to the PT.[21,22] The efficacy of these 2 restraints was proven by Simonian et al.[27] As for the psPMF and MFibL, these restraints run in a posterior direction from the inferior margin of the PHLM to the PT and the apex of the fibula head, respectively,[21-24] and they seem to be effective for controlling anterior mobility of the PHLM and potentially act as secondary restraints at 90° of flexion of the knee joint. However, MFibL, as well as age, BMI, and limb alignment, was not found to be significant in the univariate analysis, and piPMF and sex were not significant in the multivariate regression analysis.

One of the predictors detected as affecting the mobility of the PHLM was psPMF type B, with mobility expected to increase by 2.5 mm at 10 N ($P = .007$) and by 3.5 mm at 20 N ($P = .0003$) in comparison with type A. This significant difference in mobility between psPMF types A and B indicates that continuity of the psPMF on oblique coronal PDW MRI is not enough to show sound stability of the PHLM and that a low-intensity band with obvious continuity on MRI is necessary. Furthermore, when patients have a symptom caused by hypermobility of the PHLM and that is confirmed by later arthroscopy, repair or reconstruction of the psPMF in patients showing as type B or C on MRI is reasonable because the treated psPMF can be expected to show significantly less mobility.

Another significant predictor of PHLM mobility was aiPMF type C, with mobility in comparison with type A expected to increase by 5.0 mm at 10 N ($P = .019$) and by 5.6 mm at 20 N ($P = .011$). These results show that, as far as the aiPMF is concerned, its absence or discontinuity on MRI seems to be necessary to show a statistically significant increase in mobility of the PHLM in comparison with type A. Furthermore, repair or reconstruction of a discontinuous or absent aiPMF is a reasonable approach to significantly reduce hypermobility of the PHLM.

The other significant predictor at a 20-N traction force was CLS, with mobility expected to increase by 3.5 mm ($P = .022$). It is noteworthy that the multivariate regression analysis did not reveal CLS to be a significant predictor at a traction force of 10 N, with the increased mobility being only 0.3 mm ($P = .84$). The discrepancy between the results at 10 and 20 N seems to be related to something detectable only with a larger traction force, and a potential factor could be slightly increased ease of deformation of the PHLM caused by its mechanical locking.

Simonian et al.[27] objectively evaluated the stability of the LM before and after sequential sectioning of the aiPMF and psPMF in cadavers. They reported that cutting the aiPMF resulted in increased motion of 1.8 mm with a 10-N load and that cutting the psPMF resulted in an increased motion of 1.0 mm. They stated that the aiPMF seemed to lend a greater amount of control to meniscal motion. Our study seemed to show similar results to this previous one. The difference in mobility between aiPMF types A and C at 10 N was 5.0 mm, and that between psPMF types A and C was 3.3 mm, showing that discontinuity of the aiPMF on MRI induced higher mobility than discontinuity of the psPMF. Furthermore, the mean anterior motion of the LM with intact aiPMF and psPMF was 3.6 mm, and in this study, the expected mobility of knee joints with aiPMF type A and psPMF type A (indicating intact aiPMF and psPMF) at 10 N was 3.7 mm, the intercept of the multivariate analysis (Table 2). However, in the study by Simonian et al.,[27] the mean motion after cutting both PMFs was 6.4 mm, while the expected mobility of joints with both PMFs being of type C on MRI was 12.0 mm, which was calculated by adding the intercept and regression coefficients of aiPMF type C and psPMF type C (Table 2). The reason our results showed mobility approximately 2 times higher than that in the cadaver study may be that most of our cases in which both PMFs were of type C had a history of locking symptoms. The previous results showing that the PHLM did not become locked after cutting both PMFs support the thinking that locking of the PHLM does not occur at 90° of flexion of the knee joint in cases with only isolated disruption of both PMFs but needs disruption of other restraints of the PHLM as well. Therefore, the direct effect of sectioning an anatomic restraint on meniscal mobility seems to be significantly different from that measured when the restraint is damaged in vivo. When studying the popliteal hiatus of the knee, Grassi et al.[22] reported that the aiPMF blends with the MFibL at the inferior margin of the LM, which might explain the discrepancy between the results of meniscal mobility in the anatomic and clinical studies.

Kimura et al.[34] investigated on arthroscopy the meniscotibial coronary ligament of the PHLM, which is believed to include the piPMF by Grassi et al.[22] The prevalence of piPMF in anatomic studies varies from 17% to 100%,[21,35,36] while the prevalence in magnetic resonance arthrography was reported to be 40%.[36] In this study, the piPMF was absent in 71% of joints. Although the consistency and prevalence of the piPMF remain somewhat controversial, when the running direction of the ligament is considered, it seems to work as a checkrein when the PHLM moves excessively anteriorly. We expected that absence of the piPMF might be a risk factor for hypermobility of the PHLM, but although univariate analysis identified piPMF as a potential risk factor, piPMF was not finally demonstrated to be a risk factor in the multivariate analysis.

Bozkurt et al.[23] reported that the MFibL, which is a capsular ligament running between the apex of the fibular head and the posterior part of the midportion of the LM, was recognized in 100% of 50 cadaveric knee joints. Another anatomic study also showed 100% prevalence of this ligament.[24] However, the ligament was demonstrated in 42.5% of knees on PDW fast spin echo MRI studies, with this prevalence increasing to 63% in the presence of fluid in the posterolateral joint space and reducing to 16% in the absence of fluid.[32] In this study, the prevalence of the MFibL on MRI was 22%. A lack of biomechanical study of this ligament makes it difficult to understand its function thoroughly, although anatomic studies show that the MFibL seems to restrain anterior displacement of the LM, and the PHLM does not seem to be able to dislocate anteriorly without damaging this ligament. However, univariate analysis failed to identify MFibL as a potential risk factor, probably because of the low prevalence of this ligament on MRI and relatively low inter- and intraobserver agreement for MRI evaluation of the MFibL.

In this study, we used group A as a control group for group B. However, there is a concern about whether group A2 included joints with lateral knee pain induced by hypermobility of the PHLM. In this study, there was no knee joint without any pain in the lateral compartment because the institutional review board approval included lateral pain as an inclusion criterion. However, for patients in group A1, pain in the lateral compartment was always very slight and knee pain predominated in the medial or patellofemoral compartments. Therefore, given that we were ethically not allowed to measure the mobility of the PHLM of knee joints without pain, we considered group A1 the control group. Furthermore, none of the patients showed a positive figure-4 test[1] in group A2, and we found no significant differences in all the parameters between groups A1 and A2 (Table 1). Thus, we also considered group A2 part of the control group; even if knee joints with hypermobility of the PHLM were included in group A2, there should be very little effect on the results of the regression analyses. Therefore, including group A2 in this study does not seem to have compromised the results.

Limitations

This study has several limitations. First, due to the relatively short duration of the study, the number of patients who participated in the measurement was 73. The expected sample size for 5 independent predictors in multivariate regression analyses was 92. Therefore, this study was underpowered, and the results could be subject to a type II error. Second, standing anteroposterior radiographs could not be used for the measurement of limb alignment because some patients could not load their weight on their disordered leg at hospitalization and the chance to take the radiograph was lost after they left the hospital. Although clinical examination of limb alignment and measurement of limb alignment on digital photographs are different, both are based on an inspection of the legs, and digital photographs were reported to be highly reliable for measuring the leg alignment.[37] Third, the amount of meniscal mobility can change with the traction speed of the probe. Although we attempted to maintain a constant speed, we had to decrease the speed when the mobility of the meniscus was high because the probe was liable to slip off the meniscus. Fourth, the meniscal mobility measured using a probe can be influenced not only by the restraints of the PHLM but also by the mechanical property of the meniscus, which must be related to the ease of deformation of the PHLM. Although we could not measure any indices of the mechanical properties of the LM, there was no case where signal intensity of the PHLM on MRI was diffusely high, which indicates degeneration of the PHLM.[38] Fifth, this study was performed at 90° of flexion of the knee joint. As the flexion angle of the knee joint changes, the positions of the PHLM[39] and the PT[40] change, and the tension of the restraints of the LM also changes.[17,19] Therefore, different results might be obtained if the meniscal mobility is measured with the knee joint at a different flexion angle.

Conclusions

Anterior displacement of the PHLM induced by an external traction force at 90° of flexion of the knee joint was associated with abnormal MRI findings of the anteroinferior popliteomeniscal fascicle and posterosuperior popliteomeniscal fascicle, as well as a history of catching or locking symptoms.

Disclosures

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This study did not receive any award or grant.

References

1. LaPrade RF, Konowalchuk BK. Popliteomeniscal fascicle tears causing symptomatic lateral compartment knee pain: Diagnosis by the figure-4 test and treatment by open repair. *Am J Sports Med* 2005;33:1231-1236.
2. Kimura M, Shirakura K, Hasegawa A, Kobayashi Y, Udagawa E. Anatomy and pathophysiology of the popliteal tendon area in the lateral meniscus: 2. Clinical investigation. *Arthroscopy* 1992;8:424-427.
3. Simonian PT, Sussmann PS, Wickiewicz TL, et al. Popliteomeniscal fasciculi and the unstable lateral meniscus: Clinical correlation and magnetic resonance diagnosis. *Arthroscopy* 1997;13:590-596.
4. George M, Wall EJ. Locked knee caused by meniscal subluxation: Magnetic resonance imaging and arthroscopic verification. *Arthroscopy* 2003;19:885-888.
5. Higuchi H, Kimura M, Kobayashi A, Hatayama K, Takagishi K. A novel treatment of hypermobile lateral meniscus with monopolar radiofrequency energy. *Arthroscopy* 2004;20:1-5.
6. Ohtoshi K, Kimura M, Kobayashi Y, Higuchi H, Kikuchi S. Arthroscopic thermal shrinkage for hypermobile lateral meniscus. *Am J Sports Med* 2004;32:1297-1301.
7. Garofalo R, Kombot C, Borens O, Djahangiri A, Mouhsine E. Locking knee caused by subluxation of the posterior horn of the lateral meniscus. *Knee Surg Sports Traumatol Arthrosc* 2005;13:569-571.
8. Lyle NJ, Sampson MA, Barrett DS. MRI of intermittent meniscal dislocation in the knee. *Br J Radiol* 2009;82:374-379.
9. Suganuma J, Ohkoshi T. Association of internal rotation of the knee joint with recurrent subluxation of the lateral meniscus. *Arthroscopy* 2011;27:1071-1078.
10. Ahn JH, Lee SH, Kim KI, Nam J. Arthroscopic meniscus repair for recurrent subluxation of the lateral meniscus. *Knee Surg Sports Traumatol Arthrosc* 2018;26:787-792.
11. Li Z, Zhao H, Dai Z, et al. Widening of the popliteal hiatus on magnetic resonance imaging leads to recurrent subluxation of the lateral meniscus. *Knee Surg Sports Traumatol Arthrosc* 2020;28:3532-3538.
12. Van Steyn MO, Mariscalco MW, Pedroza AD, Smerek J, Kaeding CC, Flanigan DC. The hypermobile lateral meniscus: A retrospective review of presentation, imaging, treatment, and results. *Knee Surg Sports Traumatol Arthrosc* 2016;24:1555-1559.
13. Steinbacher G, Alentorn-Geli E, Alvarado-Calderón M, Barastegui D, Álvarez-Díaz P, Cugat R. Meniscal fixation is a successful treatment for hypermobile lateral meniscus in soccer players. *Knee Surg Sports Traumatol Arthrosc* 2019;27:354-360.
14. Shin HK, Lee HS, Lee YK, Bae KC, Cho CH, Lee KJ. Popliteomeniscal fascicle tear: Diagnosis and operative technique. *Arthrosc Tech* 2012;23(1):e101-e106.
15. Kamiya T, Suzuki T, Otsubo H, et al. Midterm outcomes after arthroscopic surgery for hypermobile lateral meniscus in adults: Restriction of paradoxical motion. *J Orthop Sci* 2018;23:1000-1004.
16. di Vico G, Simonetta R, Correra G, et al. Popliteomeniscal fascicles tears with lateral meniscus instability: Outcomes of arthroscopic surgical technique at mid-term follow-up. *Arch Orthop Trauma Surg* 2023;143:2573-2579.
17. Suganuma J, Inoue Y, Tani H, Sugiki T, Sassa T, Shibata R. Reconstruction of the popliteomeniscal fascicles for treatment of recurrent subluxation of the lateral meniscus. *Arthrosc Tech* 2017;6(6):e283-e290.
18. Gupte CM, Bull AM, Thomas RD, Amis AA. The meniscofemoral ligaments: Secondary restraints to the posterior drawer. Analysis of anteroposterior and rotary laxity in the intact and posterior-cruciate-deficient knee. *J Bone Joint Surg Br* 2003;85:765-773.
19. Poynton A, Moran CJ, Moran R, O'Brien M. The meniscofemoral ligaments influence lateral meniscal motion at the human knee joint. *Arthroscopy* 2011;27:365-371.
20. Deckey DG, Tummala S, Verhey JT, et al. Prevalence, biomechanics, and pathologies of the meniscofemoral ligaments: A systematic review. *Arthrosc Sports Med Rehabil* 2021;26(3):e2093-e2101.
21. Aman ZS, DePhillipo NN, Storaci HW, et al. Quantitative and qualitative assessment of posterolateral meniscal anatomy: Defining the popliteal hiatus, popliteomeniscal fascicles, and the lateral meniscotibial ligament. *Am J Sports Med* 2019;47:1797-1803.
22. Grassi A, Pizza N, Andrea Lucidi G, Macchiarola L, Mosca M, Zaffagnini S. Anatomy, magnetic resonance and arthroscopy of the popliteal hiatus of the knee: Normal aspect and pathological conditions. *EFORT Open Rev* 2021 4;6:61-74.
23. Bozkurt M, Elhan A, Tekdemir I, Tönük E. An anatomical study of the meniscofibular ligament. *Knee Surg Sports Traumatol Arthrosc* 2004;12:429-433.
24. Natsis K, Paraskevas G, Anastasopoulos N, Papamitsou T, Sioga A. Meniscofibular ligament: Morphology and functional significance of a relatively unknown anatomical structure. *Anat Res Int* 2012;2012:214784.
25. Cohn AK, Mains DB. Popliteal hiatus of the lateral meniscus. Anatomy and measurement at dissection of 10 specimens. *Am J Sports Med* 1979;7:221-226.
26. Stäubli HU, Rauschning W. Popliteus tendon and lateral meniscus. Gross and multiplanar cryosectional anatomy of the knee. *Am J Knee Surg* 1991;4:110-121.
27. Simonian PT, Sussmann PS, van Trommel M, Wickiewicz TL, Warren RF. Popliteomeniscal fasciculi and lateral meniscal stability. *Am J Sports Med* 1997;25:849-853.
28. Suganuma J, Mochizuki R, Inoue Y, Yamabe E, Ueda Y, Kanauchi T. Magnetic resonance imaging and arthroscopic findings of the popliteomeniscal fascicles with and without recurrent subluxation of the lateral meniscus. *Arthroscopy* 2012;28:507-516.
29. Achtnich A, Petersen W, Willinger L, Sauter A, Rasper M, Wörtler K, Imhoff AB, Diermeier T. Medial meniscus extrusion increases with age and BMI and is depending on different loading conditions. *Knee Surg Sports Traumatol Arthrosc* 2018;26:2282-2288.

30. Habata T, Ishimura M, Ohgushi H, Tamai S, Fujisawa Y. Axial alignment of the lower limb in patients with isolated meniscal tear. *J Orthop Sci* 1998;3:85-89.
31. Sakai H, Sasho T, Wada Y, et al. MRI of the popliteomeniscal fasciculi. *AJR Am J Roentgenol* 2006;186: 460-466.
32. Obaid H, Gartner L, Haydar AA, Briggs TW, Saifuddin A. The meniscofibular ligament: An MRI study. *Eur J Radiol* 2010;73:159-161.
33. Gupte CM, Smith A, Jamieson N, Bull AM, Thomas RD, Amis AA. Meniscofemoral ligaments—Structural and material properties. *J Biomech* 2002;35:1623-1629.
34. Kimura M, Shirakura K, Hasegawa A, Kobayashi Y, Udagawa E. Anatomy and pathophysiology of the popliteal tendon area in the lateral meniscus: 1. Arthroscopic and anatomical investigation. *Arthroscopy* 1992;8:419-423.
35. Feipel V, Simonnet ML, Rooze M. The proximal attachments of the popliteus muscle: A quantitative study and clinical significance. *Surg Radiol Anat* 2003;25: 58-63.
36. Peduto AJ, Nguyen A, Trudell DJ, Resnick DL. Popliteomeniscal fascicles: Anatomic considerations using MR arthrography in cadavers. *AJR Am J Roentgenol* 2008;190: 442-448.
37. Schmitt H, Kappel H, Moser MT, et al. Determining knee joint alignment using digital photographs. *Knee Surg Sports Traumatol Arthrosc* 2008;16:776-780.
38. Hodler J, Haghighi P, Pathria MN, Trudell D, Resnick D. Meniscal changes in the elderly: Correlation of MR imaging and histologic findings. *Radiology* 1992;184:221-225.
39. Thompson WO, Thaete FL, Fu FH, Dye SF. Tibial meniscal dynamics using three-dimensional reconstruction of magnetic resonance images. *Am J Sports Med* 1991;19:210-216.
40. Watanabe Y, Moriya H, Takahashi K, et al. Functional anatomy of the posterolateral structures of the knee. *Arthroscopy* 1993;9:57-62.