Complementary Function of the Meniscofemoral Ligament and Lateral Meniscus Posterior Root to Stabilize the Lateral Meniscus Posterior Horn

A Biomechanical Study in a Porcine Knee Model

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Background: It has been demonstrated that the load distribution function of the lateral meniscus (LM) is compromised by resecting both the meniscofemoral ligament (MFL) and LM posterior root (LMPR). However, the effect of resecting these fibers on load transmission through the LM needs to be investigated.

Purpose: To evaluate using a porcine knee model (1) the in situ forces of the MFL and LMPR and (2) the effect of resecting these fibers on the in situ force of the LM under a compressive load and valgus torque to the lateral knee compartment.

Study Design: Controlled laboratory study.

Methods: Twenty fresh-frozen porcine knees and a 6 degrees of freedom robotic system were utilized. An axial compressive load of 250 N and 5 N·m of valgus torque were applied to intact, MFL-deficient, LMPR-deficient, and MFL/LMPR-deficient knees at 30°, 60°, and 90° of flexion. The valgus angles under the applied loads were compared among the 4 states. The in situ forces of the MFL and LMPR under the applied loads were calculated under the principle of superposition. The in situ forces of the LM under the applied loads were also calculated and compared among the 4 conditions (intact, without the MFL, without LMPR, and without the MFL/LMPR).

Results: The valgus angles significantly increased after resecting both the MFL and LMPR at all the flexion angles. The in situ forces of the MFL and LMPR changed reciprocally as the knee flexed. The in situ forces of the LM significantly decreased after resecting both the MFL and LMPR, although resecting only the MFL or LMPR represented no significant effect.

Conclusion: The MFL and LMPR functioned complementarily as the posterior attachments of the LM against a compressive load and valgus torque to the lateral knee compartment in porcine knee joints.

Clinical Relevance: If the LMPR is completely detached and needs to be repaired, the MFL should be preserved because it may provide some stability to the LM posterior horn and protect the repaired LMPR.

Keywords: meniscofemoral ligament; lateral meniscus; posterior root; in situ force; biomechanics; porcine

The meniscofemoral ligament (MFL) is composed of 2 ligaments connecting the medial wall of the femoral intercondylar notch to the lateral meniscus (LM) posterior horn. The anterior MFL (aMFL) of Humphrey passes in front of the posterior cruciate ligament (PCL), while the posterior MFL (pMFL) of Wrisberg runs behind the PCL.[21] Humphry[22] first reported the presence of the MFL, and Poirier and Charpy[28] subsequently described it as the "third cruciate ligament" because of its fiber orientation along the PCL. Cadaveric studies have revealed that the incidences of the aMFL and pMFL are 17% to 83% and 69% to 100%, respectively, while at least 1 MFL exists in most knee joints (incidence of 93%-100%).[21,24,27,30] In addition, the aMFL and pMFL develop tension with knee flexion and

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extension, respectively, in a reciprocal manner,[26] and each MFL has almost 300 N of an ultimate failure load.[20] Therefore, the MFL is considered to play a substantial biomechanical role in the human knee joint.[17]

It has been reported that the MFL functions as a secondary restraint to posterior tibial translation.[17,25,31] However, the MFL connects the femur to the LM posterior horn but not the tibia, while the LM posterior horn is attached to the tibia via the LM posterior root (LMPR). Therefore, this restraining function likely occurs via the MFL–LM posterior horn–LMPR complex. On the other hand, in addition to serving as a restraint against posterior tibial translation, the MFL has been shown to contribute to the load distribution of the LM.[1] Resecting the MFL in addition to the LMPR has resulted in deterioration of the load distribution function of the LM.[4,13] These results indicate that the LM may have 2 posterior attachments: the MFL to the femur and the LMPR to the tibia. However, there have been no reports concerning this from the viewpoint of the load transmission through the LM.

The pivotal roles of the meniscus are load distribution by increasing the congruity of the tibiofemoral joint and load transmission through conversion to the circumferential tensile force.[7] As these functions of the meniscus are attributed to its anterior and posterior attachments, complete disruption of the posterior attachments of the LM would deteriorate the biomechanical function of the LM.[5] To understand the interaction of the 2 posterior attachments of the LM (the MFL and LMPR), the effect of resecting these fibers on the load transmission through the LM needs to be directly investigated. Therefore, the purposes of this study were to evaluate (1) the in situ forces of the MFL and LMPR and (2) the effect of resecting these fibers on the in situ force of the LM under a compressive load and valgus torque to the lateral knee compartment using a porcine knee model. It was hypothesized that the MFL and LMPR would function complementarily and that the in situ force of the LM would decrease only after resecting both the MFL and LMPR.

METHODS

Specimen Preparation

Twenty fresh-frozen porcine knees were used in this study. The study protocol was reviewed and determined to not require oversight by the institutional review board of Osaka University Hospital. The mean age and weight of the specimens were 24 weeks (range, 23-25 weeks) and 105 kg (range, 100-110 kg), respectively. Knees with an apparent injury to the ligaments, menisci, or articular cartilage were excluded. Each knee was thawed at room temperature for 24 hours before testing. All the muscles except for the popliteus were removed, while the patella and patellar tendon, collateral ligaments, and capsule around the knee were carefully left intact. A part of the posterior capsule was excised so that the LM posterior horn could be visualized (Figure 1A). Every porcine knee had 1 MFL, which was analogous to but thicker than the human pMFL, and a relatively thinner LMPR, whereas there was no structure analogous to the human aMFL, as previously demonstrated in quadruped knees (Figure 1B).[16] The femur and tibia were each cut 13 cm from the joint line, and both ends were potted and fixed in cylindrical molds of acrylic resin (Ostron II; GC). The fibula was cut 4 cm distal to the proximal tibiofibular joint and was fixed in its anatomic position with acrylic resin.

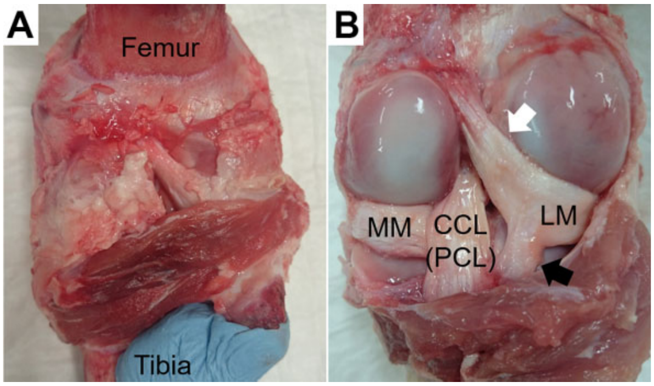

Figure 1. Posterior views of a right porcine knee joint. (A) A part of the posterior capsule was excised so that the lateral meniscus (LM) posterior horn could be visualized. (B) Every porcine knee had a thick meniscofemoral ligament (white arrow) and a thin lateral meniscus posterior root (black arrow).[18] CCL, caudal cruciate ligament; MM, medial meniscus; PCL, posterior cruciate ligament.

Apparatus

A 6 degrees of freedom robotic system was utilized in the study. The system consisted of a velocity-control 6-axis manipulator (custom designed) with a universal force-moment sensor (UFS) (SI-660-60; ATI Industrial Automation) and a control computer (Windows XP; Microsoft) linked with a high-speed motion network (Mechatrolink-II; Yaskawa Electric).[9,11,12] The manipulator was composed of the upper and lower driving mechanisms, and the UFS

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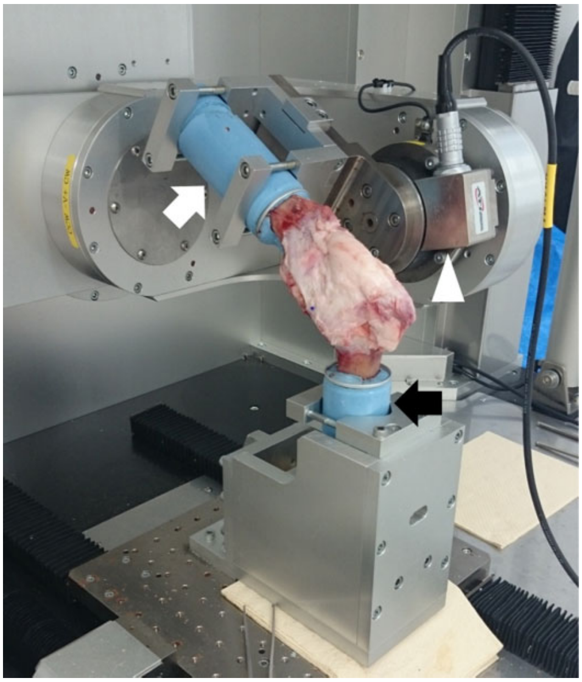

Figure 2. The 6 degrees of freedom robotic system. The tibial cylindrical molded end was connected to the upper mechanism of a 6-axis manipulator (white arrow) with the universal force-moment sensor (white arrowhead), while the femoral end was connected to the lower mechanism (black arrow).

was attached to the upper mechanism. The upper mechanism was linked to 2 translational-axis actuators (SGDS-01F12A; Yaskawa Electric) and 3 rotational-axis actuators (HA-800B-3A; Harmonic Drive Systems), while the lower mechanism was linked to 1 translational-axis actuator. All the actuators were powered by AC servomotors. The data on the position of and the force/moment acting on the knee joint were acquired through the UFS, and the control computer in a graphical language programming environment (LabView 8.6.1; National Instruments) operated the program to control both the position and the force/moment.

This system could manipulate a natural 3-dimensional (3D) motion of the knee joint by calculating and applying the 3D path to suppress the force/moment on the knee joint at zero except for the operator's intended direction. The manipulator had a position accuracy of less than ±0.015 mm in translation and ±0.01° in rotation; the clamp-to-clamp stiffness was more than 450 ± 180 N/mm in translation and 110 ± 30 N·m/deg in rotation.[2] Iteration of data acquisition, kinematic and kinetic calculation, and motion of actuators were performed at a rate of 20 Hz.

The tibial cylindrical molded end was connected firmly to the upper mechanism of the manipulator via a specially designed aluminum clamp, while the femoral end was connected firmly to the lower mechanism (Figure 2). A knee joint coordinate system developed by Grood and Suntay[14] was introduced, and a 3D digitizer (MicroScribe 3DX; Immersion) was utilized to aim the femoral insertion sites of the medial and lateral collateral ligaments (resolution: 0.13 mm; accuracy: 0.23 mm).

Testing Protocol

At the beginning of the examination, 3 cycles of flexion-extension motion between 15° and 120° of flexion with a continuous compressive load of 20 N were applied to the intact knee to exclude the influence of creep behavior in viscoelastic soft tissues. In the third cycle, the tibial position at 30°, 60°, and 90° of flexion was recorded and defined as the neutral tibial position, respectively.

First, an axial compressive load of 250 N and valgus torque of 5 N·m were applied to the intact knee at 30°, 60°, and 90° of flexion, respectively. A compressive load of 250 N was employed because the amount was equivalent to about one-fourth of the porcine weight. The valgus torque of 5 N·m corresponded to the compressive load of 250 N on the lateral edge of the LM because the distance between the joint center and lateral edge of the LM was approximately 20 mm. Each load was applied 3 times and sequentially, while the 3D path (P_i) and force/moment of the tibia relative to the femur were recorded via the UFS.

Next, the 20 porcine knees were divided into 2 groups of 10 knees. In one group, the MFL was cut through a small opening on the posterior capsule (Figure 1A), and the same procedure was followed for the MFL-deficient knee, recording the 3D path (P_m) and force/moment. In the other group, after cutting the LMPR instead of the MFL, the same procedure was followed for the LMPR-deficient knee, recording the 3D path (P_l) and force/moment. Then, the previously recorded 3D paths in the intact knee (P_i) were reproduced on the MFL-deficient or LMPR-deficient knee to calculate the in situ force of the MFL or LMPR under the applied loads. After that, the remaining attachment fiber was additionally cut in both groups, and the same procedure was followed for the MFL/LMPR-deficient knee, recording the 3D path (P_{ml}) and force/moment.

Finally, the LM was totally removed in every knee by cutting the LM anterior root and connective fibers between the LM and surrounding capsule. Then, the previously recorded 3D paths in the intact, MFL-deficient or LMPR-deficient, and MFL/LMPR-deficient knees (P_i, P_m or P_l, and P_{ml}) were reproduced on the LM-removed knee to calculate the in situ forces of the LM under the applied loads (Figure 3).

Data Acquisition

The valgus angles under an axial compressive load of 250 N and 5 N·m of valgus torque were assessed as the change from the predefined neutral position by analyzing the positional data. Then, these were compared among the intact, MFL-deficient, LMPR-deficient, and MFL/LMPR-deficient knees. The in situ forces of the MFL and LMPR under 250 N of axial compressive loading and 5 N·m of valgus torque, respectively, were calculated from the force/moment data and compared with each other. The in situ force of the ligamentous tissue of interest was calculated as the difference

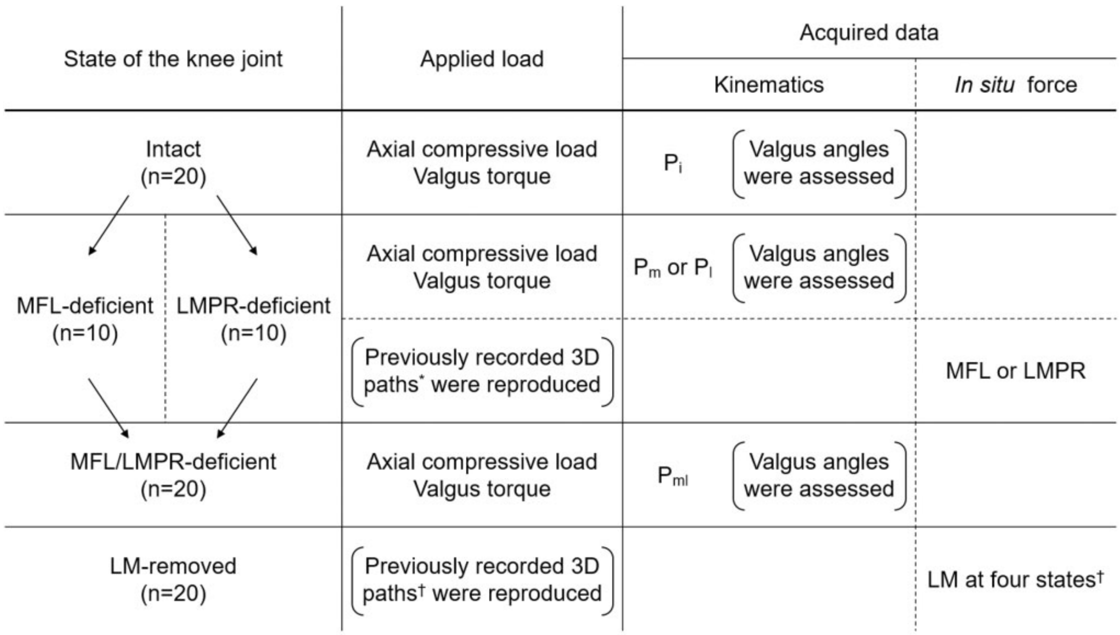

Figure 3. Testing protocol and data acquisition. *The previously recorded 3-dimensional (3D) paths in the intact knee (P_i) were reproduced on the meniscofemoral ligament (MFL)–deficient or lateral meniscus posterior root (LMPR)–deficient knee to calculate the in situ force of the MFL or LMPR under the applied loads. †The previously recorded 3D paths in the intact, MFL-deficient or LMPR-deficient, and MFL/LMPR-deficient knees (P_i, P_m or P_l, and P_{ml}) were reproduced on the lateral meniscus (LM)–removed knee to calculate the in situ forces of the LM in 4 conditions (intact, without the MFL, without the LMPR, and without the MFL/LMPR) under the applied loads.

of the acquired force/moment vector in the intact knee compared with the tissue-deficient knee based on the principle of superposition.[10,12] The in situ forces of the LM under 250 N of axial compressive loading and 5 N·m of valgus torque were also calculated in 4 conditions (intact, without the MFL, without the LMPR, and without the MFL/LMPR) in the same way and were compared among the 4 conditions. All the assessments were performed using positional and force/moment data at the third cycle under each applied load.

Statistical Analysis

All statistical analyses were performed with JMP software (JMP Pro version 13.1.0; SAS Institute). Power analysis (power: 0.8; α: 0.05; detectable difference: 3.0 for the valgus angle, 10 for the in situ forces of the MFL and LMPR, 25 for the in situ force of the LM; SD: 1.5 for the valgus angle, 4 for the in situ forces of the MFL and LMPR, 12 for the in situ force of the LM) indicated a sample size requirement of 10 participants for valid comparisons. The values of detectable difference and standard deviations utilized for sample size calculation were based on the results of our previous study.[32] The null hypothesis of normal distribution of the acquired data was tested and denied with the Shapiro-Wilk *W* test. Therefore, when the valgus angle and in situ force of the LM were assessed, the Kruskal-Wallis test for 1-way factorial analysis of variance by ranks and the Steel-Dwass test for post hoc multiple comparison were used to compare nonparametric variables among the 4 different groups. When the in situ forces of the MFL and LMPR were assessed, the Mann-Whitney rank-sum test was used to compare nonparametric variables between 2 groups. $P < .05$ was considered statistically significant.

RESULTS

Valgus Angle

The valgus angles under both 250 N of axial compressive loading and 5 N·m of valgus torque represented no significant differences in the intact knee, MFL-deficient knee, and LMPR-deficient knee. However, the valgus angles in the MFL/LMPR-deficient knee were significantly greater than those in the intact knee, MFL-deficient knee, and LMPR-deficient knee at all the flexion angles ($P < .001$ for every comparison) (Table 1).

In Situ Forces of the MFL and LMPR

The in situ forces of the MFL under 250 N of axial compressive loading and 5 N·m of valgus torque were 36 to 48 N and 53 to 67 N, respectively, and they decreased as the knee flexed. The in situ forces of the LMPR under 250 N of axial compressive loading and 5 N·m of valgus torque were 12 to 29 N and 20 to 40 N, respectively, and they reciprocally increased as the knee flexed (Figure 4).

TABLE 1
Valgus Angles Under an Axial Compressive Load of 250 N and 5 N·m of Valgus Torque[a]

	Valgus Angle, deg			
	Intact (n = 20)	MFL Deficient (n = 10)	LMPR Deficient (n = 10)	MFL/LMPR Deficient (n = 20)
250 N axial compressive load				
30° of flexion	−0.5 ± 0.4	−0.2 ± 0.6	−0.4 ± 0.6	1.0 ± 0.7[b]
60° of flexion	−1.0 ± 0.5	−0.8 ± 0.7	−0.9 ± 0.7	2.1 ± 1.1[b]
90° of flexion	−0.4 ± 0.4	−0.3 ± 0.8	−0.2 ± 0.6	5.7 ± 1.0[b]
5 N·m valgus torque				
30° of flexion	1.0 ± 0.8	1.5 ± 0.7	1.0 ± 0.6	3.2 ± 1.1[b]
60° of flexion	3.7 ± 0.6	4.1 ± 0.9	3.7 ± 1.7	7.6 ± 1.8[b]
90° of flexion	7.6 ± 0.9	8.0 ± 1.5	7.7 ± 1.5	13.3 ± 2.2[b]

[a]Data are shown as mean ± SD. LMPR, lateral meniscus posterior root; MFL, meniscofemoral ligament.
[b]Statistically significant difference compared with intact, MFL deficient, and LMPR deficient ($P < .05$).

In Situ Force of the LM

The in situ forces of the intact LM under 250 N of axial compressive loading and 5 N·m of valgus torque were 80 to 97 N and 64 to 81 N, respectively. The in situ forces of the LM without the MFL or LMPR represented no significant differences compared with those of the intact LM. However, the in situ forces of the LM without the MFL/LMPR were significantly smaller compared with those in the other 3 conditions at all the flexion angles ($P < .001$ for every comparison). The in situ forces of the intact LM decreased by 53% to 57% under the axial compressive load and 60% to 65% under valgus torque after resecting both the MFL and LMPR (Figure 5).

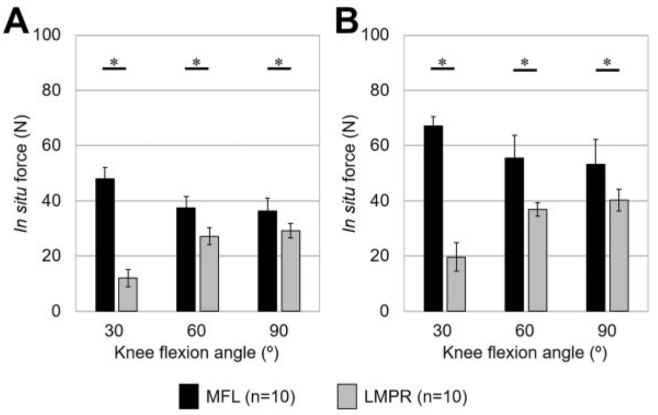

Figure 4. The in situ forces of the meniscofemoral ligament (MFL) and lateral meniscus posterior root (LMPR) under (A) an axial compressive load of 250 N and (B) 5 N·m of valgus torque. *Statistically significant difference between the in situ force of the MFL and that of the LMPR ($P < .05$).

DISCUSSION

The principal findings of this study in a porcine knee model were that (1) the MFL and LMPR functioned reciprocally as the knee flexed and (2) the in situ force of the LM decreased only after resecting both the MFL and LMPR under a compressive load and valgus torque to the lateral knee compartment.

It has previously been demonstrated that resecting both the MFL and LMPR significantly increased tibiofemoral contact pressure and decreased contact area in the lateral knee compartment under an axial compressive load, although resecting the LMPR alone had no significant effect on tibiofemoral contact mechanics.[4,13] In the present study, in response to an axial compressive load of 250 N and 5 N·m of valgus torque, the valgus angles significantly increased and the in situ forces of the LM significantly decreased after resecting both the MFL and LMPR, although resecting the MFL or LMPR alone represented no significant effect. Furthermore, the in situ forces of the MFL and LMPR changed reciprocally as the knee flexed. These results indicate that the MFL and LMPR function complementarily against a compressive load and valgus torque to the lateral knee compartment in porcine knee joints. Therefore, the MFL and LMPR are considered to assist the primary role of the LM to distribute and transmit a compressive load in the lateral knee compartment as the posterior attachments of the LM. Gupte et al[18] pointed out that the term "ligament" might be a misnomer for the MFL because the MFL connects the femur (bone) to the LM (meniscus), not bone to bone. It seems logical to postulate that the LM has 2 posterior attachment fibers and that the MFL is the "posterior femoral attachment of the LM." The presence of the femoral attachment of the LM posterior horn may be caused by low joint congruity in the lateral knee compartment,[26,29] and the MFL in quadruped knees may be thicker because their tibial slope is steeper compared with human knees.[16]

Recently, Frank et al[8] reported that resecting the LMPR in an anterior cruciate ligament (ACL)–deficient knee significantly increased anterior tibial translation at lower flexion angles and internal tibial rotation at higher flexion angles during a simulated pivot-shift test. They also demonstrated that additional resection of the MFL further destabilized the knee joint compared with the ACL/LMPR-deficient state.[8] These results indicate that not only the LMPR but also the MFL function as posterior

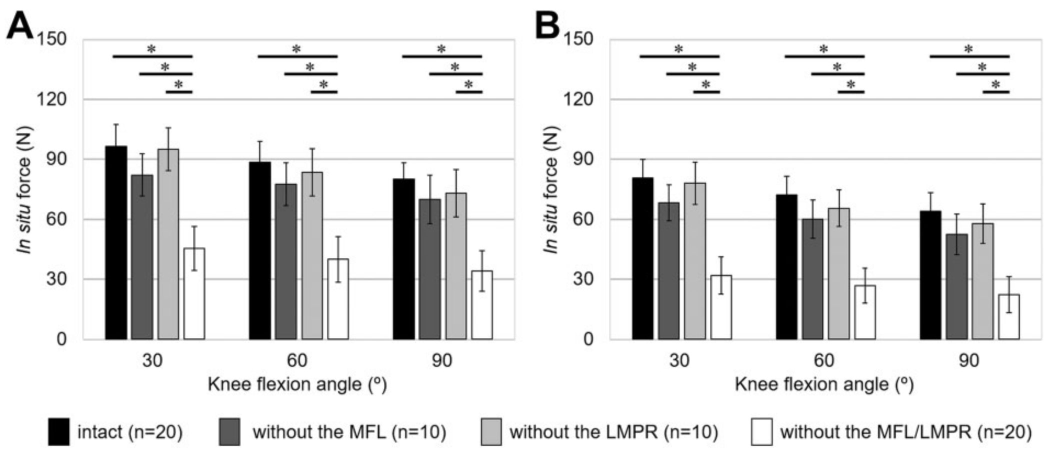

Figure 5. The in situ forces of the lateral meniscus (LM) in 4 conditions (intact, without the meniscofemoral ligament [MFL], without the lateral meniscus posterior root [LMPR], and without the MFL/LMPR) under (A) 250 N of axial compressive load and (B) 5 N·m of valgus torque. *Statistically significant difference between the in situ forces of the LM without the MFL/LMPR and those in the other 3 conditions (intact, without the MFL, and without the LMPR) ($P < .001$ for every comparison).

attachments of the LM from the viewpoint of biomechanical function as secondary restraints to anterior tibial translation in the ACL-deficient knee. Thus, tears of the LM posterior attachments need to be further classified based on the condition of the MFL, as Forkel et al[5] described. Clinically, if the LMPR is completely detached, transtibial pull-out fixation of the LMPR should be performed, as this treatment could sufficiently restore the biomechanical function of the LM.[6,13] However, identification of an LMPR tear is frequently missed on preoperative magnetic resonance imaging,[23] and it may be because of the minimal extrusion of the LM with the intact MFL. Therefore, the surgeon should carefully evaluate the condition of both the LMPR and the MFL at the time of arthroscopic surgery and preserve the MFL especially in case of an LMPR tear because the MFL may provide some stability to the LM posterior horn and protect the repaired LMPR.

This study has some limitations. First, we utilized a porcine knee model. The in situ forces of the MFL were significantly greater than those of the LMPR in the present study (see Figure 4). However, quadruped knees have 1 thicker MFL and a relatively thinner LMPR compared with human knees,[16] and the ultimate failure load of the LMPR is greater than that of the MFL in the human knee joint.[3,20] Therefore, the superiority of the strength of the MFL over the LMPR in the porcine knee joint may not be applicable to the human knee joint. Further investigations regarding the contribution of the MFL and LMPR to the load transmission of the LM using the human knee joint are needed. Second, the in situ force of the LM was possibly overestimated in the present study because there might be interactive forces between the LM and surrounding capsule. The calculated in situ force of the LM may not accurately reflect the actual force transmitted though the LM because the assumptions required for the principle of superposition were not completely followed.[15] Third, partial excision of the posterior capsule might influence knee joint kinematics, although most of the capsule was carefully left intact. Finally, the resulting in situ forces in this study might be different from in vivo forces. Neural structures suggestive of mechanoreceptors have been detected in the MFL and are supposed to have a proprioceptive role by providing a neurosensory feedback loop.[19] Thus, straining the MFL may cause active muscle contraction and alter knee joint kinematics.

CONCLUSION

The MFL and LMPR functioned reciprocally as the knee flexed, and the in situ force of the LM decreased only after resecting both the MFL and LMPR under a compressive load and valgus torque to the lateral knee compartment in porcine knee joints. Therefore, we considered the MFL and LMPR to be the posterior femoral and tibial attachments of the LM and to function complementarily to stabilize the LM against a compressive load and valgus torque to the lateral knee compartment.

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