Original Article

Posterior Root Tears of the Lateral Meniscus Only Affect Tibiofemoral Contact Forces when the Meniscofemoral Ligament Is Involved: A Cadaveric Study

Sean B. Sequeira, M.D., Saankritya Ayan, M.D., Indranil Kushare, M.D., Heath P. Gould, M.D., Allison Fillar, MD, and James Dreese, M.D.

Purpose: The objective of this study was to examine the impact of progressive radial tears in the lateral meniscal root on the lateral compartment contact forces and joint surface area through a range of motion of knee and evaluate the role of the meniscofemoral ligament (MFL) in preventing adverse tibiofemoral joint forces. **Methods:** Ten fresh frozen cadaveric knees were tested using 6 experimental conditions (0% lateral meniscal posterior root tear, 25% tear, 50% tear, 75% tear, 100% tear, 100% tear and resection of MFL) at five flexion angles (0°, 30°, 45°, 60°, and 90°) under 100-1,000-N axial load. Contact joint pressure and lateral compartment surface area were measured using Tekscan sensors. Statistical analysis, including descriptive, ANOVA, and post hoc Tukey analysis, was performed. **Results:** Progressive radial tears of the lateral meniscal root were not associated with an increase in tibiofemoral contact pressure or decrease in lateral compartment surface area. Complete lateral root tear and resection of MFL were associated with increased joint contact pressure ($P < .001$) at knee flexion angles of 30, 45, 60, and 90° and decreased lateral compartment surface ($P < .001$) at all knee flexion angles area compared to complete lateral meniscectomy alone. **Conclusion:** Isolated complete tears of lateral meniscus root and progressive radial tears of the lateral meniscus posterior root were not associated with any change to tibiofemoral contact forces. However, additional resection of the MFL increased contact pressure and decreased lateral compartment surface area.

Introduction

Posterior root tears of the lateral meniscus are a common injury, often occurring concomitantly with anterior cruciate ligament (ACL) tears. Biomechanically, the medial and lateral menisci serve as a cushion in the tibiofemoral joint to minimize tibiofemoral contact forces, which can ultimately lead to cartilage degeneration and early osteoarthritis.[1] Although the role of the medial meniscus in maintaining tibiofemoral joint pressure and the surface area has been extensively studied, the role of the lateral meniscus and meniscofemoral ligament has not been fully elucidated.[2,3]

Tibiofemoral contact pressure and joint surface area have been recognized as important kinematic parameters, as increased contact pressure and decreased joint surface area have been linked to cartilage degeneration and progression of osteoarthritis.[4] Prior studies pertaining to the lateral meniscus suggest that inferior leaf resection at 0 and 60° of knee flexion were associated with decreased contact area and increased peak contact pressure.[5] The lateral meniscal roots are critical anchoring points for equal distribution of axial loads throughout the tibial plateau.[1] Disruption of the lateral meniscus posterior root may exacerbate adverse tibiofemoral contact forces which can lead to cartilage degeneration.[6]

There is conflict in the literature regarding the role of the meniscofemoral ligament (MFL) in the distribution

From the Department of Orthopaedic Surgery, MedStar Union Memorial Hospital, Baltimore, Maryland, U.S.A.

The authors report the following potential conflicts of interest or sources of funding: H.P.G. reports editorial board membership in Arthroscopy. *J.D. reports board or committee membership in AOSSM and research support from Zimmer. Full ICMJE author disclosure forms are available for this article online, as supplementary material.*

Received August 5, 2022; accepted February 2, 2023.

Address correspondence to Sean B. Sequeira, M.D., Department of Orthopaedic Surgery, MedStar Union Memorial Hospital, 3333 North Calvert St., Suite 400, Baltimore, MD 21218, U.S.A. E-mail: sean.sequeira@medstar.net

2666-061X/22976

https://doi.org/10.1016/j.asmr.2023.02.003

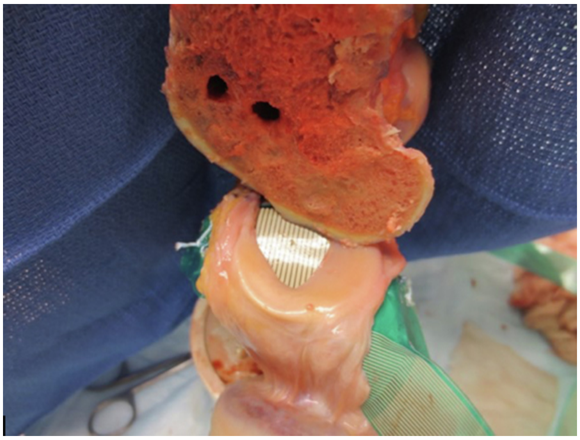

Fig 1. TekScan sensor placed following lateral condylar osteotomy to gauge tibiofemoral contact pressures in anticipation for various testing conditions.

of knee joint contact forces, particularly in the setting of progressive lateral meniscal root tears.[7,8] The MFL has been previously shown to stabilize the root of the lateral meniscus, and recent studies have suggested that extrusion of the lateral meniscus can occur when the MFL is compromised.[9] A study that evaluated 5 cadaveric knee joints found that resection of the MFL led to worsening tibiofemoral contact forces, underscoring its importance in preventing the progression of knee osteoarthritis.[10] Another study evaluated the MFL and posterior root of the lateral meniscus in a porcine model and concluded that the 2 structures are complementary for tibiofemoral loads.[11] The role of the MFL when the root of the lateral meniscus is progressively compromised is poorly understood.

The purposes of this study are to examine the impact of progressive radial tears in the lateral meniscal root on the lateral compartment contact forces and joint surface area through a range of motion of knee. A secondary aim of this investigation was to evaluate the role of the meniscofemoral ligament (MFL) in preventing adverse tibiofemoral joint forces. It was hypothesized that progressive radial tears will not increase tibiofemoral contact forces and decrease surface area, although adverse tibiofemoral contacts would occur only in the presence of a transected MFL.

Materials and Methods

Ten fresh frozen cadaveric knees with intact menisci, cruciate anatomy, and MFLs were used. Specimens with meniscal damage or cartilage degeneration beyond Outerbridge I were excluded.

The specimen preparation began with soft tissue dissection of the cadaveric knee. All muscles and tendons were removed and patellectomy was performed, taking care to preserve the collateral ligaments, cruciate ligaments, and menisci. Resin was used to pot the sample, which subsequently hardened overnight. An oscillating saw was used to create a lateral femoral condylar osteotomy, which allowed access to the lateral meniscus posterior root (Fig 1). Osteotomy has been previously reported to have no effect on the tibiofemoral load-bearing characteristics of the knee.[12] A standard knee pressure sensor device (Tekscan 4011) was placed underneath between the medial and lateral meniscus and the tibial plateau and was secured with two double-loaded Arthrex suture anchors to the anterior and posterior tibia. Calibration of the sensor device was performed, according to manufacturer's recommendation.

The knee was mounted onto a Mini Bionix load frame using a 6° of freedom fixture (Fig 2). When the axial load was applied during testing, the load frame and fixture facilitated multiplanar rotation, replicating native knee arc of motion. Furthermore, this custom construct-ensured forces were directed axially and eliminated stress riser or shear in the construct, minimizing the potential effect of any extraneous forces on the system. The apparatus also neutralized the effects of coronal malalignment of the knee (Fig 3) and facilitated testing states in various degrees of knee flexion. The first reading taken was with the intact meniscus in 0° of flexion. Further readings for intact meniscus were taken in flexion angle of 30°, 45°, 60° and 90° of flexion. Progressive tears in the lateral meniscus were

Fig 2. Demonstrated of mounted specimen to prevent coronal malalignment and evaluate testing conditions in various degrees of knee flexion.

Fig 3. Final mounted specimen with TekScan sensors in place with combined apparatus to appropriately control various forces to evaluate tibiofemoral contact forces.

created until the lateral meniscus was completely torn. Finally, the MFL was resected with a concomitant complete tear of the lateral meniscus.

Surgical Technique

The lateral meniscus posterior root attachment site was identified. The menisco-capsular junction was identified and served as the posterior boundary for the radial tear sectioning. A #15 scalpel was used to generate the radial tears 6 mm from the posterior root insertion. Successive sectioning was based upon the overall width of the native medial meniscus and was confirmed visually by two observers. Next meniscus sectioning was performed to 50%, and readings were taken again for various flexion angles as mentioned before. The sectioning was further carried to 75%, 100%, and 100% with resection of meniscofemoral ligament. The MFL was sectioned at its attachment with the meniscus. The final resection group was performed after complete meniscectomy, indicating that the full lateral meniscus had been excised. The medial meniscus was left undisturbed throughout lateral meniscus sectioning, resection of MFL, and subsequent testing.

Biomechanical Testing

The knees were loaded from 100 to 1000 N of compressive force along the tibial axis to simulate the force on the knee during normal ambulation at 5 different flexion angles of 0°, 30°, 45°, 60°, and 90°. Data were collected at a rate of 10 readings per second. A TekScan contact pressure map was generated for the lateral compartments of each knee following constant force application (Fig 4). Each knee was successively taken through axial load testing, and data were collected at each degree of knee flexion. Joint pressure and surface area were measured in the lateral compartment at flexion angles from 0 to 90°. A priori

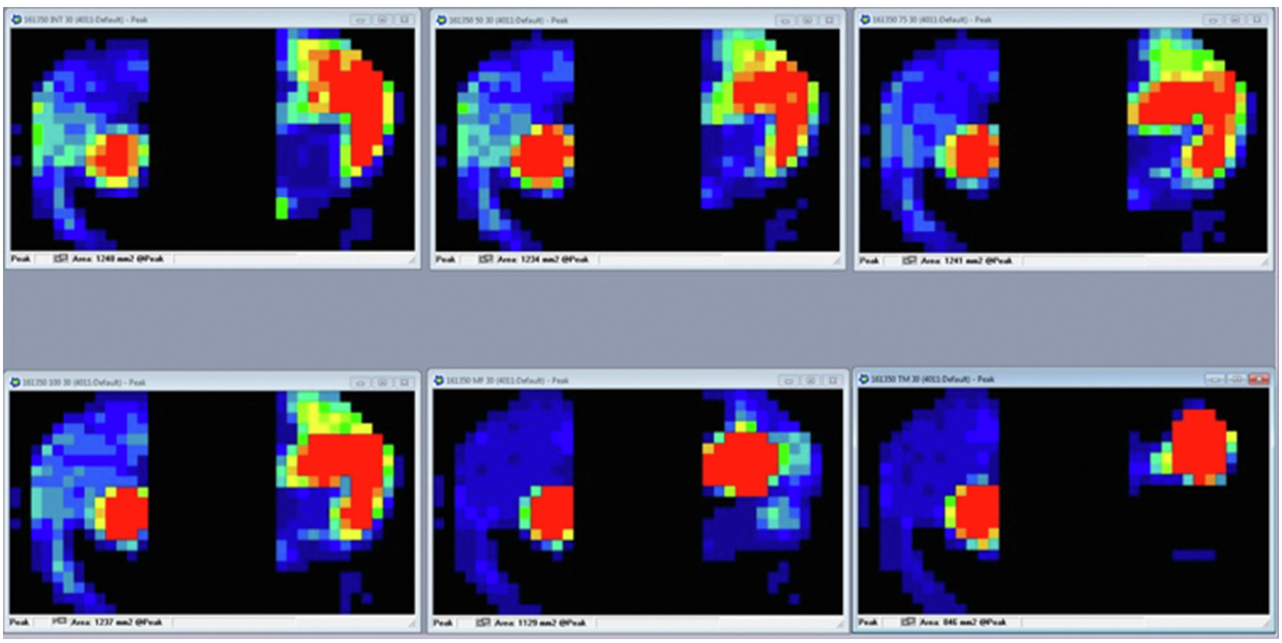

Fig 4. Example of TekScan contact map to help analyze the tibiofemoral contact forces in various testing conditions.

Table 1. The Association Between Progressive Radial Tears of the Lateral Meniscal Root and Resection of the MFL and Contact Pressure Across Various Knee Flexion Angles

	Pressure with progressive increasing tear					
Flexion Angle	Intact	50%	75%	100%	100% + MFL	*P*-value
0	1156.7±213.3	1105±160.5	1098.7±168.8	1059.9±204.5	1127.2±162.7	NS
30	1070.4±292.0	1069.5±294.8	1099.4±273.6	1098.8±250.7	1197±243.6	**0.04**
45	1127.8±251.5	1089.4±255.4	1073.1±231.2	1086.4±244	1377.3±445.5	**0.02**
60	1175.2±294.6	1130.4±333.7	1137.6±273.1	1139.8±238.0	1134.2±398.6	NS
90	1046.0±182.9	1028.8±228.6	1052.7±245.5	1081.7±389.3	1291.5±389.2	NS

NOTE. Boldface indicates statistical significance ($P < .05$). Various knee flexion angles is expressed as newton per millimeter squared. MFL, meniscofemoral ligament.

power analysis determined that 10 specimens would provide greater than 99% power to detect a statistically significant difference in peak contact pressure and joint surface area. Using a significance level of .01 and Bonferroni accounting of 5 major cross-comparisons to obtain an effect size of $d = 1.33$ performed similar to Geeslin et al., 10 specimens were required to achieve an appropriate power.[8]

Statistical Analysis

One-way repeated measures ANOVA with post hoc Tukey analysis was used to evaluate statistical significance. A P value $\leq .05$ was considered significant. Statistical analysis was performed using R statistical software package, RStudio (version 1.4.1717-3; Boston, MA).

Results

Eight male and two female cadavers were included. The average age was 77.2 (range: 58-94) years. At a flexion angle of 30° and 45°, progressive radial tear of the root of the lateral meniscus was associated with a gradual increase in tibiofemoral joint pressure (Table 1 and 2), although this relationship was not linear. Furthermore, resection of the MFL in tandem with complete root tear was associated with higher tibiofemoral joint pressure when compared to a complete root tear in isolation for 0°, 30°, 45°, 60°, and 90° of knee flexion (Tables 1 and 2). There were no significant differences in tibiofemoral joint pressure with progressive radial tearing of the root of the lateral meniscus at flexion angles 0°, 60°, and 90°.

At all flexion angles, progressive radial tear of the root of the lateral meniscus was associated with a decrease in tibiofemoral lateral contact surface area ($P = .001$), found in Tables 3 and 4. Moreover, resection of the MFL in conjunction with a complete root tear was associated with a decrease in tibiofemoral lateral contact surface area compared to a complete root tear in silo at all flexion angles.

Discussion

In the present study, progressive radial tears of the root of the lateral meniscus were not associated with increased tibiofemoral contact pressure and decreased tibiofemoral lateral joint surface area. Moreover, resection of the MFL in tandem with complete meniscectomy was associated with increased tibiofemoral contact pressure and decreased tibiofemoral lateral joint surface area than when compared to complete meniscectomy alone. The authors are not aware of any previous studies that have evaluated the relationship between progressive tears of the lateral meniscus posterior root on tibiofemoral contact pressure and surface area. These findings provide insight into the role of the lateral meniscus posterior root and the MFL in preventing early chondral wear.

These findings suggest that progressive tears of the lateral meniscus did not produce increased tibiofemoral contact pressure or decrease in lateral joint surface area, which is consistent with the literature to date. A finite

Table 2. Post Hoc Tukey Analysis of the Association Between Progressive Radial Tears of the Lateral Meniscal Root and Resection of the MFL and Contact Pressure Across Various Knee Flexion Angles

	Intact vs 50%	Intact vs 75%	Intact vs 100%	Intact vs 100% + MFL	50% vs 75%	50% vs 100%	50% vs 100% + MFL	75% vs 100%	75% vs 100% + MFL	100% vs 100% + MFL
0	0.327	0.117	**0.046**	**0.039**	0.871	0.562	0.382	0.276	**0.0315**	0.401
30	0.985	0.487	0.359	**0.008**	0.241	0.293	**0.007**	0.962	**0.018**	**0.021**
45	0.280	0.191	0.274	**0.005**	0.568	0.893	**<0.001**	0.553	**<0.001**	**<0.001**
60	0.195	0.096	0.102	**0.016**	0.835	0.728	**0.009**	0.966	**0.008**	**0.009**
90	0.782	0.889	0.284	**0.024**	0.699	0.193	**0.011**	0.265	**0.007**	**0.009**

MFL, meniscofemoral ligament.

Table 3. The Association Between Progressive Radial Tears of the Lateral Meniscal Root and Resection of the MFL and Lateral Joint Surface Area Across Various Knee Flexion Angles

	Lateral Contact Surface Area With Progressive Increasing Tear					
Flexion Angle	Intact	50%	75%	100%	100% + MFL	*P*
0	580.5 ± 59	571.6 ± 61.54	574.1 ± 62.6	564.6 ± 60.1	494.7 ± 94.9	.001
30	558.5 ± 39.6	559.3 ± 48.1	548.3 ± 50.7	525.4 ± 63.2	456.4 ± 85.86	.001
45	537.1 ± 68.9	537.4 ± 42.0	548.5 ± 41.2	515.5 ± 61.3	372.9 ± 101.5	.001
60	494.5 ± 80.2	526.5 ± 70.8	538.8 ± 52.8	499.2 ± 51.26	363.7 ± 85.2	.001
90	485.7 ± 69.9	482.7 ± 85.6	446.7 ± 100.2	452.3 ± 41.6	305.0 ± 64.0	.001

NOTE. Tear is measured in square millimeters.
MFL, meniscofemoral ligament.

element analysis by Bao et al. demonstrated that a lateral meniscectomy alone does not adversely worsen tibiofemoral contact forces in isolation.[13] Similarly, a cadaveric study of 10 porcine knees found that despite the presence of a lateral meniscal root tear, there was no adverse effect on tibiofemoral contact pressure.[7] They further postulated that the biomechanical consequences of the knee and adverse tibiofemoral contact forces are dependent upon the integrity of the MFL. Finally, cadaveric studies comparing posterior root avulsions of the lateral meniscus to an intact state found no difference in lateral compartment surface area or contact pressure, further corroborating the present study's findings.[8]

It is interesting to note that the tibiofemoral contact pressure was different across the various treatment conditions at knee flexion angles 30° and 45°, but were notably the same at all other knee flexion angles. Interestingly, Geeslin et al. also found that at knee flexion angle 45°, repair of the lateral meniscus posterior root was unable to restore tibiofemoral contact pressures to the intact level of pressure. Although there is currently no biomechanical explanation for this phenomenon, it is theorized that at this point of knee flexion, the posterior root is especially important in stabilization of tibial translation and tibiofemoral contact pressure at midflexion.[14] Although future studies will need to more comprehensively characterize this finding, the present study demonstrates the stabilizing effect of the lateral meniscus in early flexion angles. This finding requires further exploration in order to translate it into clinically meaningful and impactful patient care.

Additionally, this study demonstrated that a complete resection of the lateral meniscus posterior root, in addition to resection of the MFL, was associated with an increase in tibiofemoral contact pressure and decrease in lateral joint surface area. These findings imply that the MFL is a critical structure in the prevention of adverse tibiofemoral biomechanics and progression of cartilage degeneration. The MFL has been implicated in the reduction of intra-articular pressure of the lateral compartment of the knee and may help to disperse hoop stresses to the femur.[10] Other studies have also found that a tear of the lateral meniscus posterior root only adversely impacts tibiofemoral contact forces when in the presence of an MFL tear.[7,8] This study's biomechanical findings provide support for previous radiologic and biomechanical studies, which have suggested that the MFL exerts a stabilizing force on the root of the lateral meniscus.[15]

This study's biomechanical findings also correlate with the results of clinical studies that have evaluated lateral meniscal root tears. Shelbourne et al. concluded that there was no difference in long-term outcomes of patients with lateral meniscus posterior root tears that were left unaddressed during anterior cruciate ligament reconstruction (ACLR) compared to patients who underwent isolated ACLR without a concomitant lateral meniscal root tear.[16] Similar studies by the MOON group and Lee et al. also showed that lateral meniscus posterior root tears left in situ at the time of ACL

Table 4. Post Hoc Tukey Analysis Between the Association Between Progressive Radial Tears of the Lateral Meniscal Root and Resection of the MFL and Lateral Joint Surface Area Across Various Knee Flexion Angles

	Intact vs 50%	Intact vs 75%	Intact vs 100%	Intact vs 100% + MFL	50% vs 75%	50% vs 100%	50% vs 100% + MFL	75% vs 100%	75% vs 100% + MFL	100% vs 100% + MFL
0	0.673	0.431	0.272	<**0.001**	0.725	0.311	**<0.001**	0.296	**<0.001**	**<0.001**
30	0.894	0.312	**0.047**	<**0.001**	0.412	0.062	<**0.001**	0.104	**<0.001**	**<0.001**
45	0.958	0.277	0.121	<**0.001**	0.524	0.294	<**0.001**	0.116	**<0.001**	**<0.001**
60	0.152	**0.039**	0.621	<**0.001**	0.330	0.143	<**0.001**	**0.036**	**<0.001**	**<0.001**
90	0.787	**0.022**	**0.039**	<**0.001**	**0.031**	0.068	<**0.001**	0.558	**<0.001**	**<0.001**

MFL, meniscofemoral ligament.

reconstruction did not require reoperation at a minimum 6-year follow-up and had comparable clinical outcomes to isolated ACL injuries.[17,18] These clinical studies provide credence to this study's findings, which failed to show significant increase in peak joint contact pressure or reduction in joint surface area with isolated complete tears of the lateral meniscus. Interestingly, there are no studies that specifically evaluate clinical or functional outcomes of patients with MFL resection. Further clinical studies are needed to determine the impact of a lateral meniscal root tear in combination with MFL injury on functional outcome scores.

Clinically, the findings of this study have important ramifications for surgical decision-making. By demonstrating that an isolated lateral meniscal root tear does not adversely change the contact pressure or surface area of the knee, the present study's findings suggest that it may be reasonable to pursue nonoperative management in some patients with these isolated injuries. Furthermore, it is important to note that the posterior root of the lateral meniscus has a complete blood supply, thereby enhancing the healing potential of the root should a tear occur.[19] However, if a patient with a lateral meniscus posterior root tear demonstrates radiologic findings suggestive of concomitant MFL injury, the results of the present study and others suggest that operative treatment may be indicated to ameliorate the risk of cartilage degeneration.[7,8,10] However, these results require additional corroboration to translate to a clinical setting, since these results were performed at time 0. Furthermore, since the present study did not evaluate the posterior lateral root tear as a condition in isolation, we cannot comment as to whether that condition is associated with a secondary rupture of the MFL.

Limitations

This study does have limitations. Although the present study conformed to standard practice for a cadaveric laboratory study, it may not accurately reflect the biomechanical forces in a patient's knee in the clinical setting. Moreover, the present study only evaluated static forces and likely does not accurately mimic the stresses a native knee experiences during rehabilitation and/or physical therapy. Furthermore, lateral meniscus root tears often occur concomitantly with an ACL tear—since the present study did not include a cadaveric specimen(s) with an ACL tear, the present findings may be limited when applying these results in a clinical setting. Meticulous evaluation of change in location of peak contact pressure was also not examined in this study, which may have important implications for cartilage thickness and, therefore, limit the generalizability of this study's findings. Finally, this study only included axial loads to evaluate the impact of lateral meniscus and MFL on tibiofemoral contact forces and area—additional work should include rotational and combined forces to comprehensively understand how forces across the knee impact knee biomechanics.

Conclusion

Isolated complete tears of lateral meniscus root and progressive radial tears of the lateral meniscus posterior root were not associated with any change to tibiofemoral contact forces. However, additional resection of the MFL increased contact pressure and decreased lateral compartment surface area.

References

1. Makris EA, Hadidi P, Athanasiou KA. The knee meniscus: Structure-function, pathophysiology, current repair techniques, and prospects for regeneration. *Biomaterials* 2011;32:7411-7431.
2. Kim JG, Lee YS, Bae TS, et al. Tibiofemoral contact mechanics following posterior root of medial meniscus tear, repair, meniscectomy, and allograft transplantation. *Knee Surg Sports Traumatol Arthrosc* 2013;21:2121-2125.
3. Marzo JM, Gurske-DePerio J. Effects of medial meniscus posterior horn avulsion and repair on tibiofemoral contact area and peak contact pressure with clinical implications. *Am J Sports Med* 2009;37:124-129.
4. Fukubayashi T, Kurosawa H. The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthrotic knee joints. *Acta Orthop Scand* 1980;51:871-879.
5. Koh YG, Kim SJ, Chun YM, Kim YC, Park YS. Arthroscopic treatment of patellofemoral soft tissue impingement after posterior stabilized total knee arthroplasty. *Knee* 2008;15:36-39.
6. Ozeki N, Koga H, Sekiya I. Degenerative meniscus in knee osteoarthritis: From pathology to treatment. *Life (Basel)* 2022;12:603.
7. Forkel P, Herbort M, Schulze M, et al. Biomechanical consequences of a posterior root tear of the lateral meniscus: Stabilizing effect of the meniscofemoral ligament. *Arch Orthop Trauma Surg* 2013;133:621-626.
8. Geeslin AG, Civitarese D, Turnbull TL, Dornan GJ, Fuso FA, LaPrade RF. Influence of lateral meniscal posterior root avulsions and the meniscofemoral ligaments on tibiofemoral contact mechanics. *Knee Surg Sports Traumatol Arthrosc* 2016;24:1469-1477.
9. Brody JM, Lin HM, Hulstyn MJ, Tung GA. Lateral meniscus root tear and meniscus extrusion with anterior cruciate ligament tear. *Radiology* 2006;239:805-810.
10. Amadi HO, Gupte CM, Lie DTT, McDermott ID, Amis AA, Bull AMJ. A biomechanical study of the meniscofemoral ligaments and their contribution to contact pressure reduction in the knee. *Knee Surg Sports Traumatol Arthrosc* 2008;16:1004-1008.
11. Ohori T, Mae T, Shino K, et al. 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. *Orthop J Sports Med* 2019;7:2325967118821605.

12. Martens TA, Hull ML, Howell SM. An in vitro osteotomy method to expose the medial compartment of the human knee. *J Biomech Eng* 1997;119:379-385.
13. Bao HRC, Zhu D, Gong H, Gu GS. The effect of complete radial lateral meniscus posterior root tear on the knee contact mechanics: a finite element analysis. *J Orthop Sci* 2013;18:256-263.
14. Frank JM, Moatshe G, Brady AW, et al. Lateral meniscus posterior root and meniscofemoral ligaments as stabilizing structures in the ACL-deficient knee: A biomechanical study. *Orthop J Sports Med* 2017;5:2325967117695756.
15. Gupte CM, Smith A, McDermott ID, Bull AMJ, Thomas RD, Amis AA. Meniscofemoral ligaments revisited. Anatomical study, age correlation and clinical implications. *J Bone Joint Surg Br* 2002;84:846-851.
16. Shelbourne KD, Roberson TA, Gray T. Long-term evaluation of posterior lateral meniscus root tears left in situ at the time of anterior cruciate ligament reconstruction. *Am J Sports Med* 2011;39:1439-1443.
17. Duchman KR, Westermann RW, Spindler KP, et al. The fate of meniscus tears left in situ at the time of anterior cruciate ligament reconstruction: A 6-year follow-up study from the MOON chort. *Am J Sports Med* 2015;43:2688-2695.
18. Lee DW, Jang HW, Lee SR, Park JH, Ha JK, Kim JG. Clinical, radiological, and morphological evaluations of posterior horn tears of the lateral meniscus left in situ during anterior cruciate ligament reconstruction. *Am J Sports Med* 2014;42:327-335.
19. Fox AJS, Bedi A, Rodeo SA. The basic science of human knee menisci. *Sports Health* 2012;4:340-351.