Altered Tibiofemoral Contact Mechanics Due to Lateral Meniscus Posterior Horn Root Avulsions and Radial Tears Can Be Restored with in Situ Pull-Out Suture Repairs

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Background: An avulsion of the posterior root attachment of the lateral meniscus or a radial tear close to the root attachment can lead to degenerative knee arthritis. Although the biomechanical effects of comparable injuries involving the medial meniscus have been studied, we are aware of no such study involving the lateral meniscus. We hypothesized that in situ pull-out suture repair of lateral meniscus root avulsions and of complete radial tears 3 and 6 mm from the root attachment would increase the contact area and decrease mean and peak tibiofemoral contact pressures, at all knee flexion angles, relative to the corresponding avulsion or tear condition.

Methods: Eight human cadaveric knees underwent biomechanical testing. Eight lateral meniscus conditions (intact, footprint tear, root avulsion, root avulsion repair, radial tears at 3 and 6 mm from the posterior root, and repairs of the 3 and 6-mm tears) were tested at five different flexion angles (0°, 30°, 45°, 60°, and 90°) under a compressive 1000-N load.

Results: Avulsion of the posterior root of the lateral meniscus or an adjacent radial tear resulted in significantly decreased contact area and increased mean and peak contact pressures in the lateral compartment, relative to the intact condition, in all cases except the root avulsion condition at 0° of flexion. In situ pull-out suture repair of the root avulsion or radial tear significantly reduced mean contact pressures, relative to the corresponding avulsion or tear condition, when the results for each condition were pooled across all flexion angles.

Conclusions: Posterior horn root avulsions and radial tears adjacent to the root attachment of the lateral meniscus significantly increased contact pressures in the lateral compartment. In situ pull-out suture repairs of these tears significantly improved lateral compartment joint contact pressures.

Clinical Relevance: In situ repair may be an effective treatment to improve tibiofemoral contact profiles after an avulsion of the posterior root of the lateral meniscus or a complete radial tear adjacent to the root. In situ repairs should be further investigated clinically as an alternative to partial lateral meniscectomy.

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Without intact circumferential fibers, the knee menisci are unable to sustain hoop stresses, resulting in decreased contact areas and increased contact pressures in the knee[1]. Complete tears involving the root of the medial meniscus disrupt the circumferential fibers and result in a situation similar to that of a knee with a complete meniscectomy; contact areas in the medial compartment are decreased and contact pressures are increased[2,3]. Failing to

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TABLE I Comparisons of Tears with the Corresponding Repairs

Measurement	Flexion Angle *(deg)*	Percentage Change Relative to the Intact Condition (95% CI)*		
		Root Repair Relative to Root Avulsion	3-mm Repair Relative to 3-mm Tear	6-mm Repair Relative to 6-mm Tear
Contact area				
	0	+3 (−17, +23)	+19 (−4, +42)	+8 (−17, +32)
	30	+33 (+5, +61)	+37 (+7, +67)	+26 (−7, +59)
	45	+29 (+3, +55)	+28 (+1, +55)	+25 (−4, +55)
	60	+42 (+17, +66)†	+34 (+9, +59)†	+24 (−4, +52)
	90	+50 (+21, +78)†	+35 (+8, +63)	+25 (−6, +57)
	Pooled	+28 (+8, +49)†	+30 (+8, +52)†	+21 (−3, +45)
Mean pressure				
	0	−7 (−29, +15)	−17 (−36, +2)	−14 (−35, +7)
	30	−27 (−51, −4)	−26 (−48, −5)	−23 (−45, −1)
	45	−29 (−48, −9)†	−23 (−41, −4)	−27 (−46, −8)†
	60	−32 (−49, −14)†	−27 (−44, −10)†	−26 (−43, −8)†
	90	−37 (−55, −20)†	−32 (−50, −14)†	−27 (−45, −8)†
	Pooled	−28 (−45, −10)†	−25 (−42, −9)†	−24 (−41, −7)†
Peak pressure				
	0	−13 (−33, +8)	−12 (−30, +6)	−13 (−32, +5)
	30	−17 (−41, +6)	−29 (−49, −9)†	−26 (−46, −6)
	45	−27 (−46, −7)†	−29 (−46, −11)†	−24 (−42, −6)†
	60	−24 (−43, −5)	−14 (−33, +4)	−20 (−37, −2)
	90	−19 (−38, +1)	−26 (−44, −8)†	−14 (−33, +4)
	Pooled	−20 (−36, −5)	−22 (−37, −8)†	−20 (−34, −5)†

*The values are given as the mean, with the 95% CI in parentheses. Positive values indicate higher measurements in the repaired meniscus relative to the intact meniscus. †Holm-Bonferroni adjusted p value < 0.05.

repair meniscal root avulsions and adjacent radial tears increase cartilage degeneration and the development of knee osteoarthritis[4,5]. Historically, these tears have typically been treated with total or partial meniscectomy to achieve short-term benefits, despite studies with long-term follow-up that indicate higher rates of osteoarthritis and reoperations, as well as lower functional scores, compared with meniscal repair[6,7].

Although a few prior studies have evaluated the biomechanical consequences of an avulsion of the posterior root of the medial meniscus[2,3,8,9], we are aware of no studies evaluating the biomechanical consequences of an avulsion of the posterior root of the lateral meniscus. The lateral meniscus is especially important in young, active individuals, and a radial tear adjacent to the root attachment has debilitating effects if not repaired[10]. The lateral meniscus transmits up to 70% of the load of the lateral compartment of the knee[11], with the posterior horn transmitting 50% of the compressive load in extension and 85% of the load at 90° of flexion[12,13]. Studies with long-term follow-up have indicated that lateral meniscectomy results in a considerably poorer outcome than medial meniscectomy does[14-16]. Therefore, testing the biomechanical consequences of an in situ pull-out suture repair comparable to that described for the treatment of medial meniscus root avulsions[17] is a next logical step to find a better way to treat root avulsions of the lateral meniscus and radial tears adjacent to the root attachment.

The purpose of this study was to assess the changes in tibiofemoral contact areas and pressures after avulsion of the posterior root attachment of the lateral meniscus and after a radial tear close to the root attachment. We hypothesized that an in situ pull-out suture repair of such an avulsion or of a complete radial tear 3 or 6 mm from the root attachment would increase the tibiofemoral contact area and decrease the peak and mean contact pressures, at all knee flexion angles, relative to the avulsed or torn condition.

Materials and Methods

The study involved eight nonpaired, fresh-frozen cadaveric knees without meniscal injury and without articular cartilage degeneration beyond Outerbridge grade I[18]. The eight donors were all male and had had a mean age of 47.8 years (range, forty-two to fifty-four years). The cruciate and collateral ligaments as well as the ligamentum mucosum of the knee were preserved; the skin, subcutaneous tissues, muscles, tendons, and patella were removed. The femur, tibia, and fibula were cut approximately 20 cm proximal and 20 cm distal to the joint line. The joint line was oriented parallel to the testing surface, and the tibia and fibula were potted in a cylindrical mold filled with polymethylmethacrylate (PMMA; Fricke Dental International, Streamwood, Illinois).

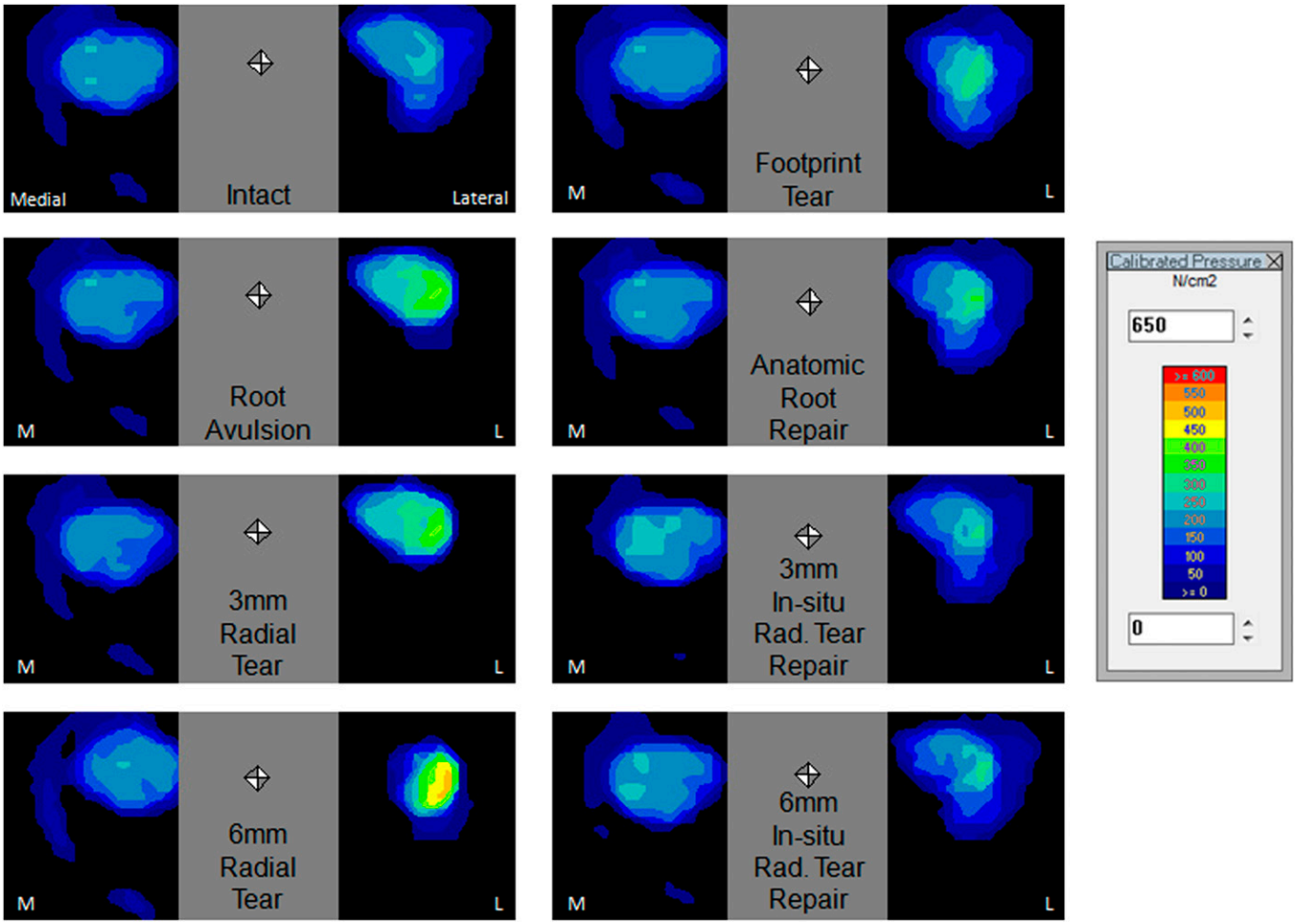

Fig. 1

Representative pressure mapping demonstrating the contact area and pressure distribution in the lateral and medial compartments of specimen 7 (a left knee) at 30° of flexion for the eight lateral meniscus conditions. The diamond shows that the distribution of pressure between the medial and lateral compartments of the knee was equal.

A 10-mm-diameter tunnel that avoided the collateral ligaments was drilled horizontally through the femoral condyles and parallel to the tibial plateau to act as the axis of rotation of the femur. A 7-mm-diameter tunnel was then drilled through the proximal aspect of the femur parallel to the 10-mm tunnel with use of a custom-made pin guide (see Appendix). An osteotomy of the lateral femoral condyle was performed with an oscillating saw to allow unobstructed visualization, measurement, and marking of the locations for tear creation. The osteotomy included the articular cartilage surfaces of the lateral femoral condyle and the fibular collateral ligament, popliteus tendon, and lateral capsule; the anterior cruciate ligament was left intact with the remainder of the femur. The osteotomy did not cross the portion of the lateral femoral condyle that was being loaded and was in contact with the sensor.

An incision was made in the posterior and anterior portions of the meniscotibial ligaments to slide a calibrated and lubricated knee pressure sensor (Model 4000; Tekscan, South Boston, Massachusetts) on top of the tibial plateau articular cartilage and underneath the medial and lateral menisci. A new sensor was used for each knee. Prior to testing, each sensor was calibrated according to the manufacturer's recommendation. Two double-loaded suture anchors secured the tabs of the sensor to the posterior aspect of the tibia on each side of the knee to keep the sensor in a consistent position for every trial. Saline solution was used to reduce shear forces on the sensor throughout the test and to prevent soft-tissue desiccation.

During pilot testing, the load recorded by a pressure sensor was observed to decrease over time when the sensor was exposed to liquids, eventually reaching a steady state at forty-eight hours. In the present study, the sensors were exposed to liquids over the course of testing because of the presence of cadaveric fluids and spraying of the knees with saline solution. To mitigate the effect of this exposure, the sensors were submerged in saline solution for forty-eight hours prior to calibration and testing[19]. However, we still measured a slight, linear decline in the mean total load outputs over the forty consecutive data captures for each knee, and we therefore normalized the acquired data with use of the measured linear rate of decline.

Reattachment of the osteotomized lateral femoral condyle was performed by drilling two 6-mm-diameter tunnels and securing two threaded bolts and nuts across the condyles. A hollow 10-mm-diameter tube was inserted in the load-bearing pivot axis. The knee was then placed in a custom-made jig, using the distal tunnel as the pivot point and load-bearing site; the 7-mm proximal tunnel allowed selection and maintenance of the knee flexion angle. The jig was attached to the actuator of a dynamic tensile testing machine (E10000; Instron, Norwood, Massachusetts), and the femur was positioned in the jig by sliding a 9-mm-diameter metal rod through the 10-mm tube in the pivot axis of the femur. The potted fibula and tibia were fixed to the base of the test frame with a custom-made pivot table that allowed for free translation and rotation; varus-valgus alignment was controlled manually. The control of varus-valgus alignment of the knee was important because this ensured that a

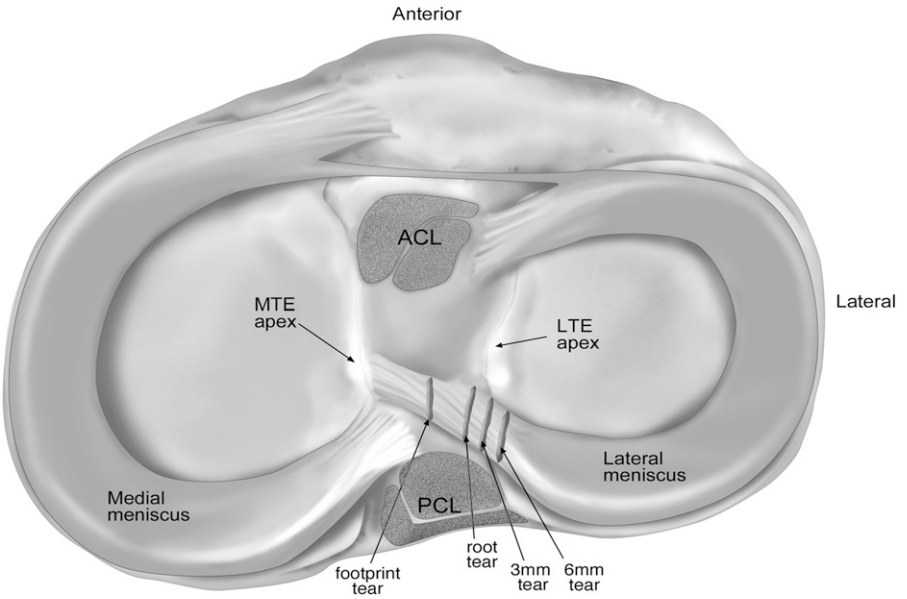

Fig. 2

Location of the tears at the site of the posterior root attachment of the lateral meniscus of a right knee. From left to right, the four tears are footprint tear, root avulsion, and radial tears at 3 and 6 mm. ACL = anterior cruciate ligament, PCL = posterior cruciate ligament, LTE = lateral tibial eminence, and MTE = medial tibial eminence.

consistent and balanced load was applied through the medial and lateral compartments throughout the testing. This ensured that the quantitative changes in pressure and area that were measured were due solely to the changes involving the meniscus condition and not due to a change in varus-valgus alignment. The center-of-force indicator from the pressure mapping software output provided real-time feedback as the knee was loaded, allowing manual correction to rebalance the load on the compartments during testing (Fig. 1). A balanced load distributed equally between the medial and lateral compartments, rather than a biased distribution of load on the medial compartment, was applied because an equal distribution could be achieved more reproducibly within the time constraints of the experiment.

The knees were tested by subjecting the lateral meniscus to eight different conditions while keeping the medial meniscus intact (Fig. 2). Condition 1 was the intact lateral meniscus, which served as the control. Condition 2 was a footprint tear created by sectioning the widening of the lateral meniscal between the posterior root attachment and the medial tibial eminence, which has been described in recent anatomic reports on the diffuse posterior root attachment of the lateral meniscus[20]. Condition 3 was an avulsion of the posterior root of the lateral meniscus. Condition 4 was an anatomic repair of the posterior root avulsion with use of an in situ pull-out suture repair technique[17]. Conditions 5 and 7 were complete radial tears of the posterior root at 3 and 6 mm, respectively, from the root attachment site; these distances were chosen to account for the fact that not all tears of the posterior horn of the lateral meniscus are located exactly at the root. Conditions 6 and 8 were in situ pull-out suture repairs of the radial tears located at 3 and 6 mm, respectively.

The posterior root attachment site of the lateral meniscus was identified, and the location of the meniscocapsular junction and the sites for creation of the radial tears (3 and 6 mm from the root attachment site) were marked with a methylene blue marker before the testing of the intact condition. After the osteotomized femoral condyle was reattached and the pressure sensor was inserted, all of the incisions and repairs were performed from the posterior aspect of the knee without having to reopen the osteotomy. The posterior horn footprint tear, root avulsion, and radial tears were cut sharply with a scalpel, taking care to avoid damaging the pressure sensor. A transosseous pull-out suture technique was used to repair the root avulsion and radial tears[17] (Fig. 3). For repair of the root avulsion, two number-2 nonabsorbable sutures were secured 2 mm from the incised edge of the lateral meniscus root. An eyelet pin was then drilled from the center of the root attachment site through the anteromedial tibial surface. Finally, the sutures were pulled through the tibia with use of the eyelet pin and were tied over a metal button, reestablishing the posterior anchor of the lateral meniscus. The same technique used for the lateral meniscus root avulsion repair was used for each subsequent radial tear repair, with the eyelet pin being placed at 3 or 6 mm from the root, depending on the condition tested.

For each condition, the specimens were tested at flexion angles of 0°, 30°, 45°, 60°, and 90°, with a 1000-N compressive axial load applied gradually along the tibial axis. The meniscus conditions were always tested in the same order, 1 through 8, but the order of the flexion angles was chosen randomly for each condition. A 50-N tensile force was applied to the knee while changing between flexion angles to avoid shear stress on the pressure sensors.

A contact pressure map of each knee was generated by the pressure mapping software (Fig. 1). The sensor comprised a grid of 26×22 sensels, each 1.27×1.27 mm. The area of each sensel was therefore 1.61 mm^2, and the overall size of the sensor was 33×28 mm. The pressure mapping system recorded the contact pressure within each sensel (in N/mm^2), and these values were used to calculate the total load (in N), contact area (in mm^2), and mean and peak contact pressures (in N/mm^2). The contact area was measured by counting the sensels with non-zero loads and multiplying the result by the size of an individual sensel. Erroneous contact stress measurements resulting from wrinkling of the sensors and from damaged sensels occurred occasionally during the testing. Sensels reporting erroneous measurements could be identified because they reported non-zero pressure values when no load was being transmitted between the femur and tibia. In such an instance, the erroneous sensel value was replaced with the mean of the values reported by the surrounding sensels, as has been done in previous studies[21]. These changes involved only 0.06% of the overall data.

One-way repeated-measures analysis of variance (ANOVA) was performed for each flexion angle to detect the overall effect of meniscus condition on each measurement (contact area, mean contact pressure, and peak contact pressure). This approach was also used to analyze measurements when they were pooled over all flexion angles. When the overall effect of the meniscus condition was significant, preplanned comparisons of each of the seven subsequent conditions with the intact condition and each of the three repair conditions with its respective tear condition were performed. The Holm-Bonferroni method was

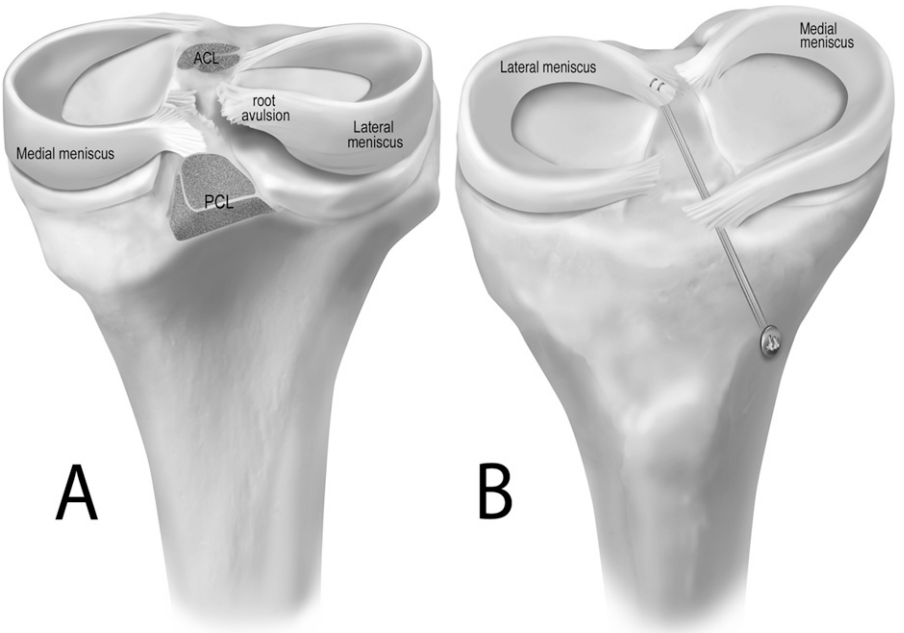

Fig. 3

Figs. 3-A and 3-B Schematic showing an in situ suture repair of the posterior root attachment of the lateral meniscus of a right knee. ACL = anterior cruciate ligament, and PCL = posterior cruciate ligament. **Fig. 3-A** Posterior view showing a root avulsion. **Fig. 3-B** Anterior view showing how two horizontal mattress sutures were secured into the meniscus, pulled anteriorly with the use of an eyelet pin, and tied over a button on the anteromedial proximal aspect of the tibia.

used to control the overall type-I error rate among these ten individual comparisons. A Holm-Bonferroni-adjusted p value of <0.05 was considered significant. The R statistical software package (R Development Core Team, Vienna, Austria) was used to perform all graphing and analyses. A power analysis was performed after testing of the first three knees to calculate the required sample size. The results demonstrated that a sample of five knees would provide 80% power for all repeated-measures ANOVA tests for the overall effect of meniscus condition on the contact area and mean and peak contact pressures, whereas seven knees would be required to achieve 80% power to detect individual differences between corresponding tear and repair conditions. Thus, we elected to test eight knees to ensure that the study had sufficient power. The 95% confidence interval (CI) was calculated for each comparison of tear and repair conditions and for each comparison of the intact condition with a subsequent condition.

Source of Funding

The study was funded by the Steadman Philippon Research Institute; no external funding was received.

Results

Lateral Compartment Contact Area

The root avulsion and 3 and 6-mm radial tears resulted in a significant decrease in the lateral compartment contact area, relative to the intact condition, at all flexion angles (see Appendix). The footprint tear did not significantly affect the contact area.

There was no significant difference in contact area between the root avulsion repair and the intact condition when pooled across all angles, but the contact areas for the 3 and 6-mm tear repairs were significantly less than that for the intact condition when pooled across all angles (Fig. 4). For both the root avulsion repair and 3-mm tear repair, the contact areas were also significantly increased relative to the corresponding tear condition when pooled across all angles; however, the 6-mm tear repair did not significantly increase the contact area relative to the 6-mm radial tear condition at any angle (Table I). None of the repair conditions had a significantly increased contact area relative to the corresponding tear or avulsion condition at flexion angles of 0°, 30°, or 45°.

Lateral Compartment Mean Contact Pressure

Relative to the intact condition, the root avulsion and 3 and 6-mm radial tears resulted in a significant increase in the mean contact pressure in the lateral compartment at all flexion angles, with the exception of the root avulsion condition at 0° (see Appendix). The footprint tear did not significantly affect the mean contact pressure.

There was no significant difference in mean contact pressure between any repair condition and the intact condition at any angle (Fig. 5). The mean contact pressure for each repair condition was significantly decreased relative to the corresponding tear condition when pooled across all angles (Table I). However, none of the repairs significantly decreased the mean contact pressure relative to the corresponding tear condition at 0° or 30°.

Lateral Compartment Peak Contact Pressure

The root avulsion and 3 and 6-mm radial tears resulted in a significant increase in peak contact pressure in the lateral

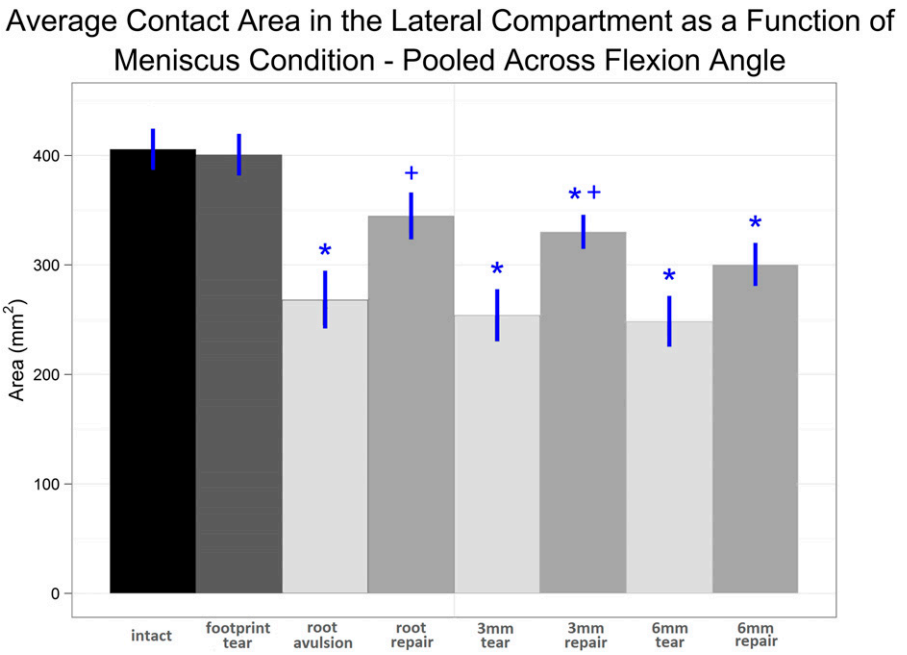

Fig. 4

Overall effect of each lateral meniscus condition on contact area in the lateral compartment when pooled across all flexion angles. The error bars indicate the standard error of the mean. *P < 0.05 compared with the intact condition. +P < 0.05 compared with the corresponding tear condition.

compartment relative to the intact condition at all flexion angles, with the exception of the root avulsion condition at 0° (see Appendix). The footprint tear did not significantly affect the peak contact pressure.

When pooled over all flexion angles, there was no significant difference between the peak contact pressure for the root avulsion repair or 3-mm repair condition and the intact condition; however, a significant difference was detected between the

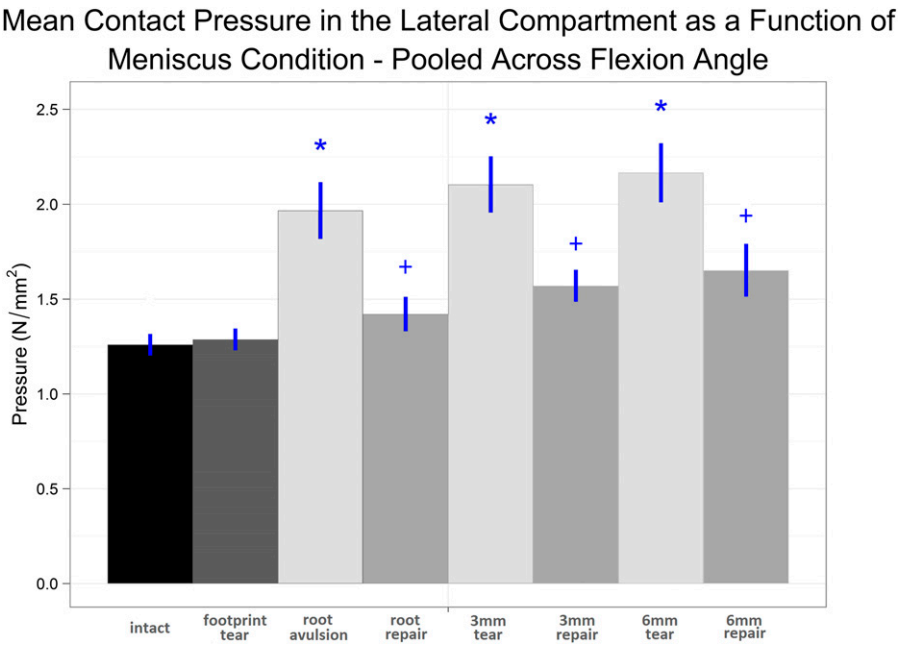

Fig. 5

Overall effect of each lateral meniscus condition on mean contact pressure in the lateral compartment when pooled across all flexion angles. The error bars indicate the standard error of the mean. *P < 0.05 compared with the intact condition. +P < 0.05 compared with the corresponding tear condition.

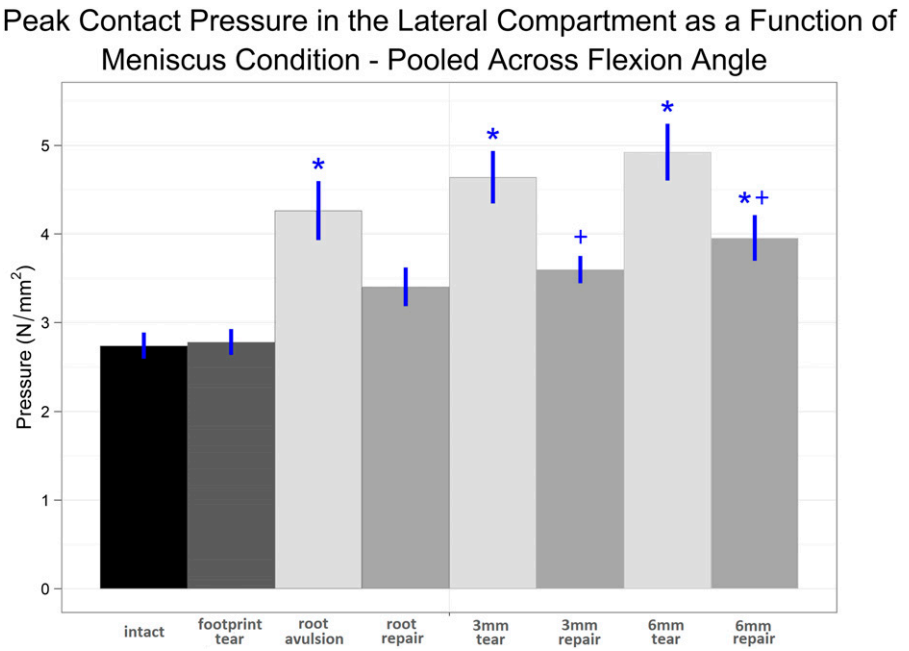

Fig. 6

Overall effect of each lateral meniscus condition on peak contact pressure (as measured by any single sensel) in the lateral compartment when pooled across all flexion angles. The error bars indicate the standard error of the mean. *P < 0.05 compared with the intact condition. +P < 0.05 compared with the corresponding tear condition.

6-mm repair and the intact condition (Fig. 6). When pooled across flexion angles, the peak contact pressure was significantly reduced following the 3 and 6-mm repairs relative to the corresponding tear conditions (Table I).

Medial Compartment Contact Area and Pressure

There were no significant differences in the medial compartment contact area or pressure among the lateral meniscus conditions at any of the tested flexion angles.

Discussion

As we had hypothesized, avulsions of the posterior root of the lateral meniscus and adjacent radial tears significantly decreased the contact area and increased the mean and peak contact pressures, whereas there were no significant differences in mean contact pressure between in situ pull-out repairs and the intact condition at any flexion angle. However, the peak contact pressure pooled across all flexion angles returned to a level not significantly different from that of the intact condition only following in situ pull-out suture repair of the root avulsion and the 3-mm tear. In situ pull-out suture repair did significantly decrease contact pressures relative to the corresponding tear condition for some conditions and flexion angles; however, in contrast to what we had hypothesized, some repairs did not differ significantly from the corresponding tears. The mean contact pressure after each of the repairs was not significantly different from that of the corresponding tear condition at 0° and 30°, suggesting that the in situ repair technique is less effective for lower angles of knee flexion and for radial tears at increasing distances from the posterior horn root attachment. However, the mean contact pressures at 45°, 60°, and 90° were significantly lower for each repair than for the corresponding tear condition, with the exception of the 3-mm tear repair condition at 45°. We believe that the improvements in contact area and decreases in mean and peak contact pressures across the majority of the root avulsion or radial tear repair conditions provide intriguing evidence that further clinical studies are justified to assess the results of radial root repairs utilizing an in situ repair technique.

To our knowledge, there have been no studies evaluating the biomechanical properties of avulsions of the posterior root attachment of the lateral meniscus or radial tears adjacent to the root. Bedi et al. reported that radial tears of the lateral meniscus at the popliteal hiatus increased peak contact pressures to levels not significantly different from those after partial lateral meniscectomy, and that the contact area was decreased significantly by radial tears spanning 90% of the meniscal width[22]. Those contact pressures were decreased significantly by an inside-out horizontal mattress suture repair[22]. Ode et al. created radial tears 4 mm posterior to the popliteal hiatus of the lateral meniscus and reported that complete radial tears significantly increased mean contact pressures and decreased contact areas[23]. They reported that an all-inside or inside-out repair resulted in contact pressures not significantly different from those of the intact condition but that contact areas after repair were still significantly less than those in the intact knee[23], which is very similar to the results that we observed.

It has been reported that approximately 15% of meniscal tears are radial tears, with approximately 20% of these tears occurring in the posterior horn of the lateral meniscus[24-26].

Other studies have reported that concomitant tearing of the lateral meniscus is associated with approximately 20% of anterior cruciate ligament (ACL) tear injuries, with 70% to 87% of these tears of the lateral meniscus involving the posterior horn[27,28]. Thus, these tears appear to occur more frequently than has been recognized clinically.

There have been several recent biomechanical studies focusing on tears involving the posterior root of the medial meniscus. Two studies indicated that such tears caused a 25% increase in the peak contact pressure relative to the intact condition and that repair restored joint biomechanics to normal conditions[2,9]. One study also failed to detect a difference between such tears and total medial meniscectomies with respect to any of the measured variables[2]. Marzo and Gurske-DePerio reported that repairing avulsions of the posterior root of the medial meniscus restored the loading profiles to those of the intact knee[3]. In the present study, tears involving the posterior root of the lateral meniscus and repairs of those tears also significantly affected contact areas and pressures in a similar manner, even though the lateral and medial menisci have different structural anatomy[20].

This study has some limitations. A static axial loading system was used, which does not replicate the variable loading experienced in the knee during gait or other physical activities; however, this loading scheme has been reported to have reproducible results[2,3,21,23]. The 1000-N load used was the maximum load that was found to allow the specimens and pressure sensors to survive the forty repeated loadings during pilot testing. In addition, the knee typically has loads applied at numerous different angles, not all of which were simulated. However, this study used five different angles to represent a typical range of angles at which loads are applied on the knee. The insertion of the pressure sensors required an osteotomy of the lateral femoral condyle and small incisions in the coronary ligaments. However, similar procedures have been described in previous studies[22,23], and similar osteotomies of the medial femoral condyle have been shown not to significantly alter tibiofemoral contact mechanics[21,29]. Also, the menisci were transected sharply to create the tears. Clinically, meniscal tissue requiring repair would be expected to be of lesser quality. Finally, as this study was performed on cadavers, caution must be used in extrapolating the findings to clinical outcomes.

In summary, the results of this study demonstrated that avulsions of the posterior root attachment of the lateral meniscus and radial tears adjacent to the root attachment significantly decreased the contact area and increased the contact pressure in the lateral compartment of the knee. In situ pull-out suture repairs of these tears significantly improved the loading profiles of the lateral compartment, and these repairs may therefore help to prevent the development of articular cartilage degeneration that has been reported to be associated with partial meniscectomy. The authors believe that an in situ pull-out suture repair may be able to help restore the circumferential continuity essential for sustaining hoop stresses in the lateral meniscus, which is not possible with the alternative treatment of partial meniscectomy. We recommend that further clinical studies evaluate the results of in situ repairs of root avulsions and adjacent radial tears in the lateral meniscus.

Appendix

eA Tables showing lateral compartment contact areas and mean and peak contact pressures for each condition and a figure showing the experimental setup are available with the online version of this article as a data supplement at jbjs.org. ■

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