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Medial meniscal extrusion greater than 4 mm reduces medial tibiofemoral compartment contact area: a biomechanical analysis of tibiofemoral contact area and pressures with varying amounts of meniscal extrusion

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Abstract

Purpose The primary objective of this study is to evaluate the contact areas, contact pressures, and peak pressures in the medial compartment of the knee in six sequential testing conditions. The secondary objective is to establish how much the medial meniscus is able to extrude, secondary to soft tissue injury while keeping its roots intact.

Methods Ten cadaveric knees were dissected and tested in six conditions: (1) intact meniscus, (2) 2 mm extrusion, (3) 3 mm extrusion, (4) 4 mm extrusion, (5) maximum extrusion, (6) capsular based meniscal repair. Knees were loaded with a 1000-N axial compressive force at 0°, 30°, 60°, and 90° for each condition. Medial compartment contact area, average contact pressure, and peak contact pressure data were recorded.

Results When compared to the intact state, there was no statistically significant difference in medial compartment contact area at 2 mm of extrusion or 3 mm of extrusion (n.s.). There was a statistically significant decrease in contact area compared to the intact state at 4 mm ($p = 0.015$) and maximum extrusion ($p < 0.001$). The repair state was able to improve medial compartment contact area, and there was no statistically significant difference between the repair and the intact states (n.s.). No significant differences were found in the average contact pressure between the repair, intact, or maximum extrusion conditions at any flexion angle (n.s.). No significant differences were found in the peak contact pressure between the repair, intact, or maximum extrusion conditions at any flexion angle (n.s.).

Conclusion In this in vitro model, medial meniscus extrusion greater than 4 mm reduced medial compartment contact area, but meniscal extrusion did not significantly increase pressure in the medial compartment. Additionally, meniscal centralization was effective in restoring the medial tibiofemoral contact area to intact state when the meniscal extrusion was secondary to meniscotibial ligament injury. The diagnosis of meniscal extrusion may not necessarily involve meniscal root injury. Since it is known that meniscal extrusion greater than 3 or 4 mm has a biomechanical impact on tibiofemoral compartment contact area and pressures, specific treatments can be established. Centralization restored medial compartment contact area to the intact state.

Keywords Knee · Meniscus · Arthroscopy · Meniscal repair · Biomechanics

Introduction

Medial meniscus extrusion is defined as the internal displacement of the meniscus in relation to the medial margin of the tibial plateau, usually resulting from tears of its bone insertions (roots) or disruption of the coronary ligaments [6, 7, 17, 28]. The amount of extrusion is quantified by measuring the distance between the medial edge of the tibial plateau

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and the most prominent medial point of the medial meniscus [6, 7]. Meniscal extrusion directly impacts the ability of the joint to adapt to load and may be an important predictor of accelerated joint degeneration [12, 22]. Krych et al. established that meniscal extrusion occurred not only by injury to the meniscal roots but also from injury to the meniscotibial ligaments. Further, Kawaguchi et al. demonstrated in an ultrasound-based study that physiologic loading is can cause meniscal extrusion to a mild degree [16].

It has been suggested that reducing meniscal extrusion could help to restore more normal meniscal position, stability, and function. Whether directly repairing a detached meniscotibial ligament restores meniscal stability has not been well established in the literature. A recent study by Paletta et al. biomechanically evaluated six cadaveric knees and established that lesions of the meniscotibial ligaments cause the meniscus to extrude and that repair of those ligaments can significantly reduce extrusion [31]. Their study did not evaluate the contact area, average contact pressure, or, peak contact pressure of their specimens before or after repair.

The primary objective of this study is to evaluate the contact areas, contact pressures, and peak pressures in the medial compartment of the knee in six sequential testing conditions. The secondary objective is to establish how much the medial meniscus is able to extrude, secondary to soft tissue injury while keeping its roots intact. The hypothesis was that medial meniscal extrusion would be possible while leaving the roots intact, and that this extrusion would be significant enough to reduce the contact area and increase the average and peak contact pressures in the medial compartment of the knee.

Materials and methods

Specimens and preparation

This study was reviewed via Human Research Determination Form by the institutional review board (IRB) of the University of Connecticut, and it was concluded that no IRB approval was required. Ten fresh-frozen cadaveric knees (five right and five left) from four male and six female donors ranging in age from 43 to 60 years (average: 52.5 years) were included. Five specimens were excluded due to chondral or meniscal lesions in the medial compartment. The exposure protocol and access to the medial compartment was the same as that used in previous studies [9, 23, 29]. The specimens used in this study were donated to registered tissue banks for the purpose of medical research and then purchased by this institution.

Specimens were thawed 24 h prior to dissection, and were dissected free of skin, soft tissue attachments, muscle, tendon, and the patella. The collateral ligaments, cruciate ligaments, medial capsule, lateral capsule, and posterior capsule were retained. The femur, tibia, and fibula were cut approximately 20 cm from the joint line and then potted in a cylindrical mold using poly (methyl methacrylate) (PMMA, Fricke Dental International Inc., Streamwood, IL, USA) with the tibial plateau oriented parallel to the testing surface and ensuring that the bone cement encased the bone up to a point 4 cm distal to the tibial tuberosity (Fig. 1a).

Taking care not to damage the collateral ligaments, a transverse tunnel was created connecting the femoral condyles and parallel to the articular surface (Fig. 1b). A rod passing through this tunnel acted as the load bearing site and flexion pivot point for the construct. Then, a second transverse tunnel of 5 mm in diameter, parallel to the first, was made with the center axis positioned 18 mm proximal to the first tunnel [29]. To obtain access to the medial meniscus, an oblique medial femoral osteotomy was performed (Fig. 1c–h) with special care to preserve the medial collateral and posterior cruciate ligaments [26]. During testing, the osteotomy was fixed with a compression screw and washer as well as a six hole titanium locking plate (Arthrex, Naples, FL) secured with five cortical locking screws (three proximal and two distal from the osteotomy). If needed, one additional compressive screw could be placed outside the plate. Any movement in the osteotomy would lead to the exclusion of the specimen. Martens et al. reported no change on tibiofemoral biomechanical parameters using a similar technique after the reattachment of the osteotomized medial femoral condyle and incision of coronary ligaments for pressure film placement (there were no excluded cases) [26].

All skin, subcutaneous tissue, and tendons were dissected. A small, posteromedial submeniscal incision (< 1 cm) was made in the capsule between its posterior root and the posterior oblique ligament (Fig. 1g). Similarly, a submeniscal incision (< 1 cm), preserving the coronary ligaments was performed anteromedially for sensor placement (Fig. 1h) [29].

Pressure sensors (Tekscan Model 4000, South Boston, MA, USA) were calibrated and equilibrated for testing according to the manufacturer's guidelines and previously published protocols [9, 14, 23, 24, 29]. A new sensor was used for each specimen to ensure the validity of the data. The pressure sensor was then inserted into the medial compartment on the bare tibial plateau articular surface and underneath the medial meniscus as previously described [9, 13, 26, 29]. The posterior aspect of the pressure sensor was sutured to the posterior capsule to ensure it would stay in the same position throughout testing.

The anatomical position of the osteotomy was ensured by positioning the plates and screws before executing the osteotomy cut. A10-mm rod was then passed through a custom-made jig attached to the actuator of a material testing system machine (MTS 858 Mini-Bionix, Eden Prarie, MN),

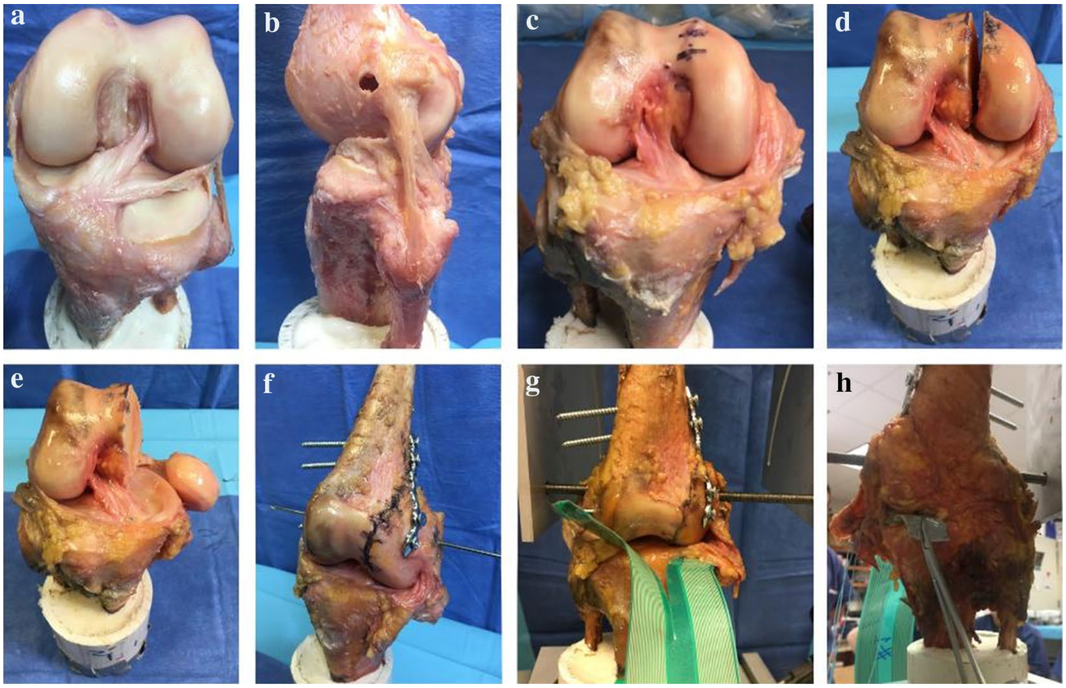

Fig. 1 Exposure protocol and access to the medial meniscus; **a** exposure; **b** transverse tunnel performed to connect the femoral condyles, with orientation parallel to the articular surface; oblique medial femoral osteotomy, drawn (**c**) and cut (**d**, **e**); **f** osteotomy fixed with a six hole titanium locking plate (Arthrex, Naples, FL) secured with five cortical locking screws; sensors positioned below the meniscus, anterior view (**g**) and posterior view (**h**)

securing the specimen in the testing apparatus [9, 23, 29]. The neutral coronal alignment was achieved by applying an axial load in each degree of flexion studied and equalizing the pressure readings in the medial and lateral compartments [9, 23, 29]. An additional 7-mm transverse tunnel was drilled in the femoral diaphysis, parallel to the first 10 mm tunnel and 7.5 cm proximal to it. Through this tunnel a 7-mm metal rod was passed so that it could control the degree of knee flexion (0°, 30°, 60° and 90°).

Testing conditions

Each knee was submitted to six sequential testing conditions: (1) intact; (2) 2 mm extrusion; (3) 3 mm extrusion; (4) 4 mm extrusion; (5) maximum extrusion; (6) capsular based meniscal repair. Prior to each step, the femoral osteotomy was opened to check the extrusion and position of the meniscus (Fig. 2). Meniscal extrusion was performed by passing two #2 Fiberwire sutures (Arthrex, Naples, FL) in the most peripheral region of the meniscus (Fig. 2a–f). The first suture was passed at the anterior border of the superficial medial collateral ligament, and the second at the posterior border of the same ligament (points B and C at Fig. 2d). These two sutures were coupled to a traction device positioned parallel to the articular surface in a way that the meniscus was pulled centrifugally (Fig. 3) relative to the joint. To measure meniscal extrusion, a fixed osseous point was established at the union of the descending edge of the medial tibial spine with the flat portion of the tibial plateau (point A at Fig. 2d). The meniscal measuring point was at the midpoint between the traction sutures described above. The distance from the bony point to the meniscal point was marked (distance AD at Fig. 2d). In the intact state, the distance between the osseous and meniscal fixed points was measured without any type of traction or release. The measurement was performed three consecutive times by the same examiner (DCA), using a digital caliper with measurements to the nearest hundredth of a mm (Absolute Digimatic; Mitutoyo, Aurora, IL). The mean of the three measurements was considered as the initial distance. In the 2 mm extrusion condition, the meniscus was placed on traction until the distance between the bony and meniscal fixed points increased by 2 mm from the initial distance. This process was repeated for 3-mm and 4-mm extrusion states. When needed, the meniscotibial ligaments were gradually released with a banana blade until the desired amount of extrusion was reached. To establish maximum extrusion, all stabilizing structures of the meniscus were released (meniscotibial, meniscocapsular and meniscofemoral ligaments), leaving only the attachments of the anterior and posterior roots. In the repair state, two 3.0 mm Suture-Tak anchors (Arthrex, Naples, FL) were inserted into the medial edge of the tibial plateau, 1 cm distal to the joint with

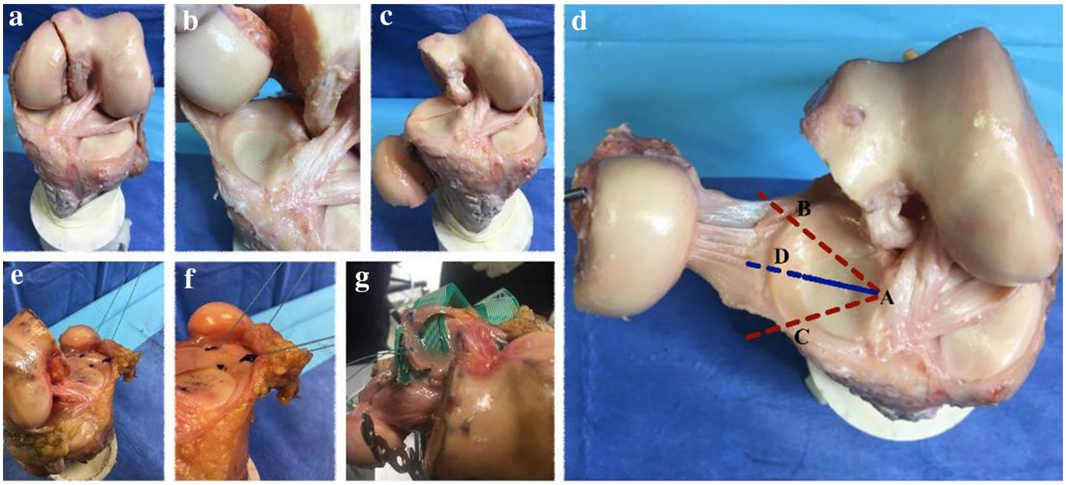

Fig. 2 Extrusion measurement protocol; **a**–**c** opening of the osteotomy; **d**–**g** standardization of measurements. Point A: a fixed osseous point established at the union of the descending edge of the medial tibial spine with the flat portion of the tibial plateau; point B: suture passed at the anterior border of the superficial medial collateral ligament; point C: suture passed at the posterior border of the medial collateral ligament; point D: fixed meniscal point established by the first contact of the bisector of the BAC angle with the meniscus; line AD corresponds to meniscal extrusion

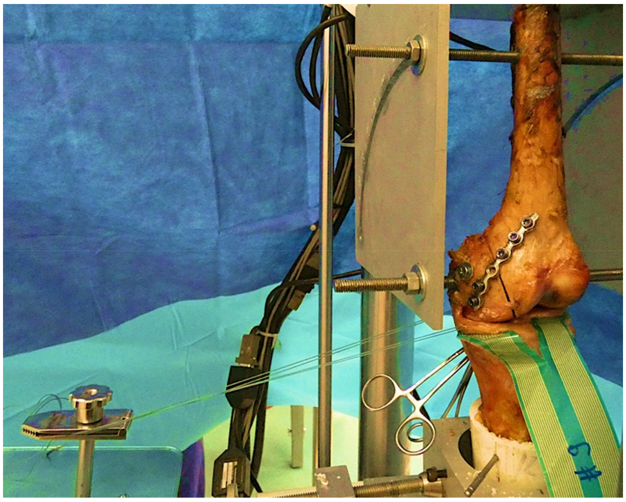

Fig. 3 Position of the knee in the MTS machine. Femoral oblique osteotomy fixed with plate and screws. Pressure sensors positioned on the tibial plateau articular cartilage and beneath the meniscus. Radial traction device of the meniscus being positioned parallel to the piece

one anchor placed just anterior to the MCL and the second anchor placed just posterior (Fig. 4). The repair sutures were passed in horizontal mattress fashion, securing the periphery of the meniscus to the medial tibial plateau (Fig. 4).

All specimens were tested at four different degrees of flexion (0°, 30°, 60°, 90°). A constant compressive axial load of 1000 N was applied along the axis for 30 s. Contact mechanics were recorded using pressure sensors (Model 4000; Tekscan, South Boston, MA) from which the contact area, peak contact pressure, and average contact pressure could be determined. Throughout testing, the sensors were placed on the bare tibial plateau articular cartilage and underneath the medial meniscus.

Statistical analysis

Descriptive statistics including mean and standard deviation were calculated to characterize the study groups. Differences in contact area and pressure were assessed using multilevel mixed effects generalized linear models. A random intercept was used to account for specimens in different conditions. Model residuals were graphically assessed to confirm assumptions of normally distributed errors. Following each analysis, pairwise comparisons of marginal mean values were carried out with adjustment for multiple comparisons using the Holm–Bonferroni sequential correction method. Results are presented as mean difference with corresponding 95% confidence intervals. An alpha level of 0.05 was set for all comparisons. All statistical analysis was performed using Stata 15.1 (StataCorp. 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LP). Sample size was determined based on data from previously reported studies. It had been determined with power analysis that six specimens would be required to detect an effect size of $d = 2$ in the tibiofemoral contact area, average, or peak contact pressure with 80% power using a significance level of 0.025 to account for two primary comparisons (intact vs maximum extrusion and maximum extrusion vs repair in our study) [23].

Fig. 4 Repair (centralization) technique. Two 3.0 mm knotless SutureTak anchors (Arthrex, Naples, FL) inserted into the medial edge of the tibial plateau, 1 cm distal to the joint with one anchor placed just anterior to the MCL and the second anchor placed just posterior. The repair sutures were passed in horizontal mattress fashion

Table 1 Increasing amounts of meniscal extrusion (mm) resulted in a subsequent decrease in contact area (mm^2)

Contact area		
	Difference relative to intact (mm^2)	p value
2 mm	− 31.2	n.s.
3 mm	− 42.1	0.100
4 mm	− 71.7	0.015
Max	− 120.5	< 0.001
Repair	− 56.2	n.s.

Values are presented as mean difference of contact area from the native meniscus; "max" represents the meniscus under tension with maximum extrusion; "repair" represents the meniscus submitted to centralization

Table 2 Contact area in the medial compartment (mm^2) across flexion angles

Angle (°)	Comparison	Difference (mm^2)	p value
0	Max vs intact	− 145.5	**0.006**
	Repair vs intact	− 94.8	n.s.
	Repair vs max	50.7	n.s.
30	Max vs intact	− 84.8	**0.015**
	Repair vs intact	− 13.5	n.s.
	Repair vs max	71.3	**0.040**
60	Max vs intact	− 117	**< 0.001**
	Repair vs intact	− 36.8	n.s.
	Repair vs max	80.2	**0.006**
90	Max vs intact	− 134.6	**< 0.001**
	Repair vs intact	− 79.6	**0.046**
	Repair vs max	55	n.s.

Bold values indicate statistical significance (defined as $p < 0.05$)

"Intact" represents the native meniscus, without extrusion; "max" represents the meniscus under tension with maximum extrusion; "repair" represents the meniscus submitted to centralization

Results

Medial compartment contact area

Increasing amounts of medial meniscal extrusion resulted in a subsequent decrease in contact area in the medial compartment (Table 1). No significant differences were found between the repair state and the intact state (n.s.) with the exception of a significant decrease in contact area at 90° in the repair state compared to the intact state ($p=0.046$). The repair state had significantly more contact area compared to the maximum extrusion state at 30° and 60° of flexion (Table 2). There was no statistically significant difference between the repair state and the maximum extrusion state at 0° or 90° of flexion. At every flexion angle there was significantly less contact area in the maximum extrusion state compared to the intact state (Fig. 5).

Medial compartment contact area across all flexion angles

The medial compartment data for each amount of extrusion was combined and averaged across all flexion angles (Fig. 5). Compared to the intact state, there was no statistically significant difference at 2 mm of extrusion or 3 mm of extrusion (n.s.). There was a statistically significant decrease in contact area compared to the intact state at 4 mm ($p=0.015$) and maximum extrusion ($p<0.001$). Finally, there was no statistically significant difference between the repair and the intact states (Table 1).

Medial compartment average and peak contact pressure

No significant differences were found in the average and peak contact pressure between the repair, intact, or

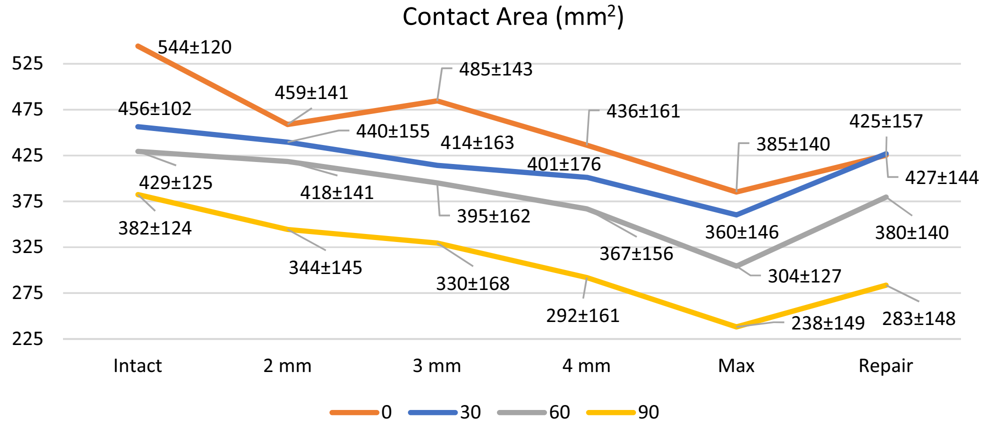

Fig. 5 Contact area in the medial compartment (mm^2) across flexion angles (blue 0°, orange 30°, gray 60° and yellow 90°)

Table 3 Contact area in the medial compartment: physiologic vs pathologic extrusion (mm^2)

Angle (°)	Comparison	Difference (mm^2)	p value
0	Physiologic vs intact	– 63.6	n.s.
	Pathologic vs intact	– 121.4	**0.003**
	Pathologic vs physiologic	57.9	n.s.
30	Physiologic vs intact	– 20.5	n.s.
	Pathologic vs intact	– 63.5	**0.018**
	Pathologic vs physiologic	43.1	**0.044**
60	Physiologic vs intact	– 20.8	n.s.
	Pathologic vs intact	– 88.2	**< 0.001**
	Pathologic vs physiologic	67.4	**< 0.001**
90	Physiologic vs intact	– 41.8	**< 0.037**
	Pathologic vs intact	– 111.3	**< 0.001**
	Pathologic vs physiologic	– 69.5	**< 0.001**

Bold values indicate statistical significance (defined as $p < 0.05$)

Contact area values from the 2- and 3-mm extrusion states were combined to form a physiologic extrusion group. Contact area values from the 4 mm and maximum extrusion states were combined to form a pathologic extrusion group. Intact represents the native meniscus

maximum extrusion conditions at any flexion angle (n.s.). Furthermore, no definitive trend was evident between increasing amounts of meniscal extrusion and peak contact pressure.

Medial compartment contact area group comparison: physiologic vs pathologic extrusion

Group comparisons of medial compartment contact area were made between physiologic and pathologic extrusion. Contact area values from the 2-mm and 3-mm extrusion states were combined to form a physiologic extrusion group. Contact area values from the 4 mm and maximum extrusion states were combined to form a pathologic extrusion group (Table 3). At 30°, 60°, and 90° of flexion, there was significantly less contact area in the pathologic extrusion group compared to the physiologic extrusion group ($p = 0.044$; $p < 0.001$; $p < 0.001$, respectively). At every flexion angle except 90°, the physiologic extrusion group had no significant difference compared to the intact state (n.s.). At every flexion angle, the pathologic extrusion group had significantly less medial compartment contact area compared to the intact state ($p = 0.003$, 0°; $p = 0.018$, 30°; $p < 0.001$, 60°; $p < 0.001$, 90°) (Table 3).

Maximum meniscal extrusion values

The average maximum meniscal extrusion for the specimens was 5.3 mm with a standard deviation of 1.1 (range 4.0–8.9 mm), while maintaining intact root attachments for each specimen. There were no significant differences between maximum meniscal extrusion between male specimens and female specimens (5.7 mm ± 1.4, 4.9 mm ± 0.65, n.s.).

Discussion

The most important finding of the present study was that with the roots left intact, medial meniscal extrusion was able to cause a significant decrease in medial compartment contact area at physiologic flexion angles. The hypothesis of this study was that medial meniscal extrusion would be possible while leaving the roots intact, and that this extrusion would be significant enough to reduce the contact area and increase the average and peak contact pressures in the medial compartment of the knee. The main findings of this study are summarized as follows: (1) medial meniscal extrusion caused a significant reduction in the tibiofemoral contact area at 30°, 60°, and 90° of flexion; (2) the tibiofemoral contact area was significantly reduced starting at 4 mm of extrusion; (3) the greater the extrusion above 4 mm, the greater the impact on the tibiofemoral contact area; (4) there is a biomechanical possibility for extrusion to occur only by injury to the meniscotibial ligaments with intact roots; (5) the maximum extrusion measured for the medial meniscus without root injury was 5.3 mm (SD 1.1); (6) meniscal centralization was effective in reestablishing the tibiofemoral contact area when the extrusion was secondary to meniscotibial ligament detachment.

Diagnosing meniscal extrusion is critical not only for the acute functional disability it imposes on the patient, but also for its direct relationship with osteoarthritis [11, 17, 33]. Several studies have demonstrated the reduction of the contact area and increase in the peak pressure after meniscectomy [2, 20, 27, 32]. Krych et al. observed degenerative changes in the vast majority of meniscal extrusion patients evaluated [21]. Allaire et al. extrapolated these studies, observing the same biomechanical findings with a posterior root tear. According to the authors, this leads to meniscal extrusion and ultimately results in similar consequences as a meniscectomy [1]. This study complements the above literature; it establishes evidence for meniscal extrusion without root damage and observes results similar to the other studies regarding the reduction of the contact area with increasing amounts of meniscal extrusion.

Costa et al. found that meniscal extrusion greater than 3 mm was linked to complex degenerative changes of its structure [8]. Choi et al. compared the results of intraoperative arthroscopic findings with preoperative magnetic resonance imaging for meniscal extrusion and was able to establish a correlation between meniscal root injury, chondral alterations, and extrusion greater than 3 mm [7]. Lerer et al. described osteoarthritis as high as 69% in patients with extrusion greater than 3 mm [25]. There has been no biomechanical evidence, however, of the above findings. The present study analyzed increasing meniscal extrusions and its impact on the tibiofemoral contact area and pressures. The current paper found that the tibiofemoral contact area diminishes as extrusion increases, and that extrusion of 4 mm (or more) caused a statistically significant decrease in contact area when compared to the intact meniscus. This further supports previous retrospective clinical studies and provides biomechanical evidence of the detrimental effect on the joint caused by meniscal extrusion greater than 3 mm. It is noteworthy that in all previous studies, the extrusion was measured by MRI when the knee was not under physiologic load.

Meniscal extrusion has previously been considered a result of root injury, radial tear, previous meniscectomy, saucerization of a discoid meniscus, or occurring after meniscal transplant [2, 7, 18, 22, 34]. Thus, all previous clinical or biomechanical studies have evaluated extrusion most commonly in the setting of a meniscal root injury. Krych et al. retrospectively evaluated 20 patients with isolated meniscal extrusion (without degenerative changes) and found alterations in the meniscotibial ligaments in 65% of patients, and all patients who had 3 mm or more extrusion had changes in these ligaments [22]. These findings brought to light the possibility of extrusion with an isolated injury to the meniscotibial ligaments. This study found that it is possible for the meniscus to extrude without root injury under physiologic load. The present paper could not only biomechanically prove what was already clinically observed by Krych et al. but also note that the maximum extrusion possible by leaving the roots intact and completely releasing the meniscotibial ligaments averaged 5.3 mm (SD 1.1). Thus, meniscal extrusion with intact roots can be clinically significant since it has the potential to exceed 4 mm, which as shown above, represents the cutoff value for statistically significant impact on contact area; however, no association was found between medial meniscal extrusion and average or peak contact pressures.

In this context, this paper highlights the fact that, until recently in the authors' experience, meniscal extrusions have been undiagnosed, untreated, or treated with meniscectomy [4, 5, 9]. Recently, surgical techniques that address meniscal extrusion have evolved, but they have focused on restoring anatomy through reinsertion of the roots [9]. Even with the appropriate use of these techniques, meniscal extrusion posed a challenge and was still visualized on postoperative MRI [3, 10, 15]. From this study, it can be indirectly inferred that intact or repaired meniscal roots may be insufficient to prevent extrusion. Koga et al. described a centralization technique, which aimed to maintain the relationship of the meniscus with the tibiofemoral joint after meniscectomy [19]. It is currently not known whether this technique is appropriate for reducing joint pressure, or if it would prevent long-term joint degeneration [19, 30]. Daney et al. performed a biomechanical study comparing the isolated posterior root repair to a root repair performed concomitantly with a centralization procedure. Despite inferring that the addition of centralization did not have an effect on the final meniscal extrusion, they report at 90° of flexion, the combined procedure resulted in significantly less extrusion [9]. They concluded that centralization can be used in selected cases, especially those with chronic progression. When extrusion involves the meniscotibial ligaments, centralization may be effective. Extrapolating the data, it can be inferred that if the extrusion results from both an injury to the root and meniscotibial ligaments, a combination of root repair and meniscal centralization should be considered.

This study is not without limitations. First, the 1 mm increments used to measure extrusion are vulnerable to variation. To temper this variation, one author made the extrusion measurements three times and an ACL board was used to apply a constant traction force. Further, it is a cadaveric biomechanical study that does not take into account the cyclic loads to which the joint is subjected. While a custom drill guide was used to drill the 10-mm-diameter transverse tunnel at a similar location in each individual test sample, slight angle variations could have affected the pivot point of the construct and hence the load distribution between medial and lateral compartments of the tibial plateau. In addition, the pressure sensors used in the study tend to gradually lose their sensitivity over the course of the test due to wear. This decrease in force sensitivity was supposed to follow a linear trend, as reported in previous studies, so a data analysis code was written to address this. Additionally, the knees were not tested at all angles of movement. Meniscal extrusion was measured from within the joint after a medial femoral condyle osteotomy which is different than MRI based measurements. This can be a confounding influence on the interpretation of the results.

The diagnosis of meniscal extrusion may not necessarily involve meniscal root injury. Paletta et al. established that centralization was effective in significantly reducing extrusion both biomechanically and with short term clinical outcomes [31]. This study built on this and found that the contact area returned to levels not statistically significantly different than the intact state after centralization, and that meniscal extrusion greater than 4 mm has a biomechanical impact on tibiofemoral compartment contact area. This information can be of clinical relevance to provide a biomechanical rationale for meniscal centralization and to help indicate provide a quantitative guideline to help determine when meniscal extrusion becomes biomechanically significant.

Conclusion

In this in vitro model, medial meniscus extrusion greater than 4 mm reduced medial compartment contact area. Meniscal extrusion did not significantly increase contact pressure in the medial compartment. Additionally, meniscal centralization was effective in restoring the medial tibiofemoral contact area to intact state when the meniscal extrusion was secondary to meniscotibial ligament injury.

Author contributions PD: experimental testing of the cadavers, writing of paper and editing. AEJ: responsible for dissection and potting of the knee cadavers, participated in the experimental testing of the cadavers, responsible for statistical data analysis, editing and writing of paper. JVN: experimental testing of the cadavers, writing of paper and editing. CCK: experimental testing of the cadavers, writing of paper and editing. DEK: responsible for dissection and potting of the knee cadavers, participated in the pilot study of the experiment, participated in the experimental testing of the cadavers. DCA: experimental testing of the cadavers, writing of paper and editing. EO: responsible for the study design of the experiment, Tekscan calibrations and data collection during the experimental testing. LMT: responsible for dissection and potting of the knee cadavers, participated in the pilot study of the experiment, participated in the experimental testing of the cadavers. LNM: responsible for Tekscan data collection during the experimental testing and statistical data analysis. MPC: statistical analysis. MC: responsible for the study design of the experiment and supervised the experimental design. KJC: responsible for the study design of the experiment, managed the pilot study of the experiment, supervised the experimental design and testing of the cadavers.

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Compliance with ethical standards

Conflict of interest Arthrex donated human cadaver knee specimens and medical devices/supplies. P.D., C.C.K. and M.C are a consultant from Arthrex.

Ethical approval All procedures performed in this study involving human participants were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standard.

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