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# Biomechanical Consequences of a Nonanatomic Posterior Medial Meniscal Root Repair

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**Background:** Posterior medial meniscal root tears have been reported to extrude with the meniscus becoming adhered posteromedially along the posterior capsule. While anatomic repair has been reported to restore tibiofemoral contact mechanics, it is unknown whether nonanatomic positioning of a meniscal root repair to a posteromedial location would restore the loading profile of the knee joint.

**Purpose/Hypothesis:** The purpose of this study was to compare the tibiofemoral contact mechanics of a nonanatomic posterior medial meniscal tear with that of the intact knee or anatomic repair. It was hypothesized that a nonanatomic root repair would not restore the tibiofemoral contact pressures and areas to that of the intact or anatomic repair state.

**Study Design:** Controlled laboratory study.

**Methods:** Tibiofemoral contact mechanics were recorded in 6 male human cadaveric knee specimens (average age, 45.8 years) using pressure sensors. Each knee underwent 5 testing conditions for the posterior medial meniscal root: (1) intact knee; (2) root tear; (3) anatomic transtibial pull-out repair; (4) nonanatomic transtibial pull-out repair, placed 5 mm posteromedially along the edge of the articular cartilage; and (5) root tear concomitant with an ACL tear. Knees were loaded with a 1000-N axial compressive force at 4 flexion angles (0°, 30°, 60°, 90°), and contact area, mean contact pressure, and peak contact pressure were calculated.

**Results:** Contact area was significantly lower after nonanatomic repair than for the intact knee at all flexion angles (mean = 44% reduction) and significantly higher for anatomic versus nonanatomic repair at all flexion angles (mean = 27% increase). At 0° and 90°, and when averaged across flexion angles, the nonanatomic repair significantly increased mean contact pressures in comparison to the intact knee or anatomic repair. When averaged across flexion angles, the peak contact pressures after nonanatomic repair were significantly higher than the intact knee but not the anatomic repair. In contrast, when averaged across all flexion angles, the anatomic repair resulted in a 17% reduction in contact area and corresponding increases in mean and peak contact pressures of 13% and 26%, respectively, compared with the intact knee.

**Conclusion:** For most testing conditions, the nonanatomic repair did not restore the contact area or mean contact pressures to that of the intact knee or anatomic repair. However, the anatomic repair produced near-intact contact area and resulted in relatively minimal increases in mean and peak contact pressures compared with the intact knee.

**Clinical Relevance:** Results emphasize the importance of ensuring an anatomic posterior medial meniscal root repair by releasing the extruded menisci from adhesions and the posteromedial capsule. Similar caution toward preventing displacement of the meniscal root repair construct should be emphasized.

**Keywords:** meniscal tear; root tear; meniscal root repair; anatomic

The meniscal roots are essential anchoring points for normal meniscal function and distribution of axial compressive loads across the tibial plateau.[1,8,12,16,17,22] Biomechanical studies have reported that the loading profile in the knee joint is compromised after a meniscal root tear due to extrusion of the meniscus and resultant increased tibiofemoral contact pressures.[1,8,12,16,17,22] In fact, Allaire et al[1] reported that a posterior root tear of the medial meniscus was indistinguishable from a total medial meniscectomy in terms of peak tibiofemoral contact pressures.

An anatomic transtibial pull-out repair has demonstrated the ability to restore the tibiofemoral contact areas and pressures to the intact knee for most testing

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conditions.[1,12,16,17,22] However, numerous issues may compromise anatomic placement of the posterior medial meniscal root attachment. Determining the anatomic position of the posterior meniscal roots can oftentimes be technically difficult,[2,23] especially if the posterior medial meniscal root tear has retracted, extruded posteromedially, and scarred into the capsule, as has been reported to occur clinically.[2,14,15] If the repair were performed in situ at this location, a nonanatomic repair would result even if the surgeon had the intention of performing an anatomic repair.

Biomechanical studies in porcine models have reported that repaired posterior medial meniscal roots resulted in significant levels of displacement in response to cyclic loading, which simulates the repetitive loading experienced in the postoperative period with knee motion and partial weightbearing.[3,6,24] The displacement of the transtibial pull-out repair has been mostly attributed to suture cutout through the meniscus due to weak suture fixation techniques,[3,5] with lesser levels of displacement also seen from suture elongation during repetitive loading[3,7,19] and displacement of the fixation of the repair at the distal tibial cortex.[3] Theoretically, the resultant displacement of the repair construct would result in an analogous situation as a nonanatomic repair construct with the root extruding posteromedially based on the curvature of the tibial plateau at the root attachment, the neighboring posterior cruciate ligament (PCL), and the geometry of the tibial plateau and femoral condyles.[10]

Stärke et al[23] tested a nonanatomic anterior root repair of the medial meniscus located 3 mm medial to the native attachment in a porcine model and found significantly decreased meniscal tensile force. However, given the investigation was performed at the anterior medial meniscal root, as well as the differing stiffness, size, and insertions of the porcine menisci in comparison to humans,[18,20] it is unknown whether this model is applicable to the posterior medial meniscal root in humans. Sekaran et al[21] also reported that a human medial meniscal transplant placed 5 mm medial to the native posterior root attachment resulted in increased tibiofemoral maximum contact pressures in cadaveric knees. However, the medial location of the transplantation does not seem to be as clinically relevant and physiologic for a meniscal root tear and repair, because it may intrude inside the intra-articular space.[10]

The purpose of this study was to compare tibiofemoral contact mechanics in response to the following conditions: (1) native intact knee, (2) posterior root tear of the medial meniscus, (3) anatomic transtibial pull-out repair of the posterior root of the medial meniscus, (4) nonanatomic transtibial pull-out repair of the posterior root of the medial meniscus placed 5 mm posteromedially, and (5) posterior medial root tear concomitant with an anterior cruciate ligament (ACL) tear. We hypothesized a nonanatomic root repair reattached 5 mm posteromedial to the native attachment would not restore the tibiofemoral contact pressures and areas to the intact knee. In addition, it was hypothesized that the nonanatomic root repair would result in significantly higher tibiofemoral contact pressures and lower contact areas than anatomic repair.

## MATERIALS AND METHODS

### Specimen Preparation

Six fresh-frozen, male, human cadaveric knee specimens with an average age of 45.8 years (range, 34-60 years) were used. Knees with evidence of meniscal damage, ligamentous damage to the cruciate or collateral ligaments, or cartilage degeneration were excluded from this study. Knees were dissected free of skin, soft tissue attachments, muscle, tendon, and the patella. The femur, tibia, fibula, and collateral and cruciate ligaments were left intact. The femur, tibia, and fibula were cut 20 cm distal to the joint line. The distal tibia and fibula were then potted in a cylindrical mold using poly(methyl methacrylate) (PMMA; Fricke Dental International) with the tibial plateau oriented parallel to the base. The bone cement encased the tibia and fibula up to a point 4 cm distal to the tibial tuberosity.

With use of a custom-made drill guide, 2 parallel tunnels separated by 8 cm between their center axes were then drilled through the femur. These tunnels were used to pass rods that secured the knees in a custom fixture and allowed for the flexion angle to be adjusted during biomechanical testing.[12,17] The distal tunnel was reamed with a 10-mm reamer, parallel to the tibial plateau, which avoided the collateral ligaments. This tunnel served as the axis of rotation for the femur and the location of load application during biomechanical testing. The proximal tunnel was reamed with a 7-mm reamer and was used to select different flexion angles in the fixture throughout testing.

The knee pressure sensors were then inserted beneath the medial and lateral menisci and along the medial and lateral tibial plateaus. Incisions were made through the anterior and posterior meniscotibial portions of the capsule, and sutures were inserted into the tabs of the sensors to facilitate sliding of the pressure sensor under the menisci and into the knee joint. Unlike previous biomechanical studies,[12,13,17] an osteotomy was not required to pass the calibrated knee pressure sensors (Model 4000;

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Tekscan). Each sensor was secured in its compartment with 2 double-loaded suture anchors inserted in the posterior aspect of the tibia and 1 double-loaded suture anchor in the anterior aspect of the tibia to prevent any movement of the sensor during testing. A new sensor was used for each specimen and was calibrated according to the manufacturer's guidelines with a sensitivity setting of 21. Previous studies have reported a steady, linear, negative decline of the pressure sensor output over the course of testing due to exposure of the sensors to liquids when testing in a cadaveric environment.[12,17] Therefore, the sensors were submerged in saline solution for 48 hours before testing, which has been reported to minimize these effects, and the sensors were kept moist through testing.[9,12]

Each knee underwent 5 testing conditions for the posterior medial meniscal root: (1) intact knee; (2) root tear; (3) anatomic transtibial pull-out repair; (4) nonanatomic transtibial pull-out repair, placed 5 mm posteromedially along the edge of the articular cartilage; and (5) root tear concomitant with an ACL tear. For all testing states, the posterior root attachment site of the medial meniscus was directly visualized from the posterior aspect of the knee. The posterior root tear (condition 2) of the medial meniscus was created by completely transecting the root directly at the posterior tibial insertion of the meniscus. This transection completely spanned the central root attachment and the supplemental shiny white fibers that have been described by previous studies.[4,10] The anatomic repair (condition 3) was then performed by visualizing the root attachment at the location of the native root insertion. Two No. 2 nonabsorbable sutures were passed through the edge of the avulsed posterior root using the 2-simple-sutures technique,[2] and a guide pin was used to drill from the middle of the root attachment on the medial tibial plateau to a point 1 cm medial to the midpoint of the tibial tubercle. The sutures were then passed through the eyelet of the guide pin and pulled through the transtibial tunnel. The sutures were then secured and tied over a surgical button on the anteromedial tibia. The nonanatomic transtibial pull-out repair (condition 4) was placed 5 mm posteromedial to the native root attachment along the edge of the cartilage (Figure 1), as measured and marked at the time of meniscal root detachment (condition 2) with digital calipers with a manufacturer-reported accuracy of $\pm$0.025 mm (Swiss Precision Instruments). The nonanatomic repair then followed the same procedure as the anatomic repair for passing the sutures and securing the sutures over a surgical button. Last, the sutures from the nonanatomic meniscal repair were cut, which restored the root tear status of the posterior medial meniscal root, and the ACL was completely transected at its midpoint (condition 5). Throughout testing and preparation, the knees were sprayed with physiologic 0.9% sodium chloride saline to prevent soft tissue desiccation, keep the pressure sensors in a moist environment, and minimize shear forces on the pressure sensors.

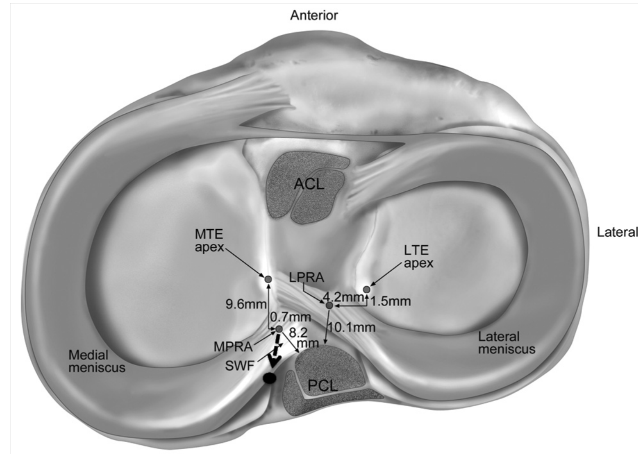


**Figure 1.** Illustration of the native anatomy of the posterior meniscal roots. The black arrow and dot demonstrate the location of the nonanatomic repair 5 mm posteromedial to the native posterior medial meniscal root attachment along the edge of the articular cartilage. ACL, anterior cruciate ligament; LPRA, lateral meniscus posterior root attachment; LTE, lateral tibial eminence; MPRA, medial meniscus posterior root attachment; MTE, medial tibial eminence, PCL, posterior cruciate ligament; SWF, shiny white fibers of posterior horn of medial meniscus. Reproduced with permission from Johannsen AM, Civitarese DM, Padalecki JR, Goldsmith MT, Wijdicks CA, LaPrade RF. Qualitative and quantitative anatomic analysis of the posterior root attachments of the medial and lateral menisci. *Am J Sports Med*. 2012;40(10):2342-2347.

## Biomechanical Testing

The potted tibia was secured in a custom pivot table[12,17] that was rigidly fixed to the base of a dynamic tensile testing machine (ElecroPuls E10000; Instron). This pivot table allowed for translation parallel to the base and manual control of varus-valgus rotation. Controlling varus-valgus alignment ensured equal distribution of load to the medial and lateral compartments during testing and consistent load distribution between test conditions. Equal medial/lateral distribution of the load was confirmed using live feedback from the pressure mapping sensors and ensured that observed differences between conditions were a result of the condition change and not changes in load distribution between compartments. The femur was then secured to a custom fixture, which was rigidly mounted to the actuator, by passing the 10-mm rod through the femoral condyles. The 10-mm rod acted as the load-bearing pivot axis. The 7-mm rod was passed through the distal femur to select the flexion angle (Figure 2).

All specimens were tested by compressing the joint with a 1000-N axial load at 4 different flexion angles (0°, 30°, 60°, 90°). The flexion angles were randomly chosen for testing of the intact condition for each knee, and then the same flexion angle order was used for subsequent conditions on the same knee. The pressure mapping software generated a contact pressure map for each condition based on pressures recorded in each cell of a 26 $\times$ 22–cell grid (Figure 3). Contact pressure was recorded by the sensor, and contact area, mean contact pressure, and peak contact pressure were calculated. Throughout testing, a steady,

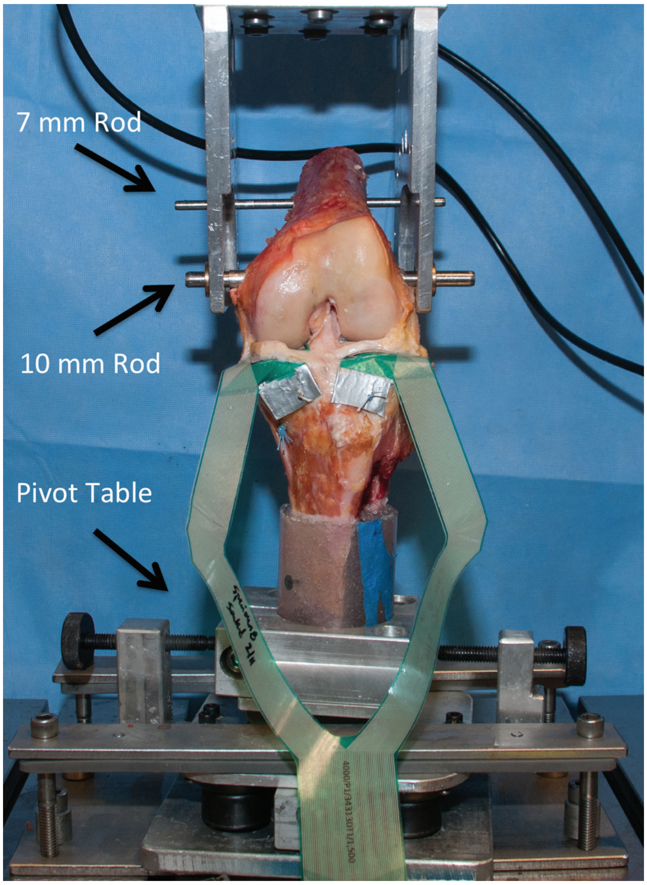


**Figure 2.** The biomechanical testing setup for a left knee. The potted tibia was secured in a custom pivot table that allowed for manual adjustment of varus-valgus alignment and was rigidly fixed to the base of a dynamic tensile testing machine. The femur was then secured within a custom fixture, which was rigidly attached to the actuator. A 10-mm rod passed through the femoral condyles and acted as the loading-bearing pivot axis, while a 7-mm rod was passed through the distal femur to select the flexion angle.

linear decrease in the pressure sensor amplitudes (2.2% mean decrease in total load for each of the 20 testing scenarios) was observed over the course of the testing for each specimen. Although we proactively attempted to minimize this decrease in sensor load output by saturating the pressure sensors in 0.9% sodium chloride saline for 48 hours before testing, as recommended by Jansson et al,[9] it was still necessary to adjust data upward slightly and progressively to mitigate this linear decline. This load output phenomenon in saturated pressure sensors, as well as the same method for counteracting the effect through data adjustment, has been previously described in studies with analogous testing conditions.[9,12,17]

## Statistical Analysis

One-factor, repeated-measures, linear mixed-effect models (LMMs) were built for each flexion angle to determine the effect of meniscus condition on the 3 measurement variables (contact area, mean contact pressure, and peak contact pressure). In addition, for the sake of summarizing similar results occurring at each of several flexion angles, measurements were averaged across all flexion angles, and this new set of data, including 6 subjects with 5 meniscus conditions each, was analyzed in the same way. Estimates of meniscus condition effects are presented along with 95% simultaneous confidence intervals. Two preplanned comparisons were conducted within each model to address the primary hypothesis of this study: (1) intact meniscus versus nonanatomic repair and (2) anatomic repair versus nonanatomic repair. Other comparisons were not formalized in this study to preserve statistical power for the primary comparisons and because they have been addressed by previous studies.[1,16,17] The Holm method was used to control the family-wise error rate of the 2 condition comparisons to $\alpha = 0.05$. The statistical software package R (R Development Core Team) was used for all data handling, analysis, and plots.

Sample size was determined with a midpoint power analysis, which was based on the primary comparisons of intact versus nonanatomic repair and anatomic repair versus nonanatomic repair. As a simplification of the planned analysis, the power calculation was made presuming a paired $t$ test and using a significance level of .025 (accounting for the 2 primary comparisons). The analysis indicated that a minimum of 6 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.

# RESULTS

## Contact Area

At each flexion angle, a nonanatomic repair resulted in significantly lower contact area than the intact medial meniscus ($P < .001$) (Table 1). When averaged across all flexion angles, the significant reduction effect on contact area of nonanatomic repair was 44% (95% CI, 35%-53%) compared with intact ($P < .001$). The avulsed meniscal root and avulsed meniscal root with sectioned ACL groups resulted in 57% and 61% reductions in intact contact area, respectively, while the anatomic repair achieved an average of 83% of the contact area of the intact meniscus (Table 1).

Contact area was also significantly lower among nonanatomic repairs than anatomic repairs at all flexion angles ($P \leq .041$) (Table 2). When averaged across all flexion angles (Figure 4), anatomic repair produced significantly higher contact area than nonanatomic repair ($P < .001$), corresponding to an increased contact area of 27% (95% CI, 17%-36%) relative to the intact mean contact area (Table 2).

## Mean Contact Pressure

At 0° and 90° of flexion, nonanatomic repair resulted in significantly higher average contact pressure than the intact meniscus ($P \leq .005$) (Table 3). When averaged across all

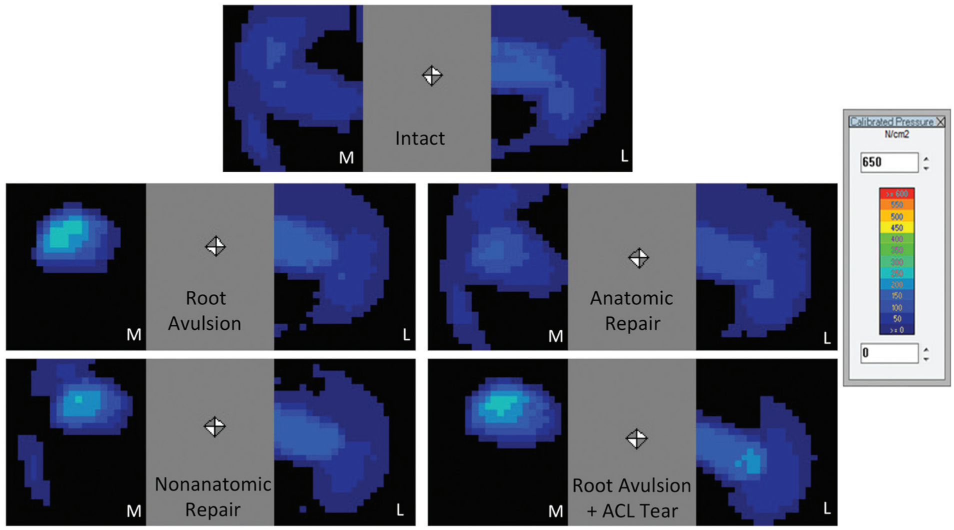


**Figure 3.** Representative pressure map of the 5 testing states for a left knee. These pressure maps show the distribution of contact pressure and area between the medial (M) and lateral (L) compartment at 30° of knee flexion. The diamond-shaped icon visibly centered between the 2 compartments demonstrates the even distribution of pressure between the 2 compartments via live feedback from the pressure mapping sensors. ACL, anterior cruciate ligament.

TABLE 1
Percentage Difference in Medial Compartment Contact Area Between Intact and Subsequent Conditions[a]

| | | Root Tear | | | Anatomic Repair | | | Nonanatomic Repair | | | Sectioned ACL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flexion Angle | Intact, mm² | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB |
| 0° | 484 | −60 | −45 | −29 | −33 | −17 | −2 | −50 | −34[b] | −19 | −63 | −48 | −32 |
| 30° | 531 | −69 | −57 | −46 | −30 | −18 | −7 | −56 | −45[b] | −33 | −81 | −69 | −57 |
| 60° | 439 | −71 | −61 | −51 | −25 | −15 | −5 | −56 | −46[b] | −36 | −76 | −66 | −56 |
| 90° | 429 | −74 | −64 | −53 | −29 | −19 | −8 | −62 | −52[b] | −41 | −76 | −66 | −55 |
| Average | 471 | −65 | −57 | −48 | −26 | −17 | −8 | −53 | −44[b] | −35 | −70 | −61 | −53 |

[a]*Intact* indicates the mean contact area of the intact menisci. A negative percentage difference (%Δ) indicates a smaller contact area than the intact meniscus. ACL, anterior cruciate ligament; LB, lower bound of 95% CI; UB, upper bound of 95% CI.
[b]Statistically significant (adjusted $P < .05$) intact versus nonanatomic repair comparison.

TABLE 2
Percentage Difference, Relative to the Intact Condition, in Medial Compartment Contact Area, Mean Contact Pressure, and Peak Contact Pressure Between Anatomic and Nonanatomic Repairs[a]

| | Contact Area, mm² | | | Mean Contact Pressure, N/mm² | | | Peak Contact Pressure, N/mm² | | |
|---|---|---|---|---|---|---|---|---|---|
| Flexion Angle | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB |
| 0° | +1 | +17[b] | +34 | −84 | −41[b] | +1 | −46 | −12 | +22 |
| 30° | +14 | +27[b] | +39 | −137 | −51 | +34 | −107 | −38 | +31 |
| 60° | +21 | +31[b] | +42 | −109 | −50 | +8 | −85 | −30 | +25 |
| 90° | +22 | +33[b] | +44 | −132 | −70[b] | −9 | −97 | −47[b] | +3 |
| Average | +17 | +27[b] | +36 | −111 | −54[b] | +4 | −76 | −33 | +11 |

[a]A positive (negative) percentage difference (%Δ) indicates higher (lower) measurement value in the anatomically repaired meniscus than the nonanatomically repaired meniscus. LB, lower bound of 95% CI; UB, upper bound of 95% CI.
[b]Statistically significant (Holm adjusted $P < .05$) anatomic versus nonanatomic repair comparison.

flexion angles (Figure 5), the significantly increased effect on contact pressure of nonanatomic repair was 67% (95% CI, 13%-121%) compared with intact ($P$ = .019) (Table 3).

When averaged across all flexion angles, the root tear, anatomic repair, and root tear with sectioned ACL states resulted in an increase in mean contact pressures of

TABLE 3
Percentage Difference in Medial Compartment Mean Contact Pressure Between Intact and Subsequent Conditions[a]

| | | Root Tear | | | Anatomic Repair | | | Nonanatomic Repair | | | Sectioned ACL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flexion Angle | Intact, $N/mm^2$ | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB |
| 0° | 1.02 | +39 | +79 | +120 | −15 | +26 | +66 | +27 | +67[b] | +108 | +61 | +101 | +142 |
| 30° | 0.92 | +30 | +111 | +192 | −69 | +12 | +93 | −18 | +63 | +144 | +169 | +254 | +340 |
| 60° | 1.16 | +51 | +107 | +162 | −51 | +4 | +60 | −1 | +55 | +110 | +95 | +150 | +205 |
| 90° | 1.15 | +68 | +126 | +184 | −45 | +13 | +71 | +26 | +84[b] | +141 | +117 | +174 | +232 |
| Average | 1.06 | +52 | +106 | +161 | −41 | +13 | +68 | +13 | +67[b] | +121 | +107 | +161 | +215 |

[a]*Intact* indicates the mean contact pressure of the intact menisci. A positive (negative) percentage difference (%Δ) indicates higher (lower) mean contact pressure than the intact meniscus. ACL, anterior cruciate ligament; LB, lower bound of 95% CI; UB, upper bound of 95% CI.
[b]Statistically significant (adjusted $P < .05$) intact versus nonanatomic repair comparison.

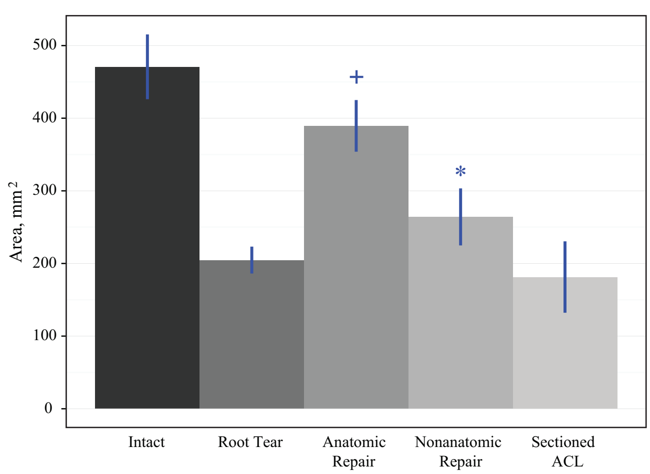


**Figure 4.** Meniscus condition effect on contact area in the medial compartment when averaged across all flexion angles. The error bars represent ±1 SD. *$P < .05$ compared with the intact condition. $^+P < .05$ compared with the nonanatomic repair. ACL, anterior cruciate ligament.

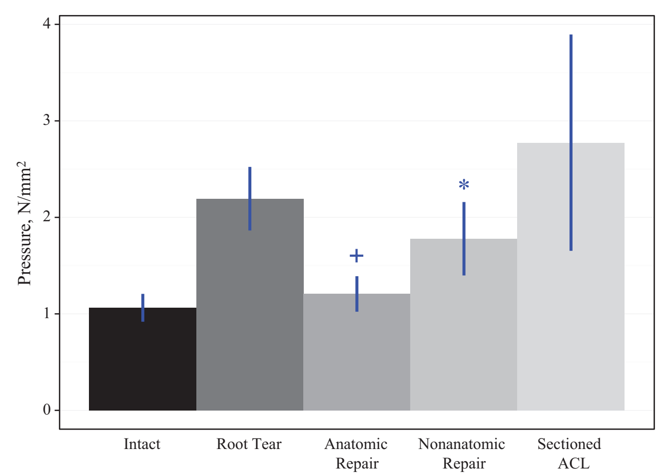


**Figure 5.** Meniscus condition effect on mean contact pressure in the medial compartment when averaged across all flexion angles. The error bars represent ±1 SD. *$P < .05$ compared with the intact condition. $^+P < .05$ compared with the nonanatomic repair. ACL, anterior cruciate ligament.

106%, 13%, and 161% in comparison to the intact knee, respectively.

Mean contact pressure was also significantly higher among nonanatomic repairs than anatomic repairs at 0° and 90° of flexion ($P \leq .032$) (Table 2). When averaged across all flexion angles, anatomic repair exhibited significantly lower mean contact pressure than nonanatomic repair ($P = .038$) with a difference of –54% relative to the intact mean contact pressure (95% CI, –111% to +4%) (Table 2).

## Peak Contact Pressure

At 0°, 30°, and 90° of flexion, nonanatomic repair resulted in significantly higher peak contact pressure than the intact meniscus ($P \leq .043$) (Table 4). When averaged across all flexion angles (Figure 6), the significantly increased effect on peak contact pressure of nonanatomic repair was 59% (95% CI, 18%-100%) compared with intact ($P = .005$) (Table 4). When averaged across all flexion angles, the root tear, anatomic repair, and root tear with sectioned ACL resulted in increased peak contact pressures of 52%, 26%, and 106%, respectively, relative to the intact knee mean peak contact pressure.

Peak contact pressure was also significantly higher among nonanatomic repairs than anatomic repairs at 90° of flexion ($P = .036$), with an increase of 47% (95% CI, –3% to 97%) relative to the intact meniscus (Table 2). When averaged across all flexion angles, anatomic repair exhibited lower peak contact pressure than nonanatomic repair, with a difference of –33% relative to the intact peak contact pressure (95% CI, –76% to +11%); however, this difference was not significant ($P = .096$) (Table 2).

## DISCUSSION

In this study, we verified our hypothesis that a nonanatomic root repair reattached 5 mm posteromedial to the native attachment did not restore the tibiofemoral mean

TABLE 4
Percentage Difference in Medial Compartment Peak Contact Pressure Between Intact and Subsequent Conditions[a]

| | | Root Tear | | | Anatomic Repair | | | Nonanatomic Repair | | | Sectioned ACL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flexion Angle | Intact, N/mm$^2$ | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB | LB | %Δ | UB |
| 0° | 2.86 | −2 | +31 | +63 | −5 | +27 | +59 | +7 | +39[b] | +71 | +14 | +47 | +79 |
| 30° | 2.56 | −1 | +64 | +129 | −32 | +33 | +98 | +6 | +71[b] | +136 | +127 | +196 | +264 |
| 60° | 3.61 | +0 | +52 | +104 | −27 | +25 | +77 | +3 | +55 | +107 | +49 | +101 | +153 |
| 90° | 3.60 | +13 | +60 | +106 | −24 | +23 | +70 | +23 | +70[b] | +117 | +63 | +110 | +156 |
| Average | 3.16 | +11 | +52 | +93 | −14 | +26 | +67 | +18 | +59[b] | +100 | +65 | +106 | +147 |

[a]*Intact* indicates the average peak contact pressure of the intact menisci. A positive (negative) percentage difference (%Δ) indicates larger (smaller) peak contact pressures than the intact meniscus. ACL, anterior cruciate ligament; LB, lower bound of 95% CI; UB, upper bound of 95% CI.
[b]Statistically significant (adjusted $P < .05$) intact versus nonanatomic repair comparison.

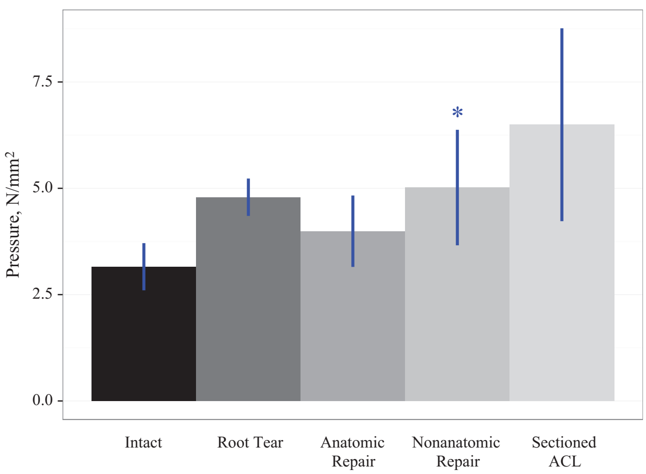


**Figure 6.** Meniscus condition effect on peak contact pressure in the medial compartment when averaged across all flexion angles. The error bars represent ±1 SD. *$P < .05$ compared with the intact condition. ACL, anterior cruciate ligament.

or peak contact pressures and contact areas compared with the intact knee when averaged across all flexion angles. With regard to our second hypothesis, anatomic repair resulted in significantly higher contact area at all angles and lower mean contact pressures when averaged across all flexion angles, as well as at 0° and 90°, of knee flexion in comparison to the nonanatomic repair. However, peak contact pressures were not significantly different between the anatomic repair and nonanatomic repair when averaged across all flexion angles or at 0°, 30°, or 60° of knee flexion, possibly due to higher observed variation among contact pressure measurements. On the basis of these results, we believe that the importance of performing an anatomic medial meniscal posterior root repair is elucidated.[1,16,17] This has important clinical implications because a nonanatomic repair, especially if the posterior medial meniscal root tear is extruded and scarred into the capsule posteromedially as commonly found clinically,[2] seems to be only slightly better than the effects of a complete posterior medial meniscal root tear.[1,16,17] Therefore, we believe that releasing the extruded meniscal root from its scarred-in position to the capsule and reducing it to an anatomic position should be the first step of a posterior medial meniscal root repair. In addition, posteromedial extrusion of the meniscus that may occur due to displacement of the transtibial pull-out root repair with cyclic loading may also result in a nonanatomic meniscal root repair construct, and therefore a careful progression of postoperative rehabilitation is warranted.[3,5,6,11]

The most important clinical implication of this study was that we found that nonanatomic repair resulted in significantly altered tibiofemoral contact mechanics in comparison to the intact knee and anatomic repair for most testing states (excluding peak contact pressure in comparison to the anatomic repair). These comprised altered contact mechanics included lower contact areas after nonanatomic repair than either the intact knee or anatomic repair at all angles. This is very concerning because it would seem to indicate that a nonanatomic posteromedial meniscal repair was analogous to conditions noted after a complete meniscal root tear, which has been reported to result in significantly lower contact areas than the intact knee or anatomic repair.[1,16,17] With regard to mean contact pressures, nonanatomic repair resulted in significantly higher mean pressures than the intact knee or anatomic repair when averaged across all flexion angles in our study. These results once again are analogous to the effects seen with a posterior medial meniscal root tear.[17] Last, we reported that the nonanatomic repair resulted in significantly higher peak contact pressures in comparison to the intact knee when averaged across all angles; however, this was not seen for the nonanatomic repair versus anatomic repair comparisons, in which only 90° was significantly different. This contrasts to the findings of Allaire et al,[1] in which a root tear resulted in significantly higher peak contact pressures than the anatomic repair or intact knee when averaged across all flexion angles (although not at 90°). Therefore, based on the 3 testing parameters in this study (tibiofemoral contact area and mean and peak contact pressures), we believe that the nonanatomic repair was very similar to a complete root tear in terms of the subsequent altered tibiofemoral contact mechanics.

The posteromedial location of where we performed the nonanatomic medial meniscal root repair in this study was chosen based on 2 main reasons. First, after a medial meniscal posterior root tear, the meniscus oftentimes extrudes and scars into the posterior capsule,[2,14,15] and the posteromedial location along the articular cartilage is believed to be the physiologic location of the extrusion due to the bony anatomy of the tibial plateau, neighboring PCL, and the geometry of the medial tibial plateau and femoral condyles.[10] If this occurs, our results indicate that it is important not to secure the root at this nonanatomic location because the root has to be released from adhesions and pulled laterally before a repair. In addition, as shown by 2 recent studies, the displacement of the posterior medial meniscal root repair in a porcine model varied between 2.2 and 3.3 mm after transtibial pull-out repair under loads representative of postoperative rehabilitation,[3,6] with the majority of displacement in the transtibial pull-out repair due to suture cutout of the meniscus.[3] Thus, this displacement could also lead to a poorly functioning meniscal root repair with an analogous situation to a nonanatomic repair that was originally positioned nonanatomically.

We believe that our study builds on the previous 2 studies that investigated the concept of a nonanatomic meniscal root placement after repair or transplantation.[21,23] Sekaran et al[21] reported that nonanatomic placement of a meniscal transplant 5 mm medial to the anatomic posterior medial meniscal attachment significantly increased the normalized maximum pressures over all flexion angles and shifted the centroid of contract area posteriorly; however, normalized contact area and normalized mean pressure were not different.[21] At a nonanatomic position 5 mm posterior to the anatomic placement of the graft, only the shifting of the centroid of contract area posteriorly was significantly different.[21] We believe that the nonanatomic location of the meniscal root repair in our study is more physiologic than the previous study because the medial positioning would likely be medial to the medial tibial eminence and in the articular space between the femoral condyle and medial tibial plateau, while the directly posterior position would potentially intrude on the anterior aspect of the PCL tibial attachment.[10] Stärke et al[23] investigated the effect of a nonanatomic placement of the anterior medial meniscal root in a porcine model. They reported that nonanatomic placement of the root by 3 mm medially or laterally significantly affected the menisci's ability to convert tibiofemoral loads into circumferential tension, thereby compromising meniscal function.[23] We believe that the results of Stärke et al[23] are similar to our findings for the effect of tibiofemoral contact mechanics, even though porcine meniscal tissue is quite different from human tissue.[18,20]

As a time zero biomechanical investigation, this study has some inherent limitations. Knees were loaded with a uniaxial compressive force, which is a simplification of the complex loading conditions experienced by the joint during functional activities. However, this was a consistent and reproducible loading scheme, which allowed for reliable comparison between conditions and has been used by numerous similar studies,[1,12,17] allowing for a more direct comparison to the literature. In addition, the knee dynamically moves through many flexion angles during functional activities. We tested 4 different flexion angles to determine the loading behavior throughout a typical range of motion. The 1000-N static load was chosen based on previous studies that indicated that this load allowed the pressure mapping sensors to withstand numerous testing conditions.[12,17] This was a time zero study in cadavers and did not account for the biological effects of healing. However, unlike previous studies,[12,13,17] an osteotomy was not required to insert the pressure sensors. As a result, any potential shifting of the femur during testing should have been minimized in this present study. Although anterior and posterior meniscotibial capsular incisions were required for pressure sensor insertion and may have had an effect on the overall joint contact loads, no obvious effect on knee stability was observed. Furthermore, our technique was similar to previous sensor cell measuring experiments.

## CONCLUSION

Nonanatomic transtibial pull-out repairs of posterior medial meniscal root tears significantly decreased tibiofemoral contact area in comparison to the intact knee or anatomic root repair. When averaged across flexion angles, and specifically at 0° and 90°, nonanatomic repair significantly increased mean contact pressures in comparison to the intact knee or anatomic repair. With regard to peak contact pressures, nonanatomic repair resulted in significantly higher pressures than the intact knee when averaged across all flexion angles, although this was not seen in comparison to anatomic repairs. The results of this study suggest that a nonanatomic repair does not restore the tibiofemoral loading profile of the intact knee, and increased emphasis should be placed clinically on an anatomic repair of the posterior medial meniscal root. Therefore, we believe that releasing an extruded meniscal root from its scarred-in position to the capsule and reducing it to an anatomic position should be the first step of a posterior medial meniscal root repair to ensure a correct anatomic meniscal root repair.

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