A Biomechanical Comparison of All-Inside Versus Transtibial Meniscus Root Repair Techniques

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Background: Meniscus root tears are associated with chondral injury, early degenerative change, and a high conversion rate to total knee arthroplasty. It is well-established that meniscus root tears lead to decreased femorotibial contact area, increased peak contact pressures, and increased stress on the articular cartilage.

Purpose: To evaluate the biomechanical characteristics of the all-inside meniscus root repair procedure and compare it with the previously described transtibial technique.

Study Design: Controlled laboratory study.

Methods: Nine paired cadaveric knees were prepared by removing skin, subcutaneous tissues, quadriceps muscles, patella, and patellar tendon, while leaving the capsule in place. Pressure-mapping sensors were inserted, and specimens underwent compressive loading to obtain peak pressures, mean pressures, and femorotibial contact area in the medial and lateral compartments. Tests were performed as static compression tests with the knee locked at 0° of flexion. Compression testing was performed in 3 states: meniscus intact, meniscus root cut, and after meniscus root repair with an all-inside repair technique. Additionally, testing was completed on 9 pairs of cadaveric knees to compare stiffness and maximal load to failure between the all-inside and transtibial meniscus root repair techniques.

Results: In the medial compartment, there were significant increases in median peak pressures and median mean pressures in the root cut state as compared with the intact state (+636 kPA [95% CI, 246 to 1026] and +190 kPA [95% CI, 49 to 330], respectively). All-inside meniscus root repair restored median peak pressures and median mean pressures to approach those of the intact meniscus (+311 kPA [95% CI, –79 to 701] and +137 kPA [95% CI, –3 to 277]). In the lateral compartment, there were also significant increases in median peak pressures and median mean pressures in the root cut state as compared with the intact state (+718 kPA [95% CI, 246 to 1191] and +203 kPA [95% CI, 51 to 355]). All-inside meniscus root repair restored median peak pressures and median mean pressures such that they were not significantly different from the intact state (+322 kPA [95% CI, –150 to 795] and +18 kPA [95% CI, –134 to 171]). There was no difference between repair techniques regarding load to failure (P = .896). Transtibial meniscus root repair had significantly more stiffness (mean ± SD, 24.8 ± 9.3 N/mm) as compared with the all-inside meniscus root repair technique (13.6 ± 3.8 N/mm, P = .015).

Conclusion: All-inside meniscus root repair reduced median peak and mean pressures to those of the native intact meniscus with the knee in extension in the cadaveric model. When compared with a transtibial meniscus root repair technique, all-inside repair demonstrated decreased stiffness and a similar load to failure.

Clinical Relevance: All-inside meniscus root repair restored mean and peak femorotibial pressures to those of the intact meniscus. Additionally, it offers a technically easier technique for management of meniscus root tears.

Keywords: meniscus root tear; meniscus; meniscal repair; all-inside repair; biomechanics

The menisci serve an important role transmitting and absorbing compressive loads through the knee. Biomechanical studies have shown that forces in the knee are absorbed by the meniscus and articular cartilage. The proportion of these forces that are transmitted through the meniscus can reach up to 99% during compressive loading.[33,34] The meniscus root attachments to the posterior tibial plateau are paramount in preventing meniscal extrusion and maintaining meniscal positioning

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during compression.[9,15,20] It is well-established that meniscus root tears (MRTs) can have a deleterious effect on knee function and are highly associated with meniscal extrusion.[6,25] Recent interest in MRTs has demonstrated their significance, as they have been associated with chondral injury, early degenerative changes, and a high conversion rate to total knee arthroplasty (TKA).[21,27,31]

From a biomechanical perspective, it is known that MRTs lead to decreased femorotibial contact area and increased peak contact pressure as compared with knees with intact meniscus roots, resulting in increased stress on the articular cartilage.[1,9,26,30,34,38] Knees that have an MRT function similarly to those that have undergone a total meniscectomy.[1,9,26,30,31,33-35,38] Furthermore, the extrusion of the medial and lateral menisci can occur quickly after MRT, demonstrating the urgency of treatment of these lesions.[13,23]

Historically, older patients with a chronic MRT have been treated nonoperatively or with partial medial meniscectomy. However, it is now well-established that this often leads to a subsequent TKA.[21,28] Consequently, there has been recent interest in developing better techniques for repairing MRTs in knees with moderate changes of osteoarthritis.[3,8] The most commonly employed techniques are the transtibial pullout repair and an all-inside suture anchor repair. From a biomechanical perspective, these techniques have performed well, restoring femorotibial contact area and contact pressure similar to those of a native knee.[1,13,23,27,30] Previous studies have demonstrated that these repair techniques are superior to partial meniscectomy or nonoperative treatment.[8,28]

Dragoo et al[8] recently described an all-inside suture repair without the need for suture anchors. When compared with the transtibial pullout repair, this technique avoids the need to drill a tibial tunnel, making meniscus root repair much simpler in the setting of concomitant anterior cruciate ligament tear or moderate osteoarthritis. Another drawback of the transtibial pullout repair is the risk of suture abrasion within the bony tunnel as well as creep of the suture, both of which reduce the strength of the repair and risk suture rupture. When compared with the all-inside suture anchor repair, the all-inside technique removes the risk for loosening of the suture anchor and provides a technically easier alternative that can be completed via traditional anteromedial and anterolateral arthroscopic portals.

Although the all-inside suture repair technique is supported by improved clinical outcomes and a reduced conversion rate to TKA,[8] it does not have biomechanical data evaluating the repair or comparing it with other meniscus root repair techniques. The goal of this study is to compare the kinematic effects of the all-inside meniscus root repair technique on the medial and lateral menisci, as well as to compare load to failure between the all-inside and transtibial meniscus root repair techniques. It was hypothesized that all-inside meniscal repair would perform biomechanically similar to the intact meniscus and that it would have a load to failure and stiffness not significantly different from those of a transtibial meniscus root repair.

METHODS

Specimen Preparation

Nine paired cadaveric knee specimens were used for this study. The cadavers were donated to a tissue bank for use in medical research. Cadaveric knees were from donors aged 39 to 59 years with a body mass index <30 and no history of osteoarthritis, knee injury, surgical history on the lower body, or any anatomic abnormalities. The senior author (J.L.D.) reviewed radiographs of cadaveric knees before acceptance into the study. One knee was randomly selected for use and dissected by removing the skin, subcutaneous tissues, quadriceps muscles, patella, and patellar tendon, although the capsule was left in place. The tibia and fibula were potted in cement mold with the tibial plateau parallel to the base using polymethylmethacrylate (PMMA) cement (GC America Inc). Two parallel lateral-to-medial tunnels were drilled 8 cm apart through the proximal femur and femoral epicondyles, parallel to the tibial plateau. The tunnel closest to the joint line was drilled with a 10-mm reamer and the tunnel farthest from the joint line drilled with a 7-mm reamer. A rod was placed through the 10-mm tunnel for load application and through the 7-mm tunnel for angle selection.

The specimen was then prepared for pressure-mapping sensor insertion (model 4000; Tekscan). The anterior aspect of the knee joint from the lateral collateral ligament (LCL) to the medial collateral ligament (MCL) was dissected, with care taken to keep the menisci intact. The submeniscal area of the tibial plateau was accessed while preserving the LCL, MCL, anterior cruciate ligament, and posterior cruciate ligament. Small dissections were then performed just posterior to the LCL/posterolateral corner and just posterior to the MCL, working to stay as far from the posterior capsule as possible.

All-inside meniscal repair was performed as described by Dragoo et al.[8] Two horizontal mattress sutures were used to reduce the meniscal lesion back to anatomic positioning, and a third suture was used to tether the meniscus to the posterior knee capsule (all-inside repair technique)

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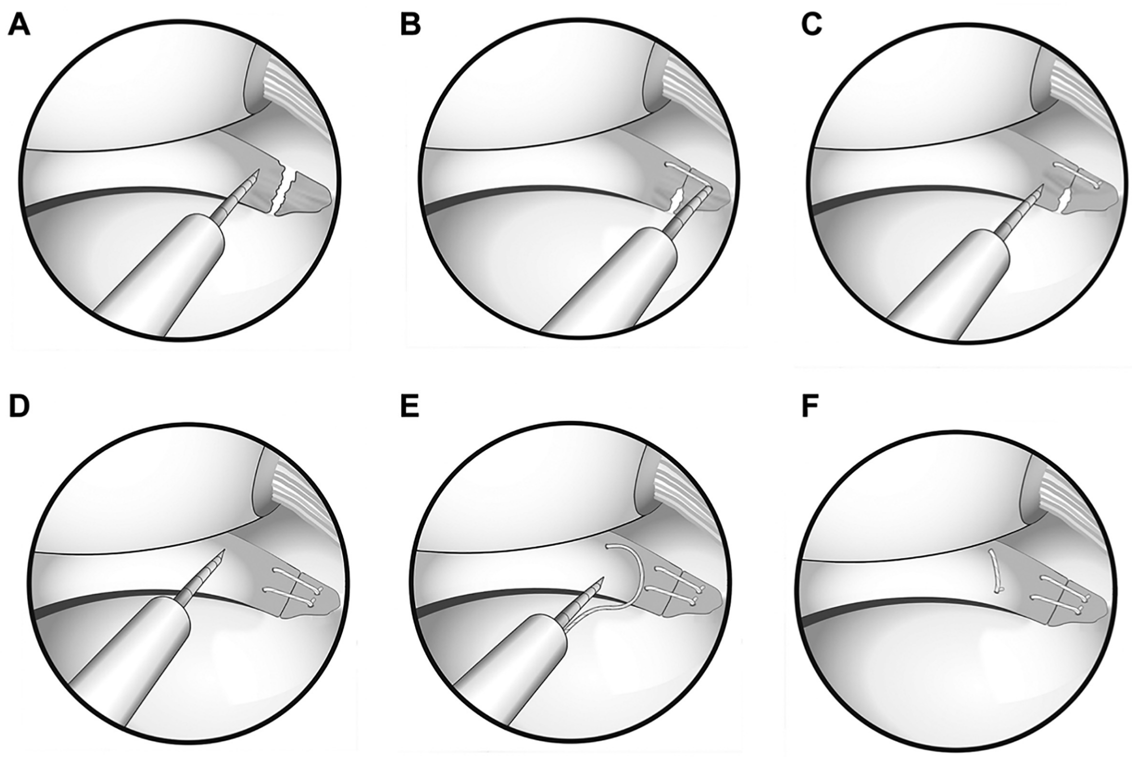

Figure 1. Illustration of all-inside meniscus root repair technique.

with 3 meniscal sutures (Fast-Fix; Smith & Nephew) (Figure 1).[8]

Transtibial repair was performed using the well-described double-tunnel pullout technique.[5] With an appropriate aiming device and guide pin (Meniscal Root Repair System; Arthrex), we drilled 2 tunnels at the location of the meniscus root attachment, with the second tunnel approximately 5 mm anterior to the first. This required a small incision just medial to the tibial tubercle for a medial MRT and lateral to the tibial tubercle for a lateral MRT. A simple suture was passed through the far posterior detached meniscus root, about 5 mm from the edge, using a suture-passing device (FirstPass; Smith & Nephew). This suture was then shuttled through the posterior transtibial tunnel. These steps were repeated with another simple suture placed in the detached meniscus root, anterior to the previous simple suture, and shuttled through the more anterior transtibial tunnel. Finally, the sutures were tied down over a cortical button (EndoButton; Smith & Nephew) to reduce the MRT.

Pressure-Testing Conditions

Sutures were placed on the tabs of the medial and lateral sensors, with care taken not to damage the sensors. A suture was passed from posterior to anterior in a submeniscal fashion through each compartment. The sensor was then carefully pulled into place beneath the medial and lateral menisci on the tibial plateau (Figure 2). Sensors were calibrated before insertion according to the manufacturer's recommendation.[14,37] The "intact state" test was then performed.

Next, the MRT was created. Under dry arthroscopic conditions, the posterior medial meniscus root was cut using a No. 11 blade to create a posterior full-thickness medial meniscus root lesion. This was completed with the sensors in place. The "cut state" test was then performed.

The sensors were subsequently removed, with the sutures kept in place to allow for easy replacement of the sensors. Sensor position was verified visually before each testing run by placing a small compressive load on the joint and visually confirming that the contact area was fully covered by the sensor placement. Under dry arthroscopic conditions, the lesioned meniscus root was repaired using the all-inside technique previously described.[8] Once the sutures were in place, the "repair state" test was performed. All 3 testing conditions were performed at 0° of knee flexion. Compressive testing was not performed on the transtibial repair technique group, given that it has been extensively reported on.[2,22,24,32]

Compressive-Testing Protocol

Pressure-mapping sensors (model 4000; Tekscan) were placed under the meniscus using the previously described technique. Before testing, the femur was secured into a custom fixture attached to the actuator of a tensile-testing machine (model E10000; Instron). The potted tibia-fibula complex was secured to a custom jig, which was fixed to

Figure 2. Testing setup with the pressure sensors applied.

a free-moving X-Y stage to allow for free translations of the tibia during testing. Axial loads were applied via a steel rod inserted across the 10-mm tunnel drilled through the femoral condyles. A 7-mm steel rod was inserted proximally through the shaft of the femur, allowing the knee flexion angle to be set at 0° for testing. A 1000-N load was applied axially through the femur and held for 30 seconds while the pressure sensor data were recorded.

Failure-Testing Protocol

After completion of the nondestructive compressive testing, the tibia and femur of each specimen were potted in PMMA. The other cadaveric knee of the pair was chosen for the transtibial repair. Each knee was then aligned in full extension, and the tibial potting block was secured to the platform of the materials testing machine. A custom apparatus was used, along with a washer load cell, to apply a 200-N axial load through the shaft of the femur to ensure contact between the femoral condyles and the tibial plateau. During the load-to-failure tests, the materials testing machine was in displacement control. The angle of pull was perpendicular to the frontal plane. After the axial load was applied, the femoral potting block was secured to the table of the materials testing machine. A wedge of bone was removed from the anterior portion of the tibia and femur to expose the anterior root of the medial meniscus and allow for the insertion of the soft tissue clamp used for failure testing. Care was taken when the wedge of bone was removed to ensure that contact was maintained between the femoral condyles and tibial plateau. The anterior root of the medial meniscus was cut to allow for gripping of the soft tissue with the clamp. Before clamping, the root was wrapped with steel wire to allow for increased clamping force without damaging the soft tissue of the meniscus. After clamping, a 5-N preload was applied before pulling to failure at 30 mm/min. Load and displacement data were recorded using the materials testing machine and used to calculate the ultimate failure load (N) and stiffness (N/mm) of each construct.

Statistical Analysis

Multivariable mixed-effect linear models were used to analyze in each compartment peak pressure, mean pressure, and contact area among specimen states (intact, root cut, and root repair), including a random effect for each specimen. Results were split by lateral and medial measurements. Subsequent pairwise comparisons between states were reported using Tukey-adjusted *P* values. The differences in failure load and stiffness between the capsular and 2-tunnel repair techniques were analyzed using paired *t* tests. Box plots were created to demonstrate the medians and quartiles of analyzed data. All analyses were completed in RStudio Version 1.1.456 using a 2-sided level of significance of .05.

RESULTS

Peak Pressure, Mean Pressure, and Contact Area

In the medial compartment at full extension, median peak pressures were significantly increased in the root cut state as compared with the intact state (Δ +636 kPA; 95% CI, 246 to 1026; *P* = .017) (Figure 3). All-inside meniscus root repair showed median peak pressures that were not significantly different from the intact state of the meniscus (Δ +311 kPA; 95% CI, –79 to 701; *P* = .293). There were no statistically significance changes in the median peak pressures in the repair versus the cut state (*P* = .266). Median mean pressures in the medial compartment were significantly greater in the root cut state versus the intact state (Δ +190 kPA; 95% CI, 49 to 330) (Figure 4). All-inside meniscal repair reduced the median mean pressures approaching the intact meniscal state (Δ +137 kPA; 95% CI, –3 to 277) but lower than the cut meniscal state. There were no significant differences in femorotibial contact area between the root cut and intact states (Δ –73 mm^2; 95% CI, –139 to 6), and this was unchanged after all-inside repair (Δ –40 mm^2; 95% CI, –106 to 26).

In the lateral compartment at full extension, median peak pressures were significantly increased in the root cut state as compared with the intact state (Δ +718 kPA; 95% CI, 246 to 1191) (Figure 5). Median peak pressures after all-inside meniscus root repair were not significantly different from the intact state (Δ +322 kPA; 95% CI, –150 to 795). Median mean pressures in the lateral

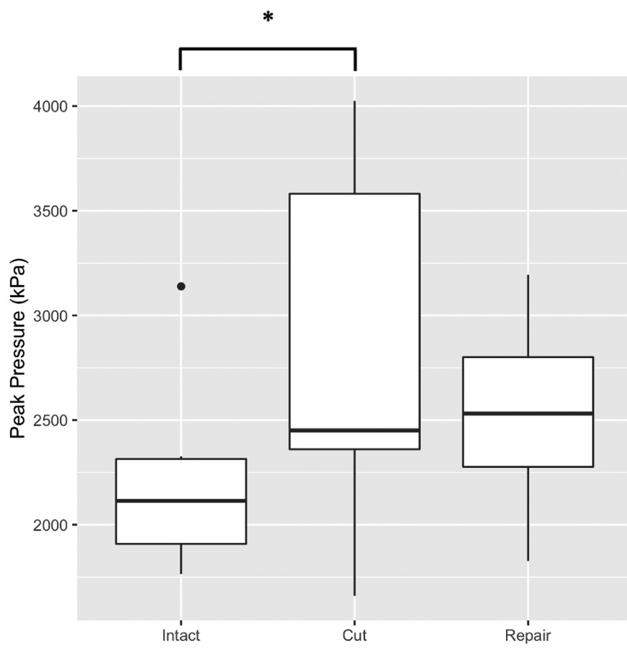

Figure 3. Medial compartment: peak pressure vs state. Data are presented as median (line), interquartile range (box), 95% CI (error bars), and outlier (circle). *$P < .05$.

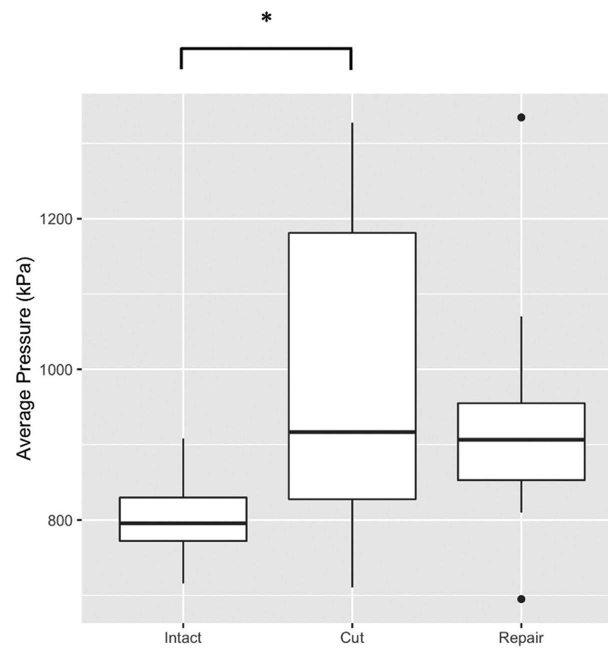

Figure 4. Medial compartment: mean pressure vs state. Data are presented as median (line), interquartile range (box), 95% CI (error bars), and outlier (circle). *$P < .05$.

compartment were significantly different between the root cut and intact states (Δ +203 kPA; 95% CI, 51 to 355) but not between the all-inside meniscal repair and the intact states (Δ +18 kPA; 95% CI, –134 to 171) (Figure 6). Similarly, there was no significant difference in femorotibial contact area between the root cut and intact states (Δ +34 mm^2; 95% CI, –40 to 108) or the all-inside meniscal repair and intact states (Δ +17 mm^2; 95% CI, –57 to 92).

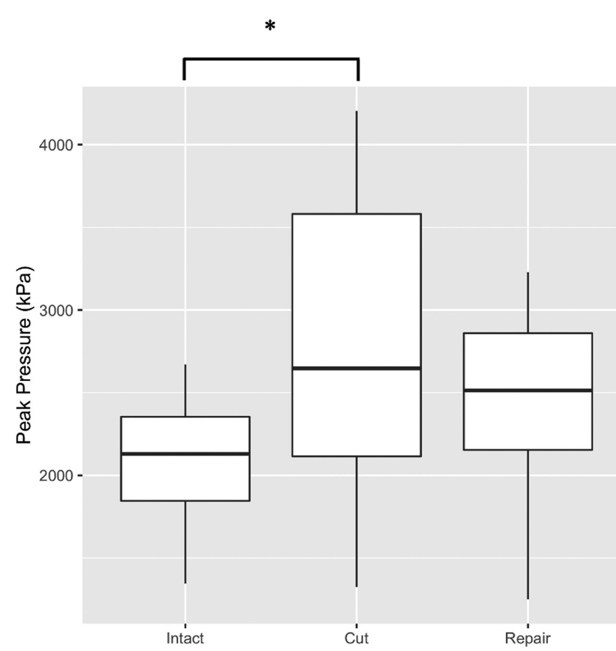

Figure 5. Lateral compartment: peak pressure vs state. Data are presented as median (line), interquartile range (box), and 95% CI (error bars). *$P < .05$.

Failure Testing

There was no difference between repair techniques regarding load to failure (P = .896) (Figure 7). The transtibial meniscus root repair had significantly more stiffness than the all-inside meniscus root repair technique (mean ± SD, 24.8 ± 9.3 N/mm versus 13.6 ± 3.8 N/mm, P = .015) (Figure 8).

DISCUSSION

This study demonstrates the ability of all-inside meniscus root repair to behave similarly to the intact meniscus. Although there was a significant difference in stiffness between the all-inside and transtibial techniques, there was no difference in the load to failure, thus demonstrating that the all-inside repair technique represents a viable alternative for treating an MRT. Furthermore, the load-to-failure values obtained in this study were equal to or exceeded those previously reported. Numerous studies have tested the ultimate load to failure of the transtibial root repair technique in medial and lateral menisci, which ranged from 108 to 368 N.[2,22,24,32] All-inside meniscus root repair has demonstrated excellent clinical results and decreased TKA conversion rates when compared with

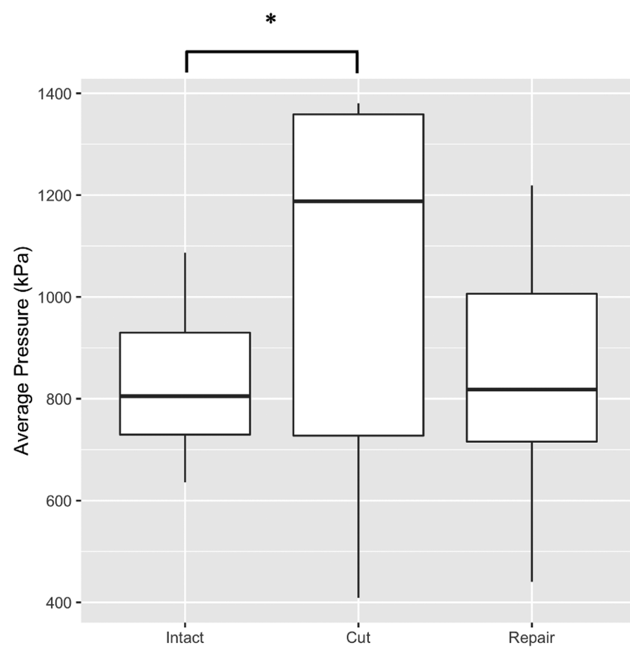

Figure 6. Lateral compartment: mean pressure vs state. Data are presented as median (line), interquartile range (box), and 95% CI (error bars). $^{*}P < .05$.

nonoperative treatment,[8] although biomechanical data supporting its utility were lacking.

The significance of the decreased stiffness of the all-inside repair technique is unknown. What is interesting about this finding was that despite the decreased stiffness of this technique, the ultimate load to failure was equivalent to that of the transtibial technique. Additionally, for both techniques, the primary mode of failure involved the sutures pulling through the meniscus. A likely explanation for the difference in stiffness could relate to the all-inside repair being anchored to the soft tissue of the posterior capsule of the knee, whereas the transtibial technique involves sutures being passed through cortical tunnels and tied over a cortical button. By virtue of the fixation methods alone, one would expect that the tissue of the posterior capsule would be more compliant and thus have a lower stiffness. The clinical relevance of this difference is also unknown, as there are risks associated with an overconstrained meniscus just as there are risks and poor outcomes associated with an extruded meniscus. Future studies directly comparing the outcomes of these 2 repair techniques and measuring the amount of meniscal extrusion present at long-term follow-up would help address this question.

There are extensive data illustrating that MRTs lead to progression to end-stage osteoarthritis and a high conversion rate to TKA.[21,28] Meta-analyses have demonstrated meniscus root repair to be superior to partial meniscectomy and nonoperative treatment, not only with regard to clinical outcomes but also from a cost-effectiveness standpoint.[10,36] Given the prevalence of MRTs in middle-aged adults and the deleterious effects associated with

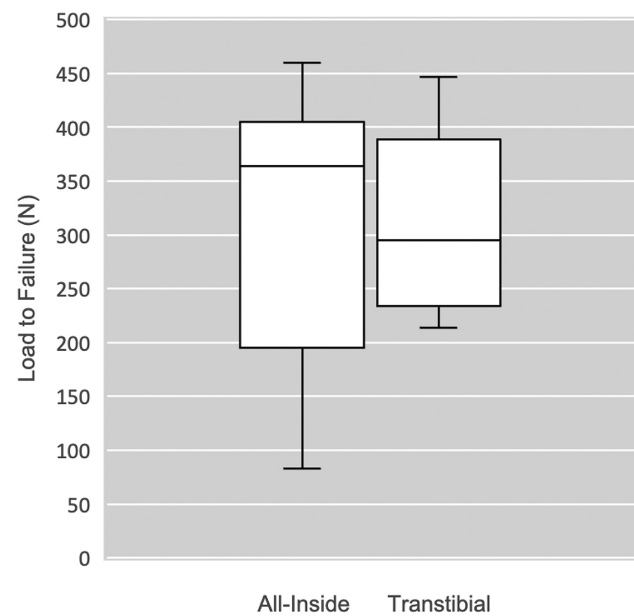

Figure 7. Load to failure of repair constructs. Data are presented as median (line), interquartile range (box), and 95% CI (error bars).

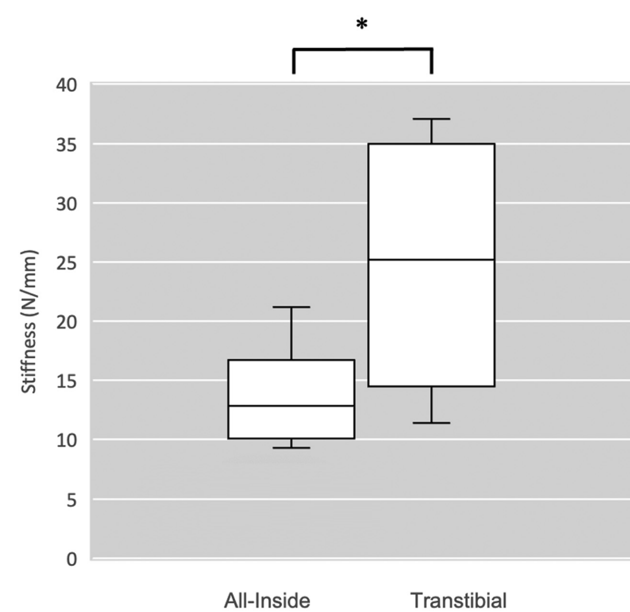

Figure 8. Stiffness of repair constructs. Data are presented as median (line), interquartile range (box), and 95% CI (error bars). $^{*}P < .05$.

nonoperative treatment, it is imperative that orthopaedic surgeons have a surgical technique that they can confidently employ when treating this pathology. The 2 most commonly utilized techniques in the literature—the transtibial pullout repair and a suture anchor–based repair—have performed favorably from a biomechanical perspective.[1,13,23,27,29,30,36] However, drawbacks exist for each technique. Suture anchor–based repair can be technically demanding, and it requires the creation of an additional posteromedial portal. Additionally, there is the potential for loosening of the anchor depending on placement, as well as irritation from the suture knot.[16,29] The transtibial pullout repair technique requires an additional incision for drilling of the tunnels. Such drilling can be particularly challenging in scenarios where concomitant procedures are being performed, such as anterior cruciate ligament reconstruction or a high tibial osteotomy. There is also a reported "bungee effect" with the transtibial technique, where the meniscus root repair can displace as a result of suture elongation within the tunnel, causing micromotion of the root. Yet, the transtibial repair demonstrated significantly greater stiffness than the all-inside repair, albeit at time zero. Motion of the sutures within the tunnel can also lead to tunnel widening or abrasion of suture material. Tensioning of the suture represents another challenge given the long distance of the suture limbs from the meniscus root to the aperture of the tibial tunnel. Last, patients can experience irritation postoperatively from the tibial fixation, particularly if a screw and washer are used.[4,11,18,19,29]

The all-inside meniscus root repair technique represents a less invasive and less technically demanding option for treating MRTs. Nevertheless, there remain potential pitfalls with this technique. There are instances when an anatomic reduction of the meniscus to the tibia is not achievable because of either the tissue quality or the size of the meniscus root remnant. In these scenarios, the goal is to achieve the best reduction possible, and an emphasis is placed on the vertical mattress suture to ensure that this reduction is maintained. Additionally, given that 2 sutures are placed into the posterior capsule, preoperative magnetic resonance images should be reviewed to determine safe zones for suture placement and to evaluate for any anatomic anomalies such as an aberrant anterior tibial artery branch.[8] Another benefit of this technique is the familiarity for orthopaedic surgeons who perform all-inside meniscal repairs for other tear patterns, as the same instrumentation is used. Additionally, this technique not only allows the meniscus to be accurately reduced back to the root remnant but also may protect against meniscal extrusion with the vertical mattress suture to the posterior capsule (Figure 1). Postoperative meniscal extrusion remains an issue with the transtibial- and suture anchor–based repair techniques.[4,5,16,36] This may lead to inferior long-term outcomes given the increased joint loading associated with increasing meniscal extrusion.[11,12,17] Studies with long-term follow-up and postoperative magnetic resonance images are required to determine how effectively all-inside repair prevents this phenomenon. However, use of a similar antiextrusion suture has shown promising results in biomechanical studies.[7]

This study is limited by factors inherent to cadaveric studies, including time-zero joint biomechanics, which do not include the effects of healing and thus may limit generalizability. There are also inherent limitations associated with the Tekscan sensors, as their introduction into the joint could affect joint loading. Additionally, compression testing was not performed on the transtibial repair technique, preventing direct comparison with the values previously established in the literature. In addition, large standard deviations were noted in some testing conditions, reflecting some degree of variability among specimens. However, a matched-pair study design was utilized to attempt to limit differences to the state of the meniscus or the meniscus root repair technique employed. Last, testing was performed only at full extension, so the performance of these repair techniques at other angles of flexion remains unknown.

Ultimately, at full extension, all-inside meniscus root repair was able to restore median peak and mean pressures such that they were not significantly different from those of the native intact meniscus in the cadaver knee. When compared with a transtibial meniscus root repair technique, all-inside repair demonstrated less stiffness but an equivalent load to failure and represents a less invasive and less technically demanding option for the surgical management of MRTs.

REFERENCES

1. Allaire R, Muriuki M, Gilbertson L, Harner C. Biomechanical consequences of a tear of the posterior root of the medial meniscus: similar to total meniscectomy. *J Bone Joint Surg Am*. 2008;90(9):1922-1931. doi:10.2106/JBJS.G.00748
2. Anz AW, Branch EA, Saliman JD. Biomechanical comparison of arthroscopic repair constructs for meniscal root tears. *Am J Sports Med*. 2014;42(11):2699-2706. doi:10.1177/0363546514549445
3. Bhatia S, LaPrade CM, Ellman MB, LaPrade RF. Meniscal root tears: significance, diagnosis, and treatment. *Am J Sports Med*. 2014; 42(12):3016-3030. doi:10.1177/0363546514524162
4. Cerminara AJ, LaPrade CM, Smith SD, Ellman MB, Wijdicks CA, LaPrade RF. Biomechanical evaluation of a transtibial pull-out meniscal root repair: challenging the bungee effect. *Am J Sports Med*. 2014;42(12):2988-2995. doi:10.1177/0363546514549447
5. Chahla J, Moulton SG, LaPrade CM, Dean CS, LaPrade RF. Posterior meniscal root repair: the transtibial double tunnel pullout technique. *Arthrosc Tech*. 2016;5(2):e291. doi:10.1016/J.EATS.2016.01.006
6. Cinque ME, Chahla J, Moatshe G, Faucett SC, Krych AJ, LaPrade RF. Meniscal root tears: a silent epidemic. *Br J Sports Med*. 2018;52(13):872-876. doi:10.1136/BJSPORTS-2017-098942
7. Daney BT, Aman ZS, Krob JJ, et al. Utilization of transtibial centralization suture best minimizes extrusion and restores tibiofemoral contact mechanics for anatomic medial meniscal root repairs in a cadaveric model. *Am J Sports Med*. 2019;47(7):1591-1600. doi:10.1177/0363546519844250
8. Dragoo JL, Konopka JA, Guzman RA, Segovia N, Kandil A, Pappas GP. Outcomes of arthroscopic all-inside repair versus observation in older patients with meniscus root tears. *Am J Sports Med*. 2020;48(5):1127-1133. doi:10.1177/0363546520909828
9. Fairbank TJ. Knee joint changes after meniscectomy. *J Bone Joint Surg Br*. 1948;30(4):664-670. doi:10.1302/0301-620X.30B4.664
10. Faucett SC, Geisler BP, Chahla J, et al. Meniscus root repair vs meniscectomy or nonoperative management to prevent knee osteoarthritis after medial meniscus root tears: clinical and economic effectiveness. *Am J Sports Med*. 2019;47(3):762-769. doi:10.1177/0363546518755754
11. Feucht M, Grande E, Brunhuber J, et al. Medial meniscus root tears biomechanical comparison between suture anchor and transtibial pull-out repair for posterior biomechanical comparison between suture anchor and transtibial pull-out repair for posterior medial

meniscus root tears. *Am J Sports Med*. 2015;42(1):187-193. doi:10.1177/0363546513502946
12. Feucht MJ, Kühle J, Bode G, et al. Arthroscopic transtibial pullout repair for posterior medial meniscus root tears: a systematic review of clinical, radiographic, and second-look arthroscopic results. *Arthroscopy*. 2015;31(9):1808-1816. doi:10.1016/j.arthro.2015.03.022
13. Hein C, Deperio J, Ehrensberger M, Marzo J. Effects of medial meniscal posterior horn avulsion and repair on meniscal displacement. *Knee*. 2011;18(3):189-192. doi:10.1016/J.KNEE.2010.04.006
14. Jansson KS, Michalski MP, Smith SD, LaPrade RF, Wijdicks CA. Tekscan pressure sensor output changes in the presence of liquid exposure. *J Biomech*. 2013;46(3):612-614. doi:10.1016/J.JBIOMECH.2012.09.033
15. Jones A, Houang M, Low R, Wood D. Medial meniscus posterior root attachment injury and degeneration: MRI findings. *Australas Radiol*. 2006;50(4):306-313. doi:10.1111/J.1440-1673.2006.01586.X
16. Jung YH, Choi NH, Oh JS, Victoroff BN. All-inside repair for a root tear of the medial meniscus using a suture anchor. *Am J Sports Med*. 2012;40(6):1406-1411. doi:10.1177/0363546512439181
17. Kaplan DJ, Alaia EF, Dold AP, et al. Increased extrusion and ICRS grades at 2-year follow-up following transtibial medial meniscal root repair evaluated by MRI. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(9):2826-2834. doi:10.1007/S00167-017-4755-8
18. Kim JH, Chung JH, Lee DH, Lee YS, Kim JR, Ryu KJ. Arthroscopic suture anchor repair versus pullout suture repair in posterior root tear of the medial meniscus: a prospective comparison study. *Arthroscopy*. 2011;27(12):1644-1653. doi:10.1016/J.ARTHRO.2011.06.033
19. Kim JH, Ryu DJ, Park JS, Shin TS, Wang JH. Arthroscopic transtibial pull-out repair of medial meniscus posterior root tear with a whip running suture technique. *Arthrosc Tech*. 2021;10(4):e1017-e1024. doi:10.1016/J.EATS.2020.11.016
20. Koenig J, Ranawat A, Umans H, Difelice G. Meniscal root tears: diagnosis and treatment. *Arthroscopy*. 2009;25(9):1025-1032. doi:10.1016/J.ARTHRO.2009.03.015
21. Krych A, Reardon P, Johnson N, et al. Non-operative management of medial meniscus posterior horn root tears is associated with worsening arthritis and poor clinical outcome at 5-year follow-up. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(2):383-389. doi:10.1007/S00167-016-4359-8
22. Krych AJ, Johnson NR, Wu IT, Smith PA, Stuart MJ. A simple cinch is superior to a locking loop for meniscus root repair: a human biomechanical comparison of suture constructs in a transtibial pull-out model. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(8):2239-2244. doi:10.1007/S00167-017-4652-1
23. LaPrade CM, Jansson KS, Dornan G, Smith SD, Wijdicks CA, LaPrade RF. 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. *J Bone Joint Surg Am*. 2014;96(6):471-479. doi:10.2106/JBJS.L.01252
24. LaPrade CM, LaPrade MD, Turnbull TL, Wijdicks CA, LaPrade RF. Biomechanical evaluation of the transtibial pull-out technique for posterior medial meniscal root repairs using 1 and 2 transtibial bone tunnels. *Am J Sports Med*. 2015;43(4):899-904. doi:10.1177/0363546514563278
25. LaPrade RF, Floyd ER, Carlson GB, Moatshe G, Chahla J, Monson JK. Meniscal root tears: solving the silent epidemic. *J Arthrosc Surg Sports Med*. 2021;2(1):47-57. doi:10.25259/JASSM_55_2020
26. Maquet P, van de Berg A, Simonet J. Femorotibial weight-bearing areas: experimental determination. *J Bone Joint Surg Am*. 1975;57(6):766-771.
27. Marzo J, Gurske-DePerio J. Effects of medial meniscus posterior horn avulsion and repair on tibiofemoral contact area and peak contact pressure with clinical implications. *Am J Sports Med*. 2009;37(1):124-129. doi:10.1177/0363546508323254
28. Ozkoc G, Circi E, Gonc U, Irgit K, Pourbagher A, Tandogan R. Radial tears in the root of the posterior horn of the medial meniscus. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(9):849-854. doi:10.1007/S00167-008-0569-Z
29. Pache S, Aman ZS, Kennedy M, et al. Meniscal root tears: current concepts review. *Arch Bone Joint Surg*. 2018;6(4):250-259.
30. Padalecki J, Jansson K, Smith S, et al. Biomechanical consequences of a complete radial tear adjacent to the medial meniscus posterior root attachment site: in situ pull-out repair restores derangement of joint mechanics. *Am J Sports Med*. 2014;42(3):699-707. doi:10.1177/0363546513499314
31. Pagnani M, Cooper D, Warren R. Extrusion of the medial meniscus. *Arthroscopy*. 1991;7(3):297-300. doi:10.1016/0749-8063(91)90131-G
32. Prado-Novoa M, Perez-Blanca A, Espejo-Reina A, Espejo-Reina MJ, Espejo-Baena A. Initial biomechanical properties of transtibial meniscal root repair are improved by using a knotless anchor as a post-insertion tensioning device. *Sci Rep*. 2020;10(1):1748. doi:10.1038/S41598-020-58656-6
33. Radin E, de Lamotte F, Maquet P. Role of the menisci in the distribution of stress in the knee. *Clin Orthop Relat Res*. 1984;185:290-294.
34. Seedhom BB, Hargreaves DJ. Transmission of the load in the knee joint with special reference to the role of the menisci, part II: experimental results, discussion and conclusions. *Eng Med*. 1979;8(4):220-228. doi:10.1243/EMED_JOUR_1979_008_051_02
35. Seo J, Li G, Shetty G, et al. Effect of repair of radial tears at the root of the posterior horn of the medial meniscus with the pullout suture technique: a biomechanical study using porcine knees. *Arthroscopy*. 2009;25(11):1281-1287. doi:10.1016/J.ARTHRO.2009.05.014
36. Stein JM, Yayac M, Conte EJ, Hornstein J. Treatment outcomes of meniscal root tears: a systematic review. *Arthrosc Sports Med Rehabil*. 2020;2(3):e251. doi:10.1016/J.ASMR.2020.02.005
37. Tekscan Inc. How do I calibrate my FlexiForce Sensor? Accessed November 26, 2022. https://www.tekscan.com/support/faqs/how-do-i-calibrate-my-flexiforce-sensor
38. Walker P, Erkman M. The role of the menisci in force transmission across the knee. *Clin Orthop Relat Res*. 1975;109:184-192. doi:10.1097/00003086-197506000-00027