Biomechanical Comparison of 3 Novel Repair Techniques for Radial Tears of the Medial Meniscus

The 2-Tunnel Transtibial Technique, a "Hybrid" Horizontal and Vertical Mattress Suture Configuration, and a Combined "Hybrid Tunnel" Technique

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Background: Historically, radial meniscal tears were treated with partial or near-total meniscectomy, which usually resulted in poor outcomes. Radial meniscal tears function similar to a total meniscectomy and are challenging to treat. Repair of radial meniscal tears should be performed to prevent joint deterioration and the need for salvage procedures in the future.

Purpose/Hypothesis: The purpose was to compare 3 repair techniques for radial tears of the medial meniscus: the 2-tunnel, hybrid, and hybrid tunnel techniques. It was hypothesized that there would be no differences among the 3 groups in regard to gapping and ultimate failure strength.

Study Design: Controlled laboratory study.

Methods: Thirty human male cadaver knees (10 matched pairs, n = 20; 10 unpaired, n = 10) were used to compare the 2-tunnel, hybrid, and hybrid tunnel repairs. A complete radial tear was made at the midbody of the medial meniscus. Repairs were performed according to the described techniques. Specimens were potted and mounted on a universal material testing machine where each specimen was cyclically loaded for 1000 cycles before experiencing a pull to failure. Gap distances at the tear site, ultimate failure load, and failure location were measured and recorded.

Results: After 1000 cycles of cyclic loading, there were no significant differences in displacement among the 2-tunnel repair (3.0 ± 1.7 mm), hybrid repair (3.0 ± 0.9 mm), and hybrid tunnel repair (2.3 ± 1.0 mm; *P* = .4042). On pull-to-failure testing, there were also no significant differences in ultimate failure strength among the 2-tunnel repair (259 ± 103 N), hybrid repair (349 ± 149 N), and hybrid tunnel repair (365 ± 146 N; *P* = .26). However, the addition of vertical mattress sutures to act as a "rip stop" significantly reduced the likelihood of the sutures pulling through the meniscus during pull-to-failure testing for the hybrid and hybrid tunnel repairs (4 of 16, 25%) as compared with the 2-tunnel repair (7 of 9, 78%; *P* = .017).

Conclusion: The results showed equivalent biomechanical testing with regard to gap distance and pull-to-failure strength among the 3 repairs. The addition of the vertical mattress sutures to act as a rip stop was effective in preventing meniscal cutout through the meniscus.

Clinical Relevance: Effective healing of radial meniscal tears after repair is paramount to prevent joint deterioration and symptom development. Each tested repair showed a biomechanically equivalent and stable construct to use to repair radial meniscal tears. The authors recommend that rip stop vertical mattress sutures be used, especially in poor-quality meniscal tissue, to prevent suture cutout.

Keywords: radial tear; inside-out repair; medial meniscus; tunnel; hybrid; rip stop sutures

Complete radial tears of the medial meniscus have been functionally described as being similar to a total meniscectomy, and they represent a challenging problem to treat.[2] Without treatment, radial tears of the medial meniscus can lead to rapid joint degeneration.[1] Historically, radial tears were treated with partial or total meniscectomy,

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but many younger patients reported continued symptoms from joint overload and early knee arthritis. This patient population often needed further procedures, which ranged from meniscal transplantation as a salvage procedure to delay joint deterioration to early total knee replacement. With the unpredictable outcomes and high reoperation rates published for radial meniscal tear resection, a renewed push for repair of radial meniscal tears has emerged.[11]

Historical techniques for the repair of radial meniscal tears involve either an all-inside horizontal mattress repair or an inside-out repair with single, double, or crossed horizontal mattress sutures.[9,13,14,17] However, consistent healing of radial meniscal repairs with these techniques has not been found.[5] A review of the biomechanical testing of these techniques suggests the need for novel repair techniques to improve the repair construct strength.[3,13,21]

Two novel repair techniques for radial meniscal tears were recently reported in the literature. In 2012, Nakata et al[15] reported on a novel technique for repair of radial meniscal tears that involved hybrid fixation, consisting of a configuration of vertical and horizontal mattress sutures across the radial tear site. In summary, the authors' technique involves first placing nonabsorbable 2-0 vertical mattress sutures parallel to the radial tear site via an inside-out fashion. Next, 3 or 4 horizontal mattress sutures are placed perpendicular to, and over the top of, the vertical sutures to approximate the tear edges. At a mean follow-up of 18 months, 89% of patients were free from knee catching, locking, pain, or swelling. Second-look arthroscopy was performed at a mean 9 months after meniscal repair, and the authors reported that 66% of meniscal tears were completely healed, 28% were partially healed, and 7% failed.

In 2015, James et al[12] presented a novel technique consisting of an inside-out horizontal mattress suture repair construct augmented with a 2-tunnel transtibial fixation to repair and anatomically reduce a radial meniscal tear. The authors presented a case report of a 29-year-old man who, at second-look arthroscopy, was confirmed to have complete healing of the entire radial meniscal tear. A follow-up study showed that this novel 2-tunnel technique was biomechanically superior to the traditional inside-out horizontal mattress suture repair technique.[3] Clinical follow-up data on 27 patients treated with this technique reported comparable results between the 2-tunnel technique for repair of radial meniscal tears and inside-out repairs of vertical meniscal tears.[6]

Therefore, the purpose of this study was to biomechanically compare 3 techniques for repair of radial tears of the medial meniscus: (1) an inside-out horizontal mattress suture repair construct augmented with a transtibial 2-tunnel suture fixation ("2 tunnel"), (2) a hybrid fixation with both a vertical and a horizontal mattress suture configuration ("hybrid"), and (3) a combined novel repair technique with vertical mattress sutures added to the transtibial repair technique ("hybrid tunnel"). We hypothesized that there would be no differences among the 3 groups in regard to gapping at the repair site and ultimate failure strength.

METHODS

Thirty human male cadaver knees were used for comparison of the 2-tunnel and hybrid repair techniques: 10 matched pairs (n = 20) and 10 unpaired (n = 10); mean age, 53.2 years (range, 27-69); mean body mass index, 22.6 kg/m^2 (range, 16-33.5). The cadaveric specimens used in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. The use of cadaveric specimens is exempt at our institution, so institutional review board approval was not required. A visual inspection of each knee was performed to evaluate each specimen for any meniscal or chondral damage. Each specimen was then dissected so that only the tibia, medial and lateral meniscus, and medial capsule remained. Care was taken not to damage the anterior or posterior horn attachments of the medial meniscus. The tibial shaft was then potted in polymethyl methacrylate to facilitate biomechanical testing. Next, a complete radial tear was created sharply at the midbody of the medial meniscus. To ensure consistency and limit variability, 1 board-eligible orthopaedic surgeon (P.S.B.) performed each meniscal repair. The 2-tunnel and hybrid repair techniques were performed in a randomized manner among the 10 matched paired knees, while the hybrid tunnel technique was solely performed on the unpaired knees.

For each inside-out meniscal repair technique, 2-0 nonabsorbable meniscal sutures were used. First, the 2-tunnel technique was performed as described by James et al[12] (Figure 1). Two 2.4-mm tunnels were created in the tibia with a sheathed drill guide (Smith & Nephew) to exit at the meniscocapsular junction, with the center of the tunnels located 5 mm apart. No. 2 high-strength nonabsorbable sutures (FiberWire; Arthrex) were placed through the transosseous drill holes and passed through each limb of the radial meniscal tear with a nitinol wire lasso (Arthrex) in a crisscross fashion. A No. 2 high-strength nonabsorbable suture was then tied over a cortical button (EndoButton; Smith & Nephew) on the anterior tibial cortex. The rationale of this technique is to treat each limb of the radial tear similar to a meniscal root tear. Once accurate and anatomic reduction was visualized, the repair was completed with 2 inside-out horizontal mattress sutures placed on the superior surface and 2 inside-out

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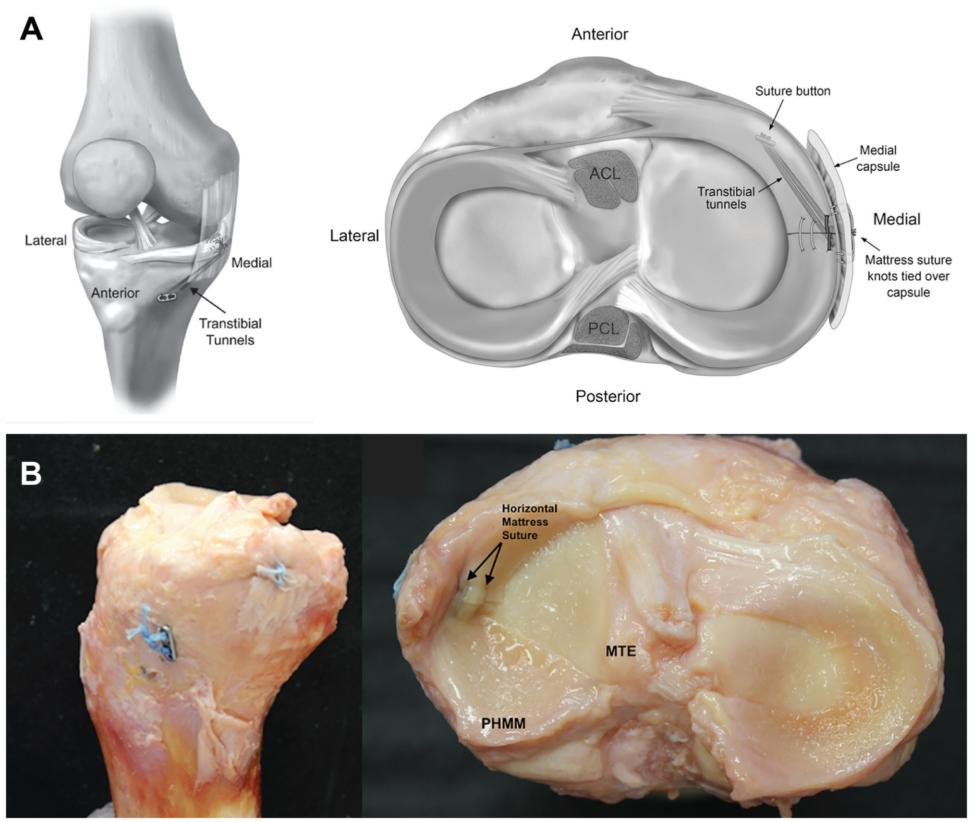

Figure 1. Superior view and side view of the (A) schematic representation and (B) cadaveric repair of the ''2-tunnel'' repair technique for radial tears of the medial meniscus. ACL, anterior cruciate ligament; MTE, medial tibial eminence; PCL, posterior cruciate ligament; PHMM, posterior horn medial meniscus. Reproduced with permission from Bhatia et al.[3]

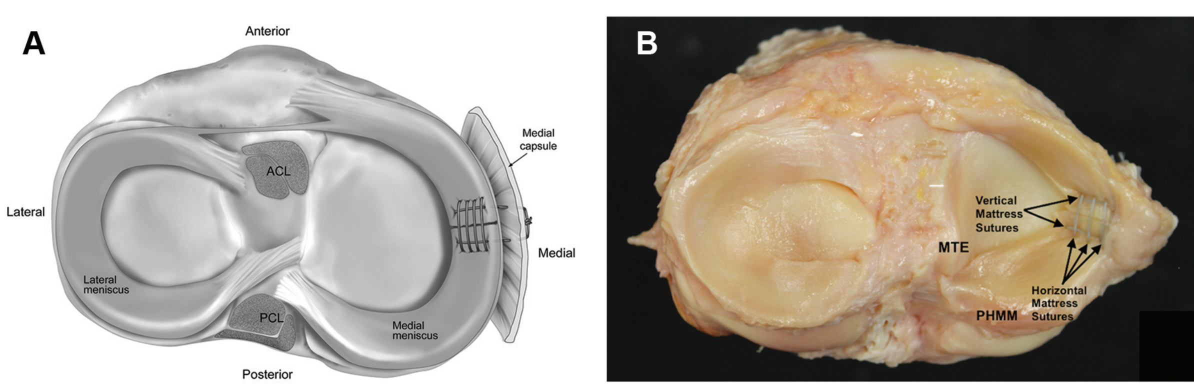

Figure 2. (A) Schematic representation and (B) cadaveric repair of the ''hybrid'' repair technique for radial tears of the medial meniscus in a left knee. ACL, anterior cruciate ligament; MTE, medial tibial eminence; PCL, posterior cruciate ligament; PHMM, posterior horn medial meniscus.

horizontal mattress sutures placed on the inferior surface of the meniscus as previously described.[3]

Specimen preparation for the hybrid suture configuration was the same as for the 2-tunnel configuration. The hybrid meniscal suture configuration technique was performed as described by Nakata et al[15] (Figure 2). First, with 2-0 nonabsorbable meniscal sutures (FiberWire; Arthrex) via an inside-out technique, a vertical mattress suture configuration was performed, reducing both radial tears to the capsule. As the authors stated, these vertical sutures function as a “rip stop” for the 4 horizontal mattress sutures that follow, which were placed with an inside-out technique perpendicular to, and over the top of, the vertical mattress sutures at the radial tear site.

To test the hybrid tunnel technique, 10 nonpaired human male cadaver knees were used and prepared in

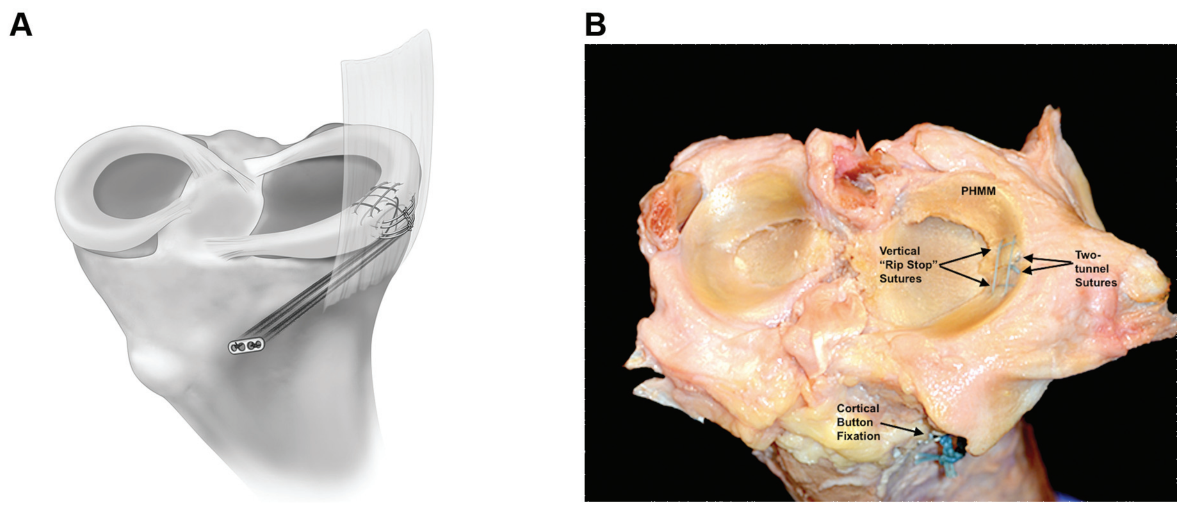

Figure 3. (A) Schematic representation and (B) cadaveric repair of the ''hybrid tunnel'' repair technique for radial tears of the medial meniscus in a right knee. PHMM, posterior horn medial meniscus.

the same manner as described earlier. The hybrid tunnel technique was completed in the manner described for the 2-tunnel technique with the addition of two 2-0 vertical mattress sutures, 1 on either side of the radial tear as in the hybrid technique to act as a rip stop for the horizontal sutures (Figure 3). This technique was added after the initial results were obtained by comparing the hybrid and 2-tunnel techniques, with the goal of testing a repair technique that combined the 2 other repairs.

Biomechanical Testing

This study used similar methods to those previously described to evaluate meniscal strength after a radial meniscal repair.[3] After the posterior horn meniscal capsular tissue was sectioned to within 15 mm of the repair construct and the posterior root was detached, each specimen was mounted on a universal testing machine (Instron E10000) (Figure 4). A ligament staple was placed through the anterior meniscus, 15 mm from the repair site, to standardize the length on the anterior side subject to displacement. Next, custom-made clamps were placed on the posterior horn meniscal tissue according to previously described techniques, 15 mm from the repair site.[12] A 2-N preload force was applied before testing. Next, specimens were cyclically loaded between 5 and 20 N at 0.5 Hz for 1000 cycles, and photographs were obtained at regular intervals (0, 10, 50, 100, 250, 500, and 1000 cycles) to measure gapping at the repair site. After cyclic loading, specimens were pulled to failure at a displacement rate of 30 mm/min while the testing machine recorded the load and displacement. Figure 4 shows the testing setup as described earlier.

Data and Statistical Analysis

Two small beads were pinned to the meniscus two-thirds of the distance away from the meniscocapsular junction and 5 mm anterior and posterior of the tear (Figure 5A).

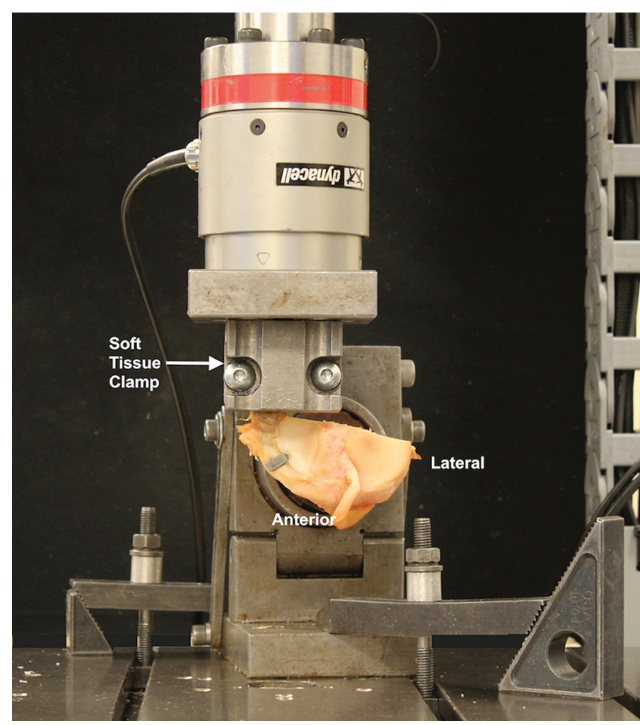

Figure 4. Axial view of the mechanical testing setup with tensile force applied to the posterolateral meniscus. A ligament staple was used to standardize the length of meniscal tissue on the anterior side of the repair subject to displacement during loading of each construct. A calibration reference was used to determine the gap distance.

Photographs were taken with a high-resolution digital single lens reflex camera (Nikon) and measurements with a custom Python software script[18] and the OpenCV image processing library.[16] First, the image was cropped to include only the portion of the image containing the radial

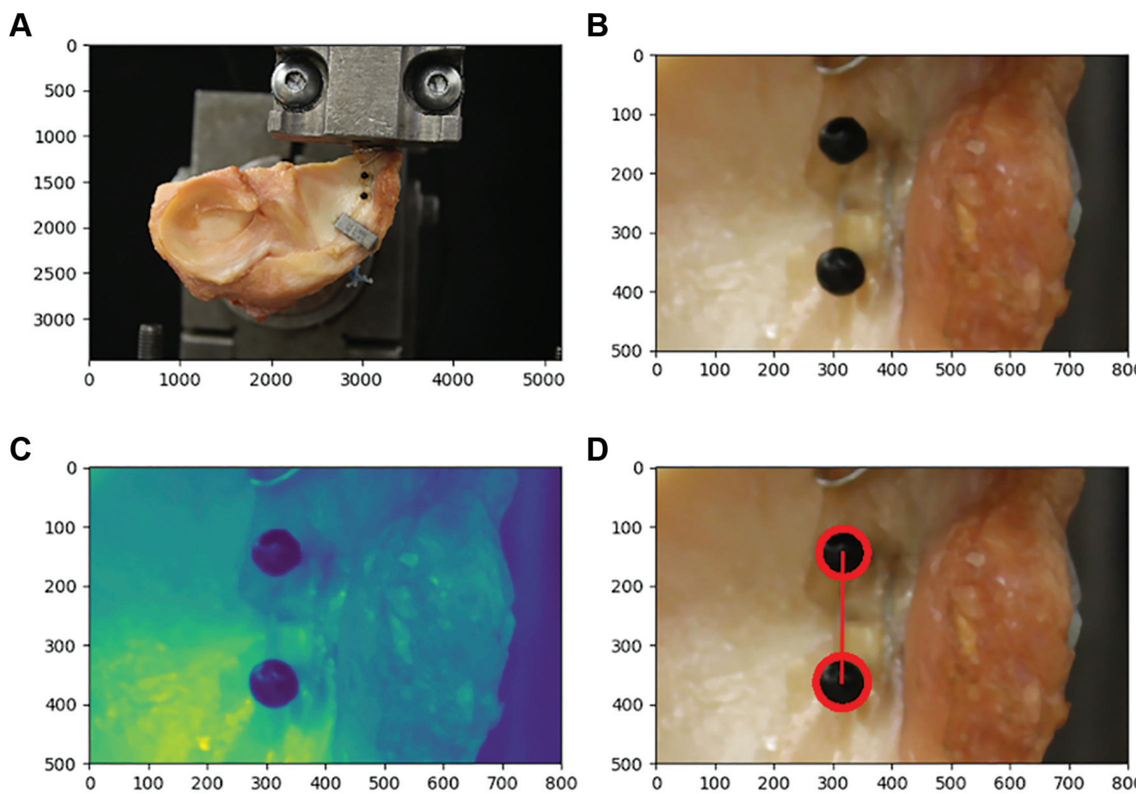

Figure 5. (A) Original image taken during testing. (B) Cropped image to include only the radial tear and the beads in the meniscus. (C) Image converted to grayscale color scheme for compatibility with the HoughCircles image-processing function. (D) Detected circles and distance measured between them in red.

tear and beads placed in the meniscus (Figure 5B). Next, the image was converted to grayscale color so that the beads could be detected with OpenCV's HoughCircles function (Figure 5C). Finally, the vertical distance between the centers of the 2 circles was calculated in pixels and converted to millimeters via comparison with the diameter of the detected circles (in pixels) and the known diameter of the beads (in millimeters) as measured with a digital caliper (Figure 5D). Gapping distances were calculated relative to the distance measured in the image taken at 0 cycles. Failure strength was calculated algorithmically from the load displacement curve with a custom Python script as a reduction $\geq$5% from the local instantaneous peak load, which was maintained for at least 1 mm of pull.

The primary aim was to compare cyclic gapping and load to failure among 3 radial meniscal tear techniques. Parametric analysis of variance with Tukey pairwise post hoc comparisons was performed for gapping and ultimate failure data. *P* values <.05 were considered statistically significant. Given the study design and assumed 2-tailed testing with an alpha level of .0167 (conservative Bonferroni correction for 3 pairwise comparisons), 10 specimens per group was sufficient to detect an effect size (*d*) of 1.57 with 80% statistical power. All analyses and plots were produced with the statistical programming language R (v 3.5.0).[19]

RESULTS

The 2-tunnel and hybrid technique repairs were tested on paired specimens, and the hybrid tunnel repairs were tested on unpaired specimens. However, we observed no meaningful dependence (no significant correlation) between paired specimens in terms of gapping or load to failure. Thus, we proceeded to compare all 3 techniques (including the hybrid tunnel repair) as equally independent groups.

There were no significant differences identified with respect to gap distances measured at each of the cycle time points when the 2-tunnel, hybrid, and hybrid tunnel techniques were compared. The gap distance measurements (mm) are reported in Table 1. All repairs were intact after the cyclic loading protocol.

The load-to-failure testing results are presented in Figure 6. There was no significant difference among the 2-tunnel, hybrid, and hybrid tunnel repair techniques with respect to load to failure.

The method-of-failure results are presented in Table 2. Among specimens that ultimately experienced suture failure or the suture tearing through the meniscus (excluding 3 cases where the tissue failed outside the repair and 2 cases where the specimen slipped on pull to failure), the 2-tunnel technique (7 of 9, 78%) was significantly more likely to tear through the meniscus than the 2 groups

TABLE 1
Gapping by Repair Technique and Cycle Number for Radial Medial Meniscal Tears

	Gapping by Technique, mm (Mean ± SD)			
Cycles	Two Tunnel	Hybrid	Hybrid Tunnel	*P* Value
0	0 ± 0	0 ± 0	0 ± 0	
10	1.5 ± 1.0	1.2 ± 0.7	1.0 ± 0.6	.412
50	1.8 ± 1.3	1.7 ± 0.7	1.4 ± 0.9	.647
100	2.0 ± 1.4	2.0 ± 0.8	1.5 ± 0.8	.459
250	2.4 ± 1.5	2.3 ± 0.8	1.8 ± 0.9	.411
500	2.7 ± 1.6	2.7 ± 0.8	2.0 ± 1.0	.347
1000	3.0 ± 1.7	3.0 ± 0.9	2.3 ± 1.0	.4042

TABLE 2
Effect of Adding the "Rip Stop" Suture to Failure Location During Pull-to-Failure Testing

	Technique, n (%)		
	Two Tunnel (n = 9)	Hybrid and Hybrid Tunnel (n = 16)	*P* Value
Sutures ripped through meniscus	7 (78)	4 (25)	.017
Suture failure	2 (22)	12 (75)	

utilizing the rip stop stitch (4 of 16, 25%) (Fisher exact test, 2-tailed *P* = .017).

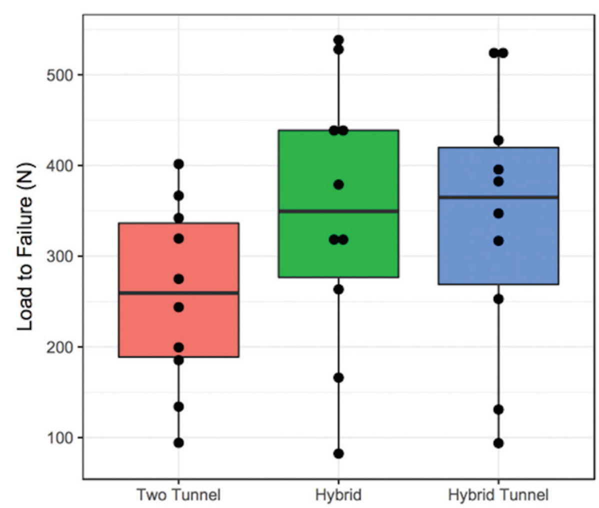

Figure 6. Boxplot comparing load to failure (N) among medial meniscus radial repair technique groups. Dots represent individual specimen observations. Thick horizontal lines represent group medians, while top and bottom of boxes represent the 25th and 75th percentiles, respectively.

DISCUSSION

The most important finding of this study was that we found no significant differences in gap distance or ultimate failure strength when comparing the 2-tunnel, hybrid, and hybrid tunnel radial repair techniques. It is unknown what the necessary failure strength is to resist displacement at the repair site to allow for an optimal meniscal healing environment. However, increased apposition of each radial tear end is likely beneficial and should favor a stronger construct that can resist displacement. When compared against previously reported failure strengths, each of these 3 radial repair techniques was stronger than the traditional simple horizontal mattress configuration.[3,13,21]

We found that the addition of the vertical mattress sutures to act as a rip stop in the hybrid and hybrid tunnel techniques significantly reduced the likelihood of the sutures' pulling through the meniscal tissue during ultimate failure testing. Although our results did not show the hybrid or hybrid tunnel repair to be a biomechanically stronger construct, adding 2 vertical mattress sutures before placing horizontal mattress sutures can help prevent the horizontal sutures from tearing through the meniscus. This is an important consideration and adjunct technique, especially for patients with poor-quality meniscal tissue. Furthermore, as opposed to previous studies of radial repair techniques, which reported failure strengths ranging from 62 to 196 N,[3,13,21] all 3 repair techniques tested in this study had failure strengths >250 N.

Our study examined 2 previously described techniques and introduces a third not previously described or tested in the literature. The number of published techniques to repair radial meniscal tears highlights the fact that the most ideal technique is unknown. Stender et al[21] examined the addition of a vertical mattress suture to act as a rip stop with horizontal sutures ("hashtag") or crossed/diagonal horizontal mattress sutures ("crosstag") in radial repairs of the lateral meniscus, and they compared each technique with a standard 2-suture horizontal mattress repair. They found that the addition of the rip stop suture resulted in significantly less gapping: 2.42 mm (horizontal mattress repair) vs 3.13 mm (crosstag repair: vertical rip stop sutures with diagonal horizontal sutures; *P* = .003) vs 4.78 mm (hashtag repair: vertical rip stop sutures with horizontal sutures; *P* = .024). But they also found failure strength comparable with that of the traditional horizontal mattress configuration: 86.08 N (hashtag repair) vs 62.5 N (crosstag repair; P = .564) vs 81.43 N (horizontal mattress repair; P = .094). The hashtag repair was similar to the current study's hybrid repair, with only 2 horizontal mattress sutures over the 2 vertical sutures. The crosstag repair placed 2 crossing, oblique sutures over the 2 vertical sutures. One important consideration not previously examined or standardized was the number of sutures used for repair. Our study utilized 4 horizontal mattress sutures for each repair, with 2 on the superior meniscal surfaces and 2 on the inferior, as this has been our clinically utilized preference. Most previous studies examined 2 sutures on the superior surface at the repair site.[5,12,21] The improved strength with our repairs as compared with values published in the literature suggests utilizing 4 horizontal mattress sutures over solely 2 horizontal mattress sutures, but additional work is needed in this area.

For radial meniscal tears, our study shows that the 3 techniques are biomechanically similar in gap distance and failure strength. However, when each technique is applied, some theoretical differences exist. The 2-tunnel and hybrid tunnel techniques have the added benefit of drilling through the tibia, releasing biologic healing mediators from the tibial bone marrow to the radial tear site. It is unknown what effect the release of pluripotent mesenchymal stem cells from drilling 2 transosseous tunnels can have on meniscal healing; nevertheless, we continue to learn about the importance of bioactive factors in addition to biomechanical strength for tissue healing, and the use of marrow venting has been noted to be beneficial to isolated meniscal repair healing.[7] In the setting of the need for concomitant tibial tunnels for multiligament reconstruction, placement of these transosseous tunnels becomes more challenging. This highlights a potential benefit of the hybrid technique, which shows similar results but does not necessitate the need for tibial tunnel drilling.

Although all-inside repair of radial meniscal tears is a technically easier technique, several authors reported poor outcomes after utilizing it.[4,5] We advocate for an inside-out approach for repair of radial tears. Previous studies examining inside-out repair reported outcomes comparable with repairs of vertical meniscal tears.[8] We believe that the hybrid tunnel technique represents an ideal technique for a complete radial meniscal tear owing to its biologic release of pluripotent stem cells from the transosseous drilling, as well as its biomechanical strength demonstrated in this study.

The current study supports the biomechanical equivalence of the 3 tested techniques, allowing for one to choose the technique best suited for the type of radial tear. With good tissue quality, the hybrid repair technique is our current preferred technique for a partial or near-complete radial meniscal tear that does not extend to the peripheral margin. For an isolated partial radial tear, we would also consider the addition of a notch microfracture, fibrin clot, or biologic injection as an adjunct to the repair. For a complete radial tear that extends into the meniscocapsular margin or has ends of the radial tear that are widely separated, we prefer the hybrid tunnel repair technique. This allows for each limb of the complete radial tear to be effectively treated as a meniscal root tear, anchoring and approximating the tear limbs to sufficiently restore the meniscal rim. Biomechanically, adding the rip stop vertical mattress suture significantly reduced the likelihood of the horizontal mattress sutures' pulling through the meniscal tissue on pull-to-failure testing. Furthermore, we believe that the transtibial tunnels add biologic properties that are an important augment to improve the likelihood of healing this challenging tear. Similar treatment strategies to augment soft tissue repairs with biologically active mediators showed success in rotator cuff repair[20] and for isolated meniscal repair.[7] We believe that the hybrid and hybrid tunnel repair techniques with the rip stop suture configuration are both valuable additions to our current options to repair radial meniscal tears.

Our study has some limitations. First, our biomechanical testing was performed on cadaveric meniscal tissue, which inherently may have altered structural properties versus in vivo meniscal tissue. Next, the true forces seen at a radial meniscal repair site during normal knee kinematics are possibly different from those tested by the material testing system used in this study. However, this study design was shown in previous studies to be effective in examining the biomechanical properties of meniscal repairs.[3,21] Nevertheless, published work supports the importance of an improved biomechanical construct to translate to in vivo connective tissue healing, especially in the setting of poor vascularity.[10,22] Additionally, we developed the idea for the hybrid tunnel technique after examining the results from the 2-tunnel and hybrid techniques, with the goal of combining the benefits from each technique. This meant that we did not plan for 3 testing groups; thus, the third group was tested on unpaired specimens. This does introduce potential bias based on specimen quality; however, we performed a correlational investigation and found no meaningful dependence between paired specimens in terms of gapping or load to failure, thereby allowing us to compare the 3 groups as equally independent groups. Finally, when testing the 2-tunnel technique, we found a higher ultimate load to failure and larger gapping distance as compared with the results of a similar study examining the same technique.[3] In our study, we utilized a computer algorithm rather than human measurement to calculate the gapping distances, which could have resulted in less human error and thus the varied results.

CONCLUSION

The 2-tunnel, hybrid, and hybrid tunnel radial meniscal repair techniques demonstrated equivalent biomechanical testing in regard to gap distance and pull-to-failure strength. The addition of the vertical mattress sutures to act as a rip stop suture was effective in preventing meniscal cut-out of the meniscus and may be utilized in poor quality tissue. On the basis of concomitant procedures, tear location, and tear extent, the surgeon can employ the appropriate technique that allows for the most optimal meniscal radial tear healing.

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REFERENCES

1. Badlani JT, Borrero C, Golla S, Harner CD, Irrgang JJ. The effects of meniscus injury on the development of knee osteoarthritis: data from the osteoarthritis initiative. *Am J Sports Med*. 2013;41(6):1238-1244.
2. Bedi A, Kelly NH, Baad M, et al. Dynamic contact mechanics of the medial meniscus as a function of radial tear, repair, and partial meniscectomy. *J Bone Joint Surg Am*. 2010;92(6):1398-1408.
3. Bhatia S, Civitarese DM, Turnbull TL, et al. A novel repair method for radial tears of the medial meniscus: biomechanical comparison of transtibial 2-tunnel and double horizontal mattress suture techniques under cyclic loading. *Am J Sports Med*. 2016;44(3):639-645.
4. Branch EA, Milchteim C, Aspey BS, Liu W, Saliman JD, Anz AW. Biomechanical comparison of arthroscopic repair constructs for radial tears of the meniscus. *Am J Sports Med*. 2015;43(9):2270-2276.
5. Choi N-H, Kim T-H, Son K-M, Victoroff BN. Meniscal repair for radial tears of the midbody of the lateral meniscus. *Am J Sports Med*. 2010;38(12):2472-2476
6. Cinque ME, Geeslin AG, Chahla J, Dornan GJ, LaPrade RF. Two-tunnel transtibial repair of radial meniscus tears produces comparable results to inside-out repair of vertical meniscus tears. *Am J Sports Med*. 2017;45(10):2253-2259.
7. Dean CS, Chahla J, Matheny LM, Mitchell JJ, LaPrade RF. Outcomes after biologically augmented isolated meniscal repair with marrow venting are comparable with those after meniscal repair with concomitant anterior cruciate ligament reconstruction. *Am J Sports Med*. 2017;45(6):1341-1348.
8. Ellman MB, LaPrade CM, Smith SD, et al. Structural properties of the meniscal roots. *Am J Sports Med*. 2014;42(8):1881-1887.
9. Furumatsu T, Kodama Y, Kamatsuki Y, Hino T, Ozaki T. Arthroscopic repair of the medial meniscus radial/oblique tear prevents the progression of meniscal extrusion in mildly osteoarthritic knees. *Acta Med Okayama*. 2017;71(5):413-418.
10. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ. The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons: an experimental study on the early stages of tendon-healing in dogs. *J Bone Joint Surg Am*. 1999;81(7):975-982.
11. Harper KW, Helms CA, Lambert HS, Higgins LD. Radial meniscal tears: significance, incidence, and MR appearance. *AJR Am J Roentgenol*. 2005;185(6):1429-1434.
12. James EW, LaPrade CM, Feagin JA, LaPrade RF. Repair of a complete radial tear in the midbody of the medial meniscus using a novel crisscross suture transtibial tunnel surgical technique: a case report. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(9):2750-2755.
13. Matsubara H, Okazaki K, Izawa T, et al. New suture method for radial tears of the meniscus: biomechanical analysis of cross-suture and double horizontal suture techniques using cyclic load testing. *Am J Sports Med*. 2012;40(2):414-418.
14. Moulton SG, Bhatia S, Civitarese DM, Frank RM, Dean CS, LaPrade RF. Surgical techniques and outcomes of repairing meniscal radial tears: a systematic review. *Arthroscopy*. 2016;32(9):1919-1925.
15. Nakata K, Shino K, Kanamoto T, et al. New technique of arthroscopic meniscus repair in radial tears. In: Doral MN, ed. *Sports Injuries*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2012:305-311.
16. OpenCV. HoughCircles transform. https://opencv.org. Accessed June 2018.
17. Pareek A, O'Malley MP, Levy BA, Stuart MJ, Krych AJ. Inside-out repair for radial meniscus tears. *Arthrosc Tech*. 2016;5(4):e793-e797.
18. Python Software Foundation. *Python: A Programming Language That Lets You Work Quickly and Integrate Systems More Effectively*. Wilmington, DE: Python Software Foundation; 2017.
19. R Core Team. R: a language and environment for statistical computing. https://www.R-project.org/. Accessed July 10, 2018.
20. Snyder SJ, Burns J. Rotator cuff healing and the bone marrow ''crimson duvet'' from clinical observations to science. *Tech Shoulder Elbow Surg*. 2009;10(4):130-137.
21. Stender ZC, Cracchiolo AM, Walsh MP, Patterson DP, Wilusz MJ, Lemos SE. Radial tears of the lateral meniscus-two novel repair techniques: a biomechanical study. *Orthop J Sports Med*. 2018;6(4):2325967118768086.
22. Tamboli M, Mihata T, Hwang J, McGarry MH, Kang Y, Lee TQ. Biomechanical characteristics of the horizontal mattress stitch: implication for double-row and suture-bridge rotator cuff repair. *J Orthop Sci*. 2014;19(2):235-241.