# Biomechanical Comparison of Vertical Mattress and Cross-stitch Suture Techniques and Single- and Double-Row Configurations for the Treatment of Bucket-Handle Medial Meniscal Tears

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**Background:** Given the variety of suturing techniques for bucket-handle meniscal repair, it is important to assess which suturing technique best restores native biomechanics.

**Purpose/Hypothesis:** To biomechanically compare vertical mattress and cross-stitch suture techniques, in single- and double-row configurations, in their ability to restore native knee kinematics in a bucket-handle medial meniscal tear model. The hypothesis was that there would be no difference between the vertical mattress and cross-stitch double-row suture techniques but that the double-row technique would provide significantly improved biomechanical parameters versus the single-row technique.

**Study Design:** Controlled laboratory study.

**Methods:** Ten matched pairs of human cadaver knees were randomly assigned to the vertical mattress (n = 10) or cross-stitch (n = 10) repair group. Each knee underwent 4 consecutive testing conditions: (1) intact, (2) displaced bucket-handle tear, (3) single-row suture configuration on the femoral meniscus surface, and (4) double-row suture configuration (repair of femoral and tibial meniscus surfaces). Knees were loaded with a 1000-N axial compressive force at 0°, 30°, 60°, 90°, and 120° of flexion for each condition. Resultant medial compartment contact area, average contact pressure, and peak contact pressure data were recorded.

**Results:** Intact state contact area was not restored at 0° (P = .027) for the vertical double-row configuration and at 0° (P = .032), 60° (P < .001), and 90° (P = .007) of flexion for the cross-stitch double-row configuration. No significant differences were found in the average contact pressure and peak contact pressure between the intact state and the vertical mattress and cross-stitch repairs with single- and double-row configurations at any flexion angles. When the vertical and cross-stich repairs were compared across all flexion angles, no significant differences were observed in single-row configurations, but in double-row configurations, cross-stitch repair resulted in a significantly decreased contact area, average contact pressure, and peak contact pressure (all P < .001).

**Conclusion:** Single- and double-row configurations of the vertical mattress and cross-stitch inside-out meniscal repair techniques restored native tibiofemoral pressure after a medial meniscal bucket-handle tear at all assessed knee flexion angles. Despite decreased contact area with a double-row configuration, mainly related to the cross-stitch repair, in comparison with the intact state, the cross-stitch double-row repair led to decreased pressure as compared with the vertical double-row repair. These findings are applicable only at the time of the surgery, as the biological effects of healing were not considered.

**Clinical Relevance:** Medial meniscal bucket-handle tears may be repaired with the single- or double-row configuration of vertical mattress or cross-stitch sutures.

**Keywords:** medial meniscus; bucket-handle tear; in situ repair; medial compartment load; Tekscan pressure sensors

Bucket-handle tears, defined as longitudinal tears with an attached fragment displaced away from the remnant meniscus,[43] have been reported to account for up to 10% of all meniscal tears[32] and represent a unique challenge to treat owing to their complexity. Repair of bucket-handle

tears has traditionally been achieved via an inside-out technique with vertical mattress sutures,[10] which was validated to result in comparable clinical outcomes among patients treated for nondisplaced vertical tears of the meniscus (usually smaller and less complex).[34]

The vertical mattress suture pattern for meniscal repairs is performed because of its reported biomechanical superiority over horizontal mattress sutures.[13,20,23,25,39,40,42] However, it remains unknown whether restoration of native joint kinematics and contact pressures may be more optimally achieved with a different suture configuration, such as by stacking crisscrossed oblique sutures,[1,3,9,14,18,33,40] also referred to as the cross-stitch suture technique.[14] Meniscal repair with cross-stitch suture orientation was shown in canines to restore native joint contact pressures and area at an equivalent standing angle of 20° to 30° of human knee flexion,[21,37,40] warranting investigation into its efficacy in human knees across a larger flexion arc.

While the cross-stitch suture repair pattern was suggested to be comparable to the more widely utilized vertical mattress suture pattern, there is a paucity of literature directly comparing the effectiveness of either in the repair of bucket-handle tears. As such, the ideal suture configuration for a bucket-handle repair has yet to be elucidated. Furthermore, the effect of single-row suturing (superior surface only) versus double-row suturing (superior and inferior surfaces) with the same quantity of sutures on tibiofemoral contact pressure is unknown. Therefore, the purpose of this study was to biomechanically compare the vertical mattress and cross-stitch suture techniques and the single- and double-row configurations in a bucket-handle medial meniscal tear model, analyzing contact area, average contact pressure, and peak contact pressure. Our hypotheses were that (1) there would be no difference between the vertical mattress and cross-stitch double-row suture techniques and (2) the double-row technique would provide significantly improved biomechanical parameters (contact area, average contact pressure, and peak contact pressure) as compared with the single-row technique.

## METHODS

### Specimen Preparation

Ten matched-pair fresh-frozen male human cadaver knee specimens with a mean age of 53.1 years (range, 42-60 years) were used in this study. Knees with arthroscopic evidence of meniscal damage, ligament tears of the cruciate or collateral ligaments, or cartilage degeneration (greater than grade I Outerbridge classification) were excluded. The cadaveric specimens were donated to registered tissue banks for the purpose of medical research and then purchased by our institution. The use of cadaveric specimens for research does not require Institutional Review Board approval at Vail Health Hospital.

Specimens were thawed 24 hours before dissection and testing and were dissected free of skin, soft tissue attachments, muscle, tendon, and the patella. The collateral and cruciate ligaments of the knee and the medial, lateral, and posterior aspects of the capsule were retained. The femur, tibia, and fibula were cut approximately 20 cm from the joint line. The cut ends of the distal tibia and fibula were then potted in a cylindrical mold with PMMA (polymethyl methacrylate; Fricke Dental International Inc), with the tibial plateau oriented parallel to the testing surface and with the bone cement encasing the bone up to a point 4 cm distal to the tibial tuberosity.

With a custom drill guide, a 10-mm-diameter transverse tunnel was drilled through the medial and lateral femoral epicondyles, oriented parallel to the articular surfaces of the femoral condyles.[27,35] Special care was taken to avoid disrupting the origins of the collateral ligaments during this process. A rod passing through this tunnel acted as the load-bearing site and flexion pivot point for the construct. Next, a 5-mm-diameter transverse tunnel was drilled, parallel to the first, with the center axis positioned 18 mm proximal and posterior to the first tunnel. An oblique medial femoral condyle osteotomy was performed to permit medial compartment access, avoiding injury of the medial collateral ligament, to create the different meniscus conditions (Figure 1).[30] Careful execution of this process allowed for the preservation of the posterior cruciate ligament attachment to the medial femoral wall and all medial meniscal structures. A compression screw was applied through this tunnel with washers and a nut to reattach the medial femoral condyle and maintain the original anatomic position throughout testing. Given the high stresses placed on the osteotomy during deep flexion testing, the osteotomy reduction and fixation was bolstered using a 1.85 mm × 7.6 mm metal plate and four 3.5 inch dual-cortical wood screws (No. 8; McMaster Carr).

To allow for the insertion of a pressure sensor between the meniscus and tibial plateau, the anterior meniscotibial

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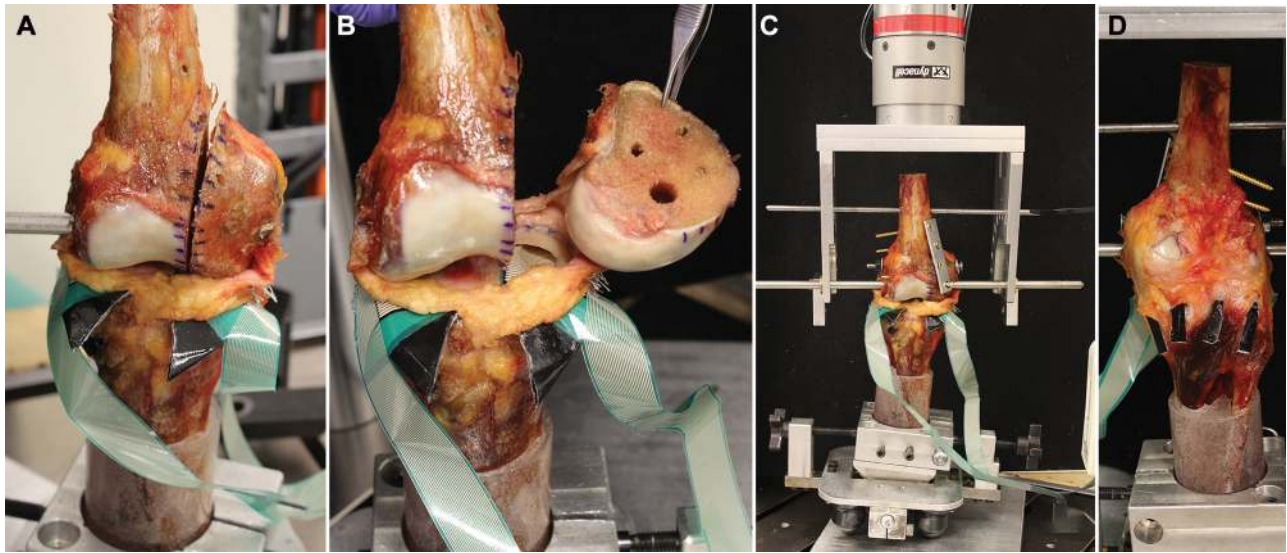¶Twin Cities Orthopedics, Edina, Minnesota, USA.

**Figure 1.** Anterior views of the right knee: (A) medial condyle osteotomy, (B) testing setup, (C) 0° of flexion. Posterior view: (D) testing setup with the right knee at 0° of flexion.

(coronary) ligaments of the medial and lateral menisci were detached at their insertion onto the tibia extending from just anterior to the medial and lateral collateral ligaments to the anterior roots, thereby preserving the anterior root attachments. Two small incisions (5 mm) were made to detach the posterior coronary ligaments of the medial and lateral menisci, preserving the posterior oblique ligament and popliteus musculotendinous junction, respectively.[19,30] To ensure sufficient capsule for subsequent meniscal suture, all anterior and posterior accesses for pressure sensor placement started 10 mm below the tibial plateau; then, the capsule and coronary ligaments were carefully peeled off from their tibial attachments in an inferior-to-superior direction. Martens et al[30] reported no change in tibiofemoral biomechanics parameters with a similar technique after the reattachment of the osteotomized medial femoral condyle and incision of coronary ligaments for pressure film placement.

## Testing Setup

New pressure sensors (model 4000; Tekscan) were calibrated and equilibrated for testing according to the manufacturer's guidelines and previously published protocols developed at this institution.[22,27] A new sensor was used for each specimen to ensure the validity of the data. The 2-pronged sensors were then inserted into the medial and lateral compartments between the tibial articular cartilage and meniscus.[19,30]

The orientation of the medial condyle was ensured to be anatomic by lining up markings drawn along the osteotomy site prior to cutting. The 10-mm rod was then passed through a custom-made jig attached to the actuator of a dynamic tensile testing machine (E10000; Instron), securing the specimen in the testing apparatus (Figure 1).

Varus or valgus angulation of the specimen was adjusted while an axial load was applied to the specimen through the range of flexion angles to equalize axial load distribution on the medial and lateral compartments. Distribution of the total load was confirmed to be equal on the medial and lateral compartments with live feedback from the pressure sensors. This process ensured that observed differences in pressure and contact area measurements were due to the condition changes and not subtle inconsistencies in the placement of the femoral pivot axis or unequal load distribution between compartments.[26,35] Once this varus/valgus angulation was set, it remained constant throughout the testing protocol.

Finally, a transverse, 7-mm tunnel was reamed through the shaft of the femur, approximately 7.5 cm proximal to and parallel to the 10-mm pivot tunnel. A 7-mm steel rod was passed through this tunnel to allow for selection of flexion angles during testing (0°, 30°, 60°, 90°, and 120°). This tunnel was reamed after the varus/valgus angulation was set because pilot testing revealed that small errors in the angle of this rod in the fixture could affect the measurements of the pressure sensors at different flexion angles. The specimen was frequently sprayed with saline solution to prevent desiccation of the tissues throughout the testing period.

## Testing Conditions

Each knee pair underwent 4 sequential testing conditions of the medial meniscus: (1) intact, (2) simulated longitudinal displaced bucket-handle tear, (3) single-row repair on the femoral meniscus surface, and (4) double-row repair adding sutures to the tibial surface of the meniscus. From each pair, 1 knee was randomly assigned to receive the vertical repair and 1 knee, the cross-stitch repair. After each condition, the knee was removed from the testing apparatus, and the osteotomy opened for visualization of the meniscus and to allow for consistent tears and repairs to be performed in all specimens. The bucket-handle tear was created with a No. 15 scalpel blade and was 5 cm in
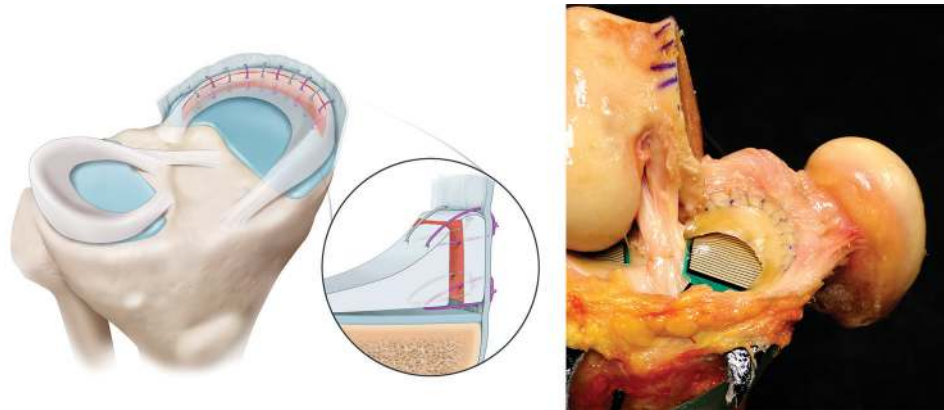
**Figure 2.** Vertical mattress meniscal suture technique with double-row configuration in a right knee.
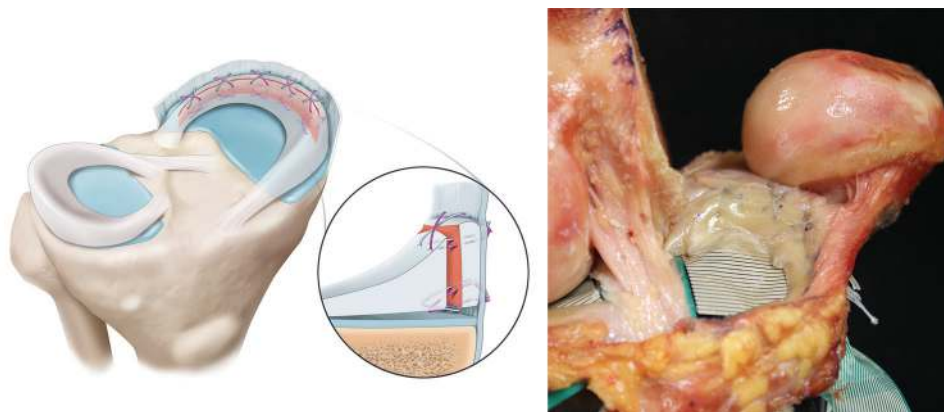


**Figure 3.** Cross-stitch meniscal suture technique with double-row configuration in a right knee.

length circumferentially, extending along 1 to 3 mm from the meniscocapsular junction, from posterior to anterior, 1 cm from the posterior root attachment site to a point just anterior to the meniscotibial ligament of the deep medial collateral ligament. The torn meniscus was secured in the displaced position with a No. 2-0 nonabsorbable suture (FiberWire; Arthrex) passed through the tear site and tied to a wood screw passed through the tibial tuberosity. In condition 3, the randomly assigned repair was performed in inside-out fashion with a meniscus protector suturing set (Arthrex) and No. 2-0 nonabsorbable suture (FiberWire). Each suture was tied with 5 half-stitches over the capsule with appropriate tension. The first row of sutures (single-row configuration) was placed on the femoral aspect of the medial meniscus for this condition. The vertical mattress repair was completed with 10 vertical mattress sutures placed 5 mm apart, passing through the tear and capsular portions of the meniscus. The suture entry points on the capsule and meniscus were the same for the cross-stitch repair but in a crossed configuration so that 5 sets of 2 cross-stitch sutures were placed over the tear with each cross-stitch placed 5 mm apart. In condition 4, the assigned repair was repeated and added to the tibial aspect of the meniscus to create a double-row configuration (Figures 2 and 3).

## Biomechanical Testing

All specimens were tested by loading the joint with a constant 1000-N axial compressive load along the axis of the tibia for 30 seconds at 5 flexion angles (0°, 30°, 60°, 90°, 120°) for each condition. Contact pressure mechanics were recorded with pressure-mapping sensors (model 4000; Tekscan) from which the contact area, peak contact pressure, and average contact pressure could be determined. Before each knee flexion angle was tested, a load of 200 N was placed on the knee, and the position of the pressure sensor was adjusted to ensure that the maximum possible load was being transmitted to the sensor. Dead cells that resulted from damage to sensors during testing were reconciled during postprocessing by filling in the data set with values averaged from the surrounding rows and columns of cells.

## Data Processing

Tekscan pressure sensors have been reported to linearly lose sensitivity for peak load amplitude during compressive biomechanical testing.[26] To account for this, the rate of decline was assessed throughout testing and found to be 0.7% per test. The raw mean and peak contact pressure data were processed with a detrending adjustment of 0.7%
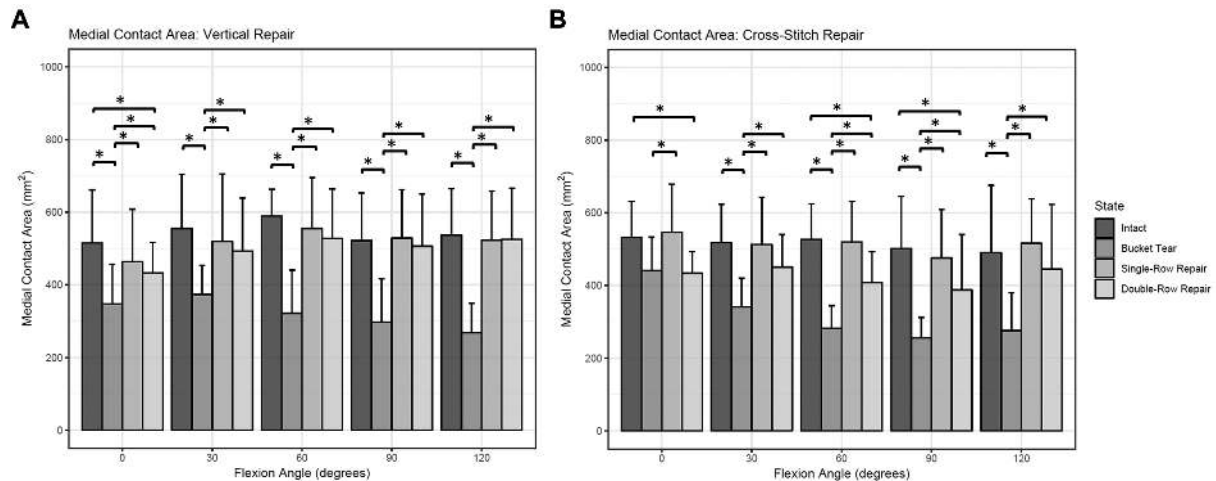
**Figure 4.** Medial compartment contact area in (A) the vertical repair group and (B) the cross-stitch repair group for a bucket-handle medial meniscus at all flexion angles. Values are presented as mean ± SD. *P < .05.

per test to account for this decline, in the same manner as previous studies.[17,22,26,35]

## Statistical Analysis

To account for the repeated measures nature of the experimental design, linear mixed effects models were used to compare contact area, average contact pressure, and peak contact pressure between knee states and between paired specimens on which different suturing techniques were performed (vertical mattress vs cross-stitch). One-factor linear mixed effects models were constructed to compare knee states at each flexion angle and for each repair technique separately. Vertical mattress and cruciate techniques, performed on matched specimens, were directly compared with 2-factor linear mixed effects models (technique and flexion angle). This approach was used separately for single- and double-row repairs. Residual diagnostics were performed to ensure a quality model fit and that model assumptions were met. Tukey post hoc comparisons were used to make pairwise comparisons between groups. As a simplification of the full linear mixed effects model analysis, we considered the statistical power of individual repeated measures comparisons of group means. Based on the assumption of 2-tailed parametric testing and an alpha level of 0.05, 10 specimens for each group (vertical mattress and cross-stitch suture techniques) were sufficient to detect an effect size of $d = 1.0$ with 80% statistical power. Thus, statistically nonsignificant results where the observed effect size was <1 may be underpowered in this study. Therefore, the study was powered to detect differences between means that were >1 SD. The statistical software R (v 3.5.0) was used for all plots and analyses.[6,36,41]

## RESULTS

### Medial Compartment Contact Area

*Vertical Mattress Repair Group.* No significant differences were found at any flexion angle for the contact area between the single- or double-row configurations and the intact state, with the exception of a significant decrease in contact area at 0° between the double-row and the intact state. Single- and double-row configurations had significantly increased contact area at all flexion angles when compared with the bucket-handle tear state (Figure 4A).

*Cross-stitch Repair Group.* No significant differences were found at any flexion angle between the single-row configuration and the intact state; however, at 0°, 60°, and 90°, the contact area was significantly decreased between the double-row configuration and the intact state. Single- and double-row configurations had significantly increased contact area at all flexion angles when compared with the bucket-handle tear state, except at 0° for the double-row configuration (Figure 4B).

### Medial Compartment Average Contact Pressure

*Vertical Mattress Repair Group.* No significant differences were found in the average contact pressure for the vertical repair group at any state at any flexion angle (Figure 5A).

*Cross-stitch Repair Group.* No significant differences were found between the single- and double-row configurations and the intact state at any flexion angle. When compared with the bucket-handle tear state, average contact pressure was significantly decreased in the single- and double-row configurations groups at 30°, 60°, 90°, and 120° (Figure 5B).

### Medial Compartment Peak Contact Pressure

*Vertical Mattress Repair Group.* No significant differences were found in the peak contact pressure at any flexion angle for the vertical repair group, with the exception of a significant increase in the peak pressure at 0° between the intact and bucket-handle tear states (Figure 6A).

*Cross-stitch Repair Group.* No significant differences were found between the single- and double-row suture
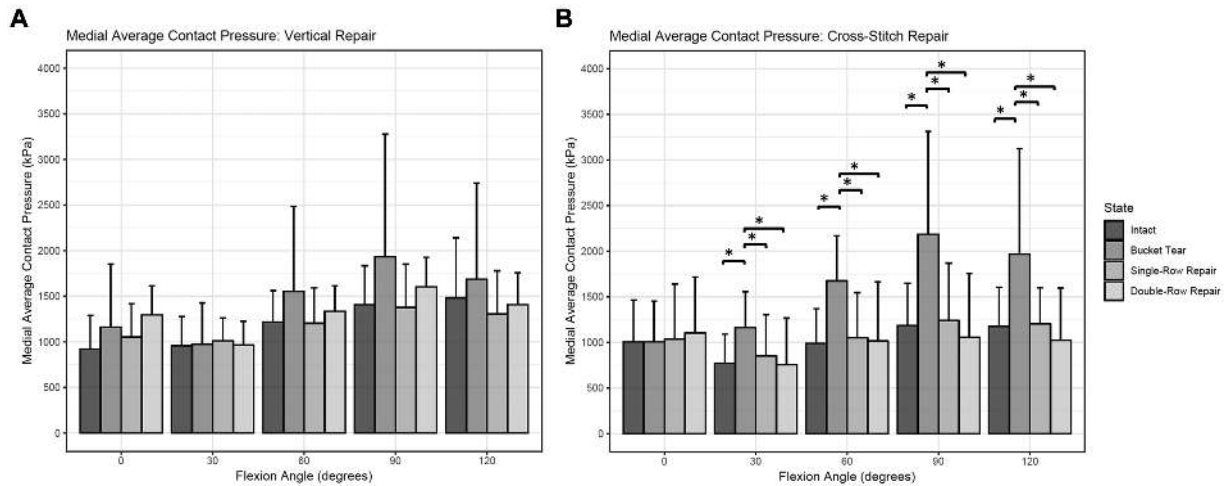
**Figure 5.** Medial average pressure in (A) the vertical repair group and (B) the cross-stitch repair group for a bucket-handle medial meniscus at all flexion angles. Values are presented as mean ± SD. *$P < .05$.
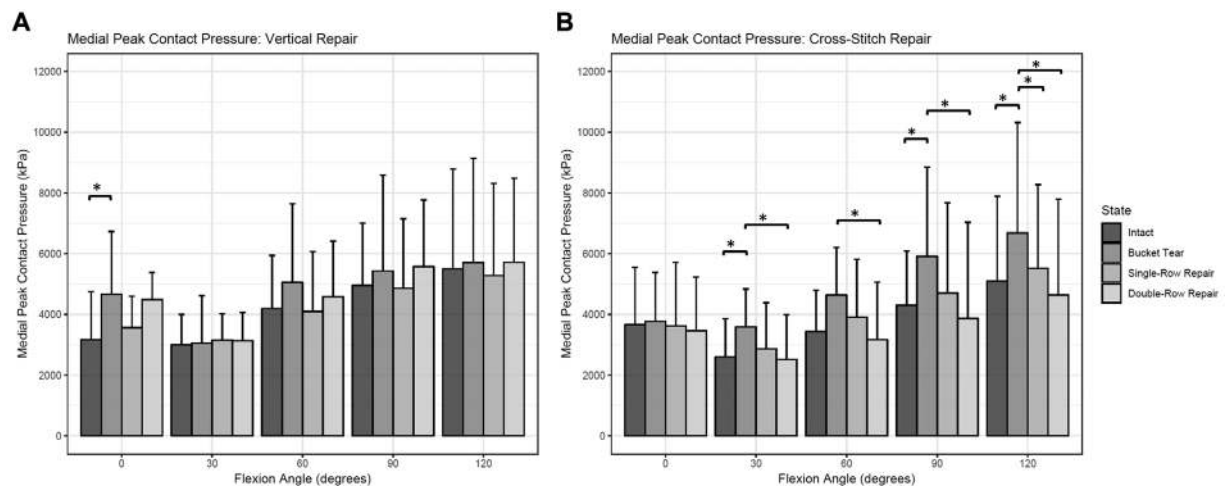


**Figure 6.** Medial peak pressure in (A) the vertical repair group and (B) cross-stitch repair group for a bucket-handle medial meniscus at all flexion angles. Values are presented as mean ± SD. *$P < .05$.

configurations and the intact state at any flexion angle. The double-row repair significantly decreased the peak contact pressure at all flexion angles, except for 0°, when compared with the bucket-handle tear state. The single-row repair saw a significant decrease in contact pressure only at 120° of flexion (Figure 6B).

### Intragroup Comparison: Single Row vs Double Row

Intragroup comparisons were examined through 1-factor linear mixed effects models to check for any effects from using the single- or double-row suture technique. No significant differences were found in any of the metrics analyzed at any flexion angle between the single- and double-row configurations for both the vertical mattress and cross-stitch suture techniques (Figures 4-6).

### Group Comparison: Vertical Mattress vs Cross-stitch

Comparisons were made between groups to check for any effects from using the vertical mattress or cross-stitch suture technique at all flexion angles. No significant differences were found between the vertical and cross-stitch groups in the single-row configuration for any of the metrics analyzed. In the double-row configuration, the cross-stitch suture technique showed a significantly decreased contact area (72 mm$^2$) as well as significant decreases in mean (333.21 kPa) and peak (1167.02 kPa) contact pressures when compared with the vertical suture technique (all $P < .001$).

### DISCUSSION

The most important findings of this study were that single- and double-row vertical mattress and cross-stitch inside-

out meniscal repair techniques restored native tibiofemoral pressure after a medial meniscal bucket-handle tear at a majority of assessed knee flexion angles within the detectable limits determined from the power analysis. The cross-stitch double-row configuration repair resulted in a decrease in mean and peak pressure but also a decrease in contact area when compared with the vertical mattress double-row configuration across all flexion angles simultaneously. Our hypothesis that the double-row configuration would be the best biomechanical configuration was not fully confirmed. In spite of the fact that the cross-stitch double-row meniscal suture technique led to decreased pressure in comparison with the vertical mattress double-row meniscal suture technique, both repair conditions restored tibiofemoral pressure in comparison with their respective intact states, and there was no difference directly comparing single- and double-row configurations for either the cross-stitch or vertical mattress suture technique. Additionally, the single-row configuration for the cross-stitch and vertical mattress suture techniques was enough to restore the contact areas of their intact states. However, the double-row configuration—with the same number of sutures in the femoral and tibial meniscus surfaces—led to decreased contact area in comparison with the intact state for the cross-stitch suture technique at most of the evaluated knee flexion angles and for the vertical mattress at just 0° of flexion.

Our results suggest that, in the clinical setting, a medial meniscal bucket-handle tear may be repaired with the single- or double-row configuration of the vertical mattress or cross-stitch suture technique. During the surgical procedure, the surgeon can choose to use a hybrid suture technique (cross-stich and vertical mattress) for a bucket-handle meniscal tear, preferring just 1 vertical mattress suture when a small area needs to be addressed and a cross-stitch suture technique when a part of the injury presents a complex tear pattern that must be involved in a larger area and could not be easily repaired with vertical mattress sutures. Concerning single- and double-row configurations, a double-row configuration should be used to achieve anatomic reduction because a single-row configuration applied to the femoral surface of the meniscus can pull it away from the tibial plateau, introducing inferior meniscal gapping. Given all these aspects and that the final clinical result is determined by biological healing, we cannot make a definitive recommendation of just 1 suturing technique (vertical mattress or cross-stitch) or 1 configuration (single or double row) for a medial meniscal bucket-handle tear.

An interesting finding in our study was that, despite decreased contact area, the cross-stitch double-row repair led to decreased pressure in comparison with the vertical mattress double-row repair at some flexion angles. These results are conflicting because the pressure is expected to increase in the face of a decreased contact area, as proved by the biomechanical analyses of partial and total meniscectomy.[3,8,24,28,40] This suggests that, in this configuration, the load was transmitted away from the pressure sensor. A possible explanation is that the cross-stitch double-row configuration repair worked like a net, enfolding more

meniscal tissue than the vertical mattress double-row configuration repair. This effect would pull the meniscus away from the center of the medial plateau through all the length of the bucket-handle injury to a portion of the plateau that was unable to be covered by the pressure sensor, consequently decreasing contact area. Despite this decrease in contact area, it was found that this "net effect" improved the meniscus function of absorbing loads by decreasing tibiofemoral pressure at time zero of the repair. Although contact area is a relevant parameter in tibiofemoral biomechanics, average contact pressure and peak contact pressure are more important, clinically relevant, and related to the development of osteoarthritis, as they represent the relation between force and area.[16,35]

Regarding comparisons between the cross-stitch and vertical mattress sutures, 2 other studies biomechanically evaluated single-row configurations and found no differences, similar to our single-row results.[33,40] Milchteim et al[33] compared 2 parallel vertical mattress sutures to 2 crossed sutures for a 1-cm complete longitudinal tear on a cadaveric human meniscus and observed no significant differences in failure load and stiffness. In a canine model, Thiemen et al[40] compared contact pressures following repair of a bucket-handle tear with a horizontal, vertical, or cross-stitch repair technique and found no differences among repair groups with a 150-N limit crescent load at a single knee flexion angle. In contrast, our study was able to detect some significant differences between the double-row vertical mattress and double-row cross-stitch repairs with a higher axial load (1000 N), analyzing multiple flexion angles (0°, 30°, 60°, 90°, and 120°).

Recent biomechanical studies showed that the type of meniscal deficiency is directly correlated to joint contact pressures.[11,26,27] Despite this, few studies biomechanically evaluated medial meniscal bucket-handle injury and treatment in human knees.[5,7,8,29] In the current study, we found that the cross-stitch and vertical repair techniques with the single-row configuration restored native contact mechanics across all flexion angles and that the double-row configuration of these same suturing techniques restored native contact mechanics for the majority of tested flexion angles. In a similar study, Marchetti et al[29] reported that an inside-out repair of a bucket-handle tear with vertical sutures resulted in restoration of contact area and pressure values close to those of the native knee. However, the authors also reported that a single-row vertical repair technique was unable to restore intact contact area and peak contact pressure at flexion angles ≥45°.

By demonstrating that the cross-stitch and vertical repair techniques were both capable of restoring tibiofemoral contact pressures and areas to near-native conditions, our study adds biomechanical validation to the growing body of clinical literature advocating for the repair of meniscal tears over meniscectomy.[12,31,44] In clinical settings, bucket-handle repairs were reported to have excellent postoperative outcome scores at a mean follow-up of at least 2 years with low complication and failure rates.[4,15,38] In a retrospective case series study by Abdelkafy,[2] 38 patients with long vertical longitudinal meniscal tears were submitted to combined cruciate and horizontal

suture techniques. From these 38 patients, 32 patients (6 patients were lost, including 2 failures that were submitted to a meniscectomy in the first postoperative year) were assessed after a mean 4.6 years and had good clinical outcomes (International Knee Documentation Committee score: n = 27, grade A; n = 5, grade B; mean modified Lysholm score: 91.3; mean SF-36: 88.4; mean visual analog scale for operation satisfaction: 8; mean visual analog scale for pain: 1.5). Furthermore, in a recent study, Moatshe et al[34] reported that patients with a bucket-handle tear and patients with a vertical meniscal tear treated with inside-out vertical mattress sutures had comparable results regarding patient-reported outcome scores at 2-year follow-up (SF-12 physical and mental component summaries, Western Ontario and McMaster Universities Osteoarthritis Index, Lysholm, Tegner). The reported clinical outcomes of repaired bucket-handle tears can be attributed to the biomechanical evidence of improved joint kinematics in knees with repaired meniscal tissue. However, further patient outcome studies are needed to evaluate the efficacy of the cross-stitch repair technique in a clinical setting.

We acknowledge some limitations of the present study. Inherent to any time-zero cadaveric biomechanical study, this study model does not take into account any postoperative healing of the meniscus and the cyclic loading to which the surgical procedures are submitted. Given this study's sample size, we cannot conclusively rule out group comparisons with true effect sizes that are <1 (Cohen *d*). While a custom drill guide was used to drill the 10-mm-diameter transverse tunnel in a similar location on each testing specimen, slight variations in angle could have had an effect on the construct pivot point and consequently on load distribution between the medial and lateral tibial plateau compartments. To rectify this, a custom pivot table was used to maintain varus/valgus alignment of each specimen so that both tibial plateaus were submitted to equal loads across all flexion angles.[35] Additionally, the Tekscan pressure sensors used in the study tended to gradually lose their sensitivity throughout the testing period because of pressure sensor crinkling, sensor load saturation above calibration, sensor record changes owing to liquid exposure, and injured sensing structures. We assumed that this decrease in force sensitivity followed a linear trend, as reported in previous studies, so data analysis code was written to account for this.[35] The meniscal conditions were not tested through full knee range of motion, but we chose the most representative flexion angles (0°, 30°, 60°, 90°, 120°). A full double-row configuration was evaluated, matching each femoral surface meniscal suture on the tibial surface, as it was observed that using only a single row of sutures at the meniscocapsular junction introduced inferior meniscal gapping from the tibial plateau and that the placement of the second row of sutures at the inferior aspect of the meniscus helped to reduce the meniscus back to the tibial plateau. A partial double-row configuration, with fewer sutures on the tibial surface, was not evaluated but may be the topic of future studies because the current full double-row configuration decreased the contact area in comparison with the intact state.

## CONCLUSION

Single- and double-row configurations of the vertical mattress and cross-stitch inside-out meniscal repair techniques restored native tibiofemoral pressure after a medial meniscal bucket-handle tear at all assessed knee flexion angles. Despite decreased contact area with a double-row configuration, mainly related to the cross-stitch repair, in comparison with the intact state, the cross-stitch double-row repair led to decreased pressure in comparison with the vertical double-row repair. These findings are applicable only at the time of the surgery as the biological effects of healing were not considered.

## ACKNOWLEDGMENT

## REFERENCES

1. Abdelkafy A. Modified cruciate suture technique for arthroscopic meniscal repair: a technical note. *Knee Surg Sports Traumatol Arthrosc*. 2007;15(9):1116-1120.
2. Abdelkafy A. Short- to mid-term results of arthroscopic meniscal repair of long vertical longitudinal tears using combined cruciate and horizontal suture techniques: a retrospective study. *Eur J Orthop Surg Traumatol*. 2015;25(2):367-374.
3. Abdelkafy A, Wlk M, Krasny C, Landsiedl F. The "cruciate suture" for arthroscopic meniscal repair: a new technique. *Arthroscopy*. 2006;22(10):1134.e1-1134.e5.
4. Ahn JH, Kim KI, Wang JH, Kyung BS, Seo MC, Lee SH. Arthroscopic repair of bucket-handle tears of the lateral meniscus. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(1):205-210.
5. Baratz ME, Fu FH, Mengato R. Meniscal tears: the effect of meniscectomy and of repair on intraarticular contact areas and stress in the human knee. A preliminary report. *Am J Sports Med*. 1986;14(4):270-275.
6. Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Statistical Software*. 2015;67(1):1-48.
7. Becker R, Wirz D, Wolf C, Göpfert B, Nebelung W, Friederich N. Measurement of meniscofemoral contact pressure after repair of bucket-handle tears with biodegradable implants. *Arch Orthop Trauma Surg*. 2005;125(4):254-260.
8. 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.
9. 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.
10. Burns TC, Giuliani JR, Svoboda SJ, Owens BD. Meniscus repair and transplantation techniques. *J Knee Surg*. 2011;24(3):167-174.
11. 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.
12. Chahla J, Cinque ME, Godin JA, et al. Meniscectomy and resultant articular cartilage lesions of the knee among prospective National

Football League players: an imaging and performance analysis. *Am J Sports Med*. 2018;46(1):200-207.

13. Chahla J, Serra Cruz R, Cram TR, Dean SC, LaPrade RF. Inside-out meniscal repair: medial and lateral approach. *Arthrosc Tech*. 2016; 5(1):e163-e168.

14. Cruz-López F, Trueba C, Almazán A, et al. Meniscal repair using the inside-out technique with cross stitch. *Sports Med Arthrosc Rev*. 2012;20(2):101-105.

15. Fillingham YA, Riboh JC, Erickson BJ, Bach BR Jr, Yanke AB. Inside-out versus all-inside repair of isolated meniscal tears: an updated systematic review. *Am J Sports Med*. 2017;45(1):234-242.

16. Franciozi CE, Tarini VA, Reginato RD, et al. Gradual strenuous running regimen predisposes to osteoarthritis due to cartilage cell death and altered levels of glycosaminoglycans. *Osteoarthritis Cartilage*. 2013;21(7):965-972.

17. Geeslin AG, Civitarese D, Turnbull TL, Dornan GJ, Fuso FA, LaPrade RF. Influence of lateral meniscal posterior root avulsions and the meniscofemoral ligaments on tibiofemoral contact mechanics. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(5):1469-1477.

18. Gunes T, Bostan B, Erdem M, Asci C, Sen C, Kelestemur MH. The ''butterfly'' suture technique for meniscal repair. *Arch Orthop Trauma Surg*. 2011;131(3):331-333.

19. Harris ML, Morberg P, Bruce WJ, Walsh WR. An improved method for measuring tibiofemoral contact areas in total knee arthroplasty: a comparison of K-scan sensor and Fuji film. *J Biomech*. 1999;32(9):951-958.

20. Iuchi R, Mae T, Shino K, Matsuo T, Yoshikawa H, Nakata K. Biomechanical testing of transcapsular meniscal repair. *J Exp Orthop*. 2017;4(1):2.

21. Jaegger G, Marcellin-Little DJ, Levine D. Reliability of goniometry in Labrador Retrievers. *Am J Vet Res*. 2002;63(7):979-986.

22. 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.

23. Kocabey Y, Taser O, Nyland J, et al. Pullout strength of meniscal repair after cyclic loading: comparison of vertical, horizontal, and oblique suture techniques. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(10):998-1003.

24. Koh JL, Yi SJ, Ren Y, Zimmerman TA, Zhang LQ. Tibiofemoral contact mechanics with horizontal cleavage tear and resection of the medial meniscus in the human knee. *J Bone Joint Surg Am*. 2016;98(21):1829-1836.

25. Kohn D, Siebert W. Meniscus suture techniques: a comparative biomechanical cadaver study. *Arthroscopy*. 1989;5(4):324-327.

26. LaPrade CM, Foad A, Smith SD, et al. Biomechanical consequences of a nonanatomic posterior medial meniscal root repair. *Am J Sports Med*. 2015;43(4):912-920.

27. 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.

28. Lee SJ, Aadalen KJ, Malaviya P, et al. Tibiofemoral contact mechanics after serial medial meniscectomies in the human cadaveric knee. *Am J Sports Med*. 2006;34(8):1334-1344.

29. Marchetti DC, Phelps BM, Dahl KD, et al. A contact pressure analysis comparing an all-inside and inside-out surgical repair technique for bucket-handle medial meniscus tears. *Arthroscopy*. 2017;33(10):1840-1848.

30. Martens TA, Hull ML, Howell SM. An in vitro osteotomy method to expose the medial compartment of the human knee. *J Biomech Eng*. 1997;119(4):379-385.

31. McDermott ID, Amis AA. The consequences of meniscectomy. *J Bone Joint Surg Br*. 2006;88(12):1549-1556.

32. Metcalf MH, Barrett GR. Prospective evaluation of 1485 meniscal tear patterns in patients with stable knees. *Am J Sports Med*. 2004;32(3):675-680.

33. Milchteim C, Branch EA, Maughon T, Hughey J, Anz AW. Biomechanical comparison of parallel and crossed suture repair for longitudinal meniscus tears. *Orthop J Sports Med*. 2016;4(4):2325967116640263.

34. Moatshe G, Cinque ME, Godin JA, Vap AR, Chahla J, LaPrade RF. Comparable outcomes after bucket-handle meniscal repair and vertical meniscal repair can be achieved at a minimum 2 years' follow-up. *Am J Sports Med*. 2017;45(13):3104-3110.

35. Padalecki JR, Jansson KS, Smith SD, 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.

36. R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing; 2018.

37. Sabanci SS, Ocal MK. Comparison of goniometric measurements of the stifle joint in seven breeds of normal dogs. *Vet Comp Orthop Traumatol*. 2016;29(3):214-219.

38. Saltzman BM, Cotter EJ, Wang KC, et al. Arthroscopically repaired bucket-handle meniscus tears: patient demographics, postoperative outcomes, and a comparison of success and failure cases [published online June 1, 2018]. *Cartilage*. doi:10.1177/1947603518783473

39. Seil R, Rupp S, Kohn DM. Cyclic testing of meniscal sutures. *Arthroscopy*. 2000;16(5):505-510.

40. Thieman KM, Pozzi A, Ling HY, Lewis D. Comparison of contact mechanics of three meniscal repair techniques and partial meniscectomy in cadaveric dog stifles. *Vet Surg*. 2010;39(3):355-362.

41. Wickham H. *ggplot2: Elegant Graphics for Data Analysis*. New York, NY: Springer; 2009.

42. Woodmass JM, LaPrade RF, Sgaglione NA, Nakamura N, Krych AJ. Meniscal repair: reconsidering indications, techniques, and biologic augmentation. *J Bone Joint Surg Am*. 2017;99(14):1222-1231.

43. Wright DH, De Smet AA, Norris M. Bucket-handle tears of the medial and lateral menisci of the knee: value of MR imaging in detecting displaced fragments. *AJR Am J Roentgenol*. 1995;165(3):621-625.

44. Xu C, Zhao J. A meta-analysis comparing meniscal repair with meniscectomy in the treatment of meniscal tears: the more meniscus, the better outcome? *Knee Surg Sports Traumatol Arthrosc*. 2015;23(1):164-170.