Original Research

Continuous Vertical Inside-Out Versus Traditional Vertical Inside-Out Meniscal Repair

A Biomechanical Comparison

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Background: Biomechanical assessment of meniscal repairs is essential for evaluating different meniscal suturing methods and techniques. The continuous meniscal suture technique is a newer method of meniscal repair that may have biomechanical differences compared with traditional techniques.

Purpose: To evaluate the displacement, stiffness after cyclical loading, and load to failure for a continuous vertical inside-out meniscal suture versus a traditional vertical inside-out meniscal suture in a porcine medial meniscus.

Study Design: Controlled laboratory study.

Methods: A total of 28 porcine knees were acquired and divided into 2 test groups of 14 medial meniscus each. A 2.0-cm longitudinal red-white zone cut was made in the body of the medial meniscus for each knee. The continuous suture (CS) group received 4 vertical stitches performed with a continuous vertical meniscal suture technique, and the inside-out suture (IO) group received a traditional vertical suture with 4 stitches. Two traction tapes were passed between the sutures and positioned in the biomechanical testing fixture device. Each specimen underwent load-to-failure testing at 5 mm/s, and displacement, system stiffness, and maximum load to failure were compared between the groups.

Results: The displacement after the cyclic test was 0.53 ± 0.12 and 0.48 ± 0.07 mm for the CS and IO groups, respectively. There was no significant difference between the groups (P = .2792). The stiffness at the ultimate load testing was 36.3 ± 1.9 and 35.3 ± 2.4 N/mm for groups CS and IO, respectively, with no significant difference between the groups (P = .2557). In the load-to-failure test, the ultimate load was 218.2 ± 63.9 and 238.3 ± 71.3 N in the CS and IO groups, respectively, with no significant group differences (P = .3062).

Conclusion: A continuous vertical meniscal suture created a configuration for treating longitudinal meniscal lesions that was beneficial and biomechanically similar to a traditional vertical suture technique.

Clinical Relevance: The study findings indicate that use of the continuous vertical inside-out meniscal suture technique is a possible therapeutic option.

Keywords: biomechanics; inside-out; meniscal repair; primary fixation

Untreated meniscal injuries or those in which a meniscectomy was performed can lead to early joint degeneration.[11,13] Meniscal repair preserves the meniscal tissue, increasing the chance of healing in the injured area of

The Orthopaedic Journal of Sports Medicine, 11(11), 23259671231209951
DOI: 10.1177/23259671231209951

the meniscus and contributing considerably to the preservation of the affected knee compartment.[11,28]

Vertical longitudinal tears are injuries commonly found in the medial meniscus.[20] Treatment of an unstable longitudinal meniscal lesions has traditionally been repaired with an inside-out technique.[2,24,25,28] Recently, 2 modified inside-out meniscal suture techniques, the vertical and horizontal continuous meniscal repair, were described by our author group.[26,27] We developed the continuous meniscal suture technique to simplify the surgical technique of inside-out meniscus repair and minimize the time required to perform it.[26,27]

Several studies have evaluated the different types of meniscal sutures biomechanically in animal models[3,9,11,22,31] and cadaveric knees.[5,8,14,18] These studies assessed which configuration and surgical technique have a lower chance of failure when the meniscal tissues are subjected to multiple load cycles.[3,5,8,9,11,14,18,22,31] However, biomechanical evaluations comparing the continuous inside-out meniscal suturing technique with the gold standard of inside-out meniscal suturing have not been performed. These evaluations are necessary to compare the biomechanical performance of the 2 surgical techniques, thus allowing the comparison of the similarity or superiority of one technique to the other.

The purpose of this study was to biomechanically assess the repair site displacement or gapping, repair stiffness, and resistance to failure between the continuous vertical inside-out and traditional vertical inside-out meniscal sutures. We hypothesized that the continuous vertical inside-out repair would present biomechanical results cited above similar to traditional sutures.

METHODS

Study Specimens

This study did not require authorization from an animal ethics committee because the porcine knees involved were acquired from commercial food establishments. A total of 28 porcine knees were used in this study and obtained from hybrid animals with an approximate age and weight of 6 months and 105 kg, respectively. The knees were used less than 24 hours after the animal was sacrificed. They were kept in a refrigerator at approximately 3°C until the dissection. The joint remained closed until the time of dissection. At this time, the knees were kept at room temperature. The femur was resected by careful dissection while avoiding injury to the medial meniscus during dissection. If any injury to the meniscus was observed because of dissection or a previous injury, the knee was excluded from the analysis. A total of 14 knees were then allocated to receive continuous vertical inside-out meniscal sutures (CS group), while the other 14 knees were allocated to receive traditional vertical inside-out meniscal sutures (IO group) (Figure 1).

Experimental Protocol

A 2 cm–long longitudinal tear was created 4 mm from the boundary between the meniscus and capsule at the medial meniscal body (Figure 2). Before suturing, the tears were not extended into the anterior and posterior meniscal horns to make the repair process easier. Four vertical stitches were used for the repair on the femoral surface of the meniscus (Figure 1). Each point was equidistant from the others by approximately 3 to 4 mm. A No. 1 S-Tape (Síntegra Surgical Sciences; thickness 0.08 mm; width 0.45 mm), and the meniscus 4 ALL meniscal suturing device (Síntegra Surgical Sciences) was used for the meniscus suturing in the CS group. The same suture tape was used in the IO group with the Protector Meniscus meniscal suture device (Arthrex). Two traction tapes (S-Tape thickness 0.70 mm, and width 1.10 mm, made of ultrahigh-molecular-weight polyethylene [Teleflex]) were passed between the sutures and were positioned in the biomechanical testing fixture device. They were required for radial pulling of the meniscal edges in an opposite direction in an attempt to fail the suture. Six traction tapes were placed, 2 in each space between the suture tapes pulled in opposite directions (Figure 3). After performing the repair, the meniscal tear was extended to completely divide the meniscus, ensuring that load transmission occurred only through the repair material so that only the suture threads maintain contact between the injured meniscal edges.[1,3,11,22] In this way, the biomechanical tests did not undergo any changes in relation to some type of tissue maintaining contact between meniscal injuries.

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Final revision submitted March 2, 2023; accepted June 2, 2023.
One or more of the authors has declared the following potential conflict of interest or source of funding: Research support and material were received from Síntegra Surgical Sciences. J.L.R.d.F. has received nonconsulting fees from Síntegra Surgical Sciences, grants from Síntegra Surgical Sciences, and has 2 patents pending. R.F.L. has received royalties from Arthrex, Ossur, Smith & Nephew, and Elsevier; consulting fees from Smith & Nephew and Ossur; and nonconsulting fees from Smith & Nephew and Linvatec. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.
Ethical approval was not sought for the present study.

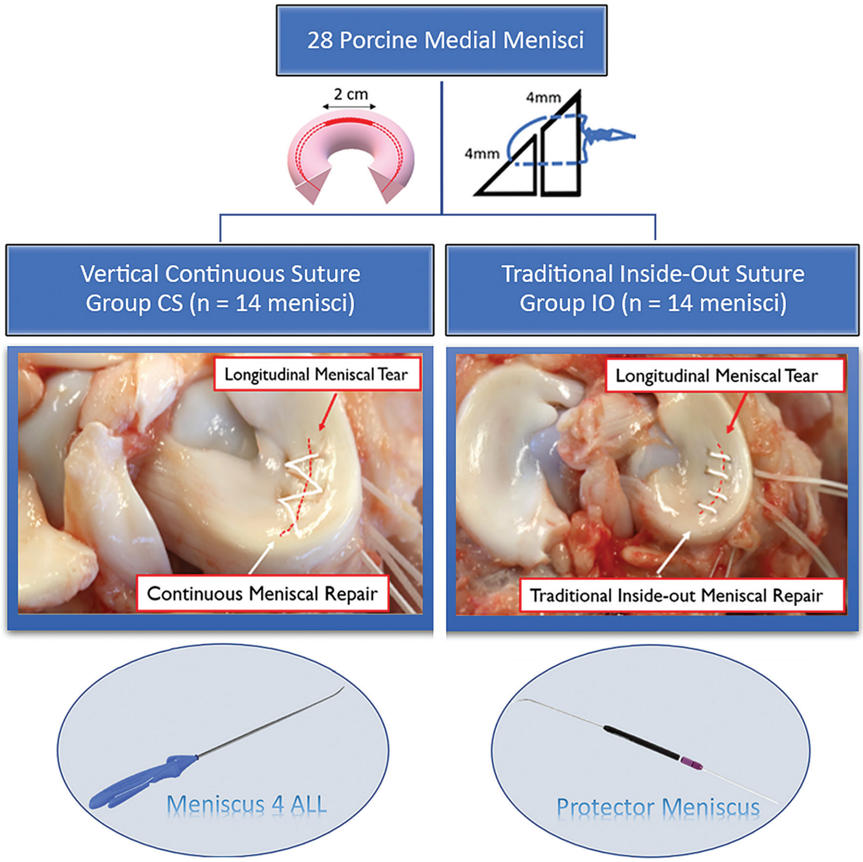

Figure 1. Schematic illustration of the 2 study groups. CS group, with 14 medial menisci, submitted to vertical continuous meniscal repair, and IO group, with 14 medial menisci, submitted to traditional vertical inside-out meniscal repair. The CS group used 4 stitches using the Meniscus 4-ALL device, and the IO group used 4 stitches using the Protector Meniscus device.

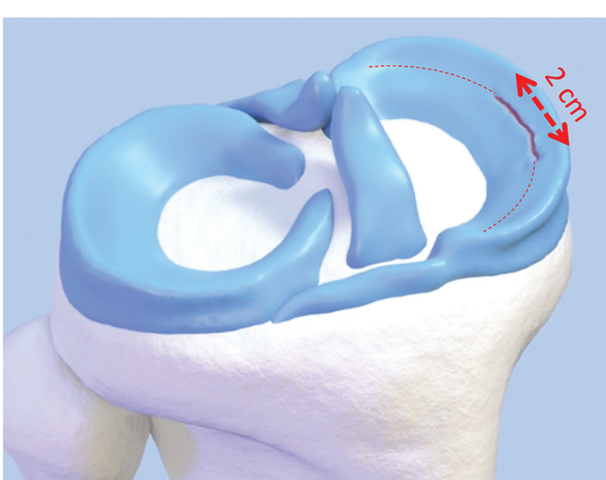

Figure 2. Longitudinal tear initially created 2 cm in length (red area) in transition from the red zone to the white zone of the medial meniscus. The red dotted area represents the region that will be sectioned after the 4 sutures have been performed.

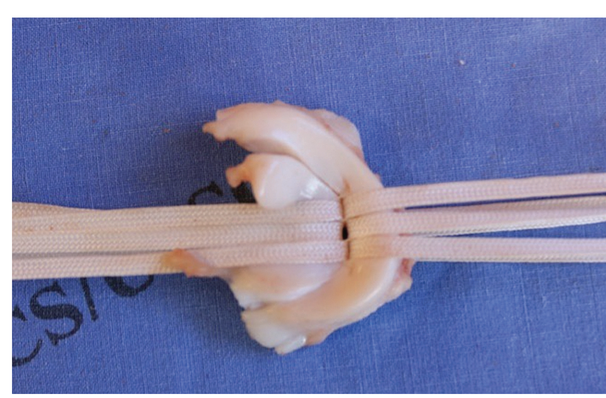

Figure 3. A total of 6 traction tapes (0.4 × 3.5 mm) passed in opposite directions, positioned at each gap between the sutures. We also visualized the enlarged lesion reaching the meniscal edges, simulating a worst-case scenario where only the suture keeps the meniscal fragments together.

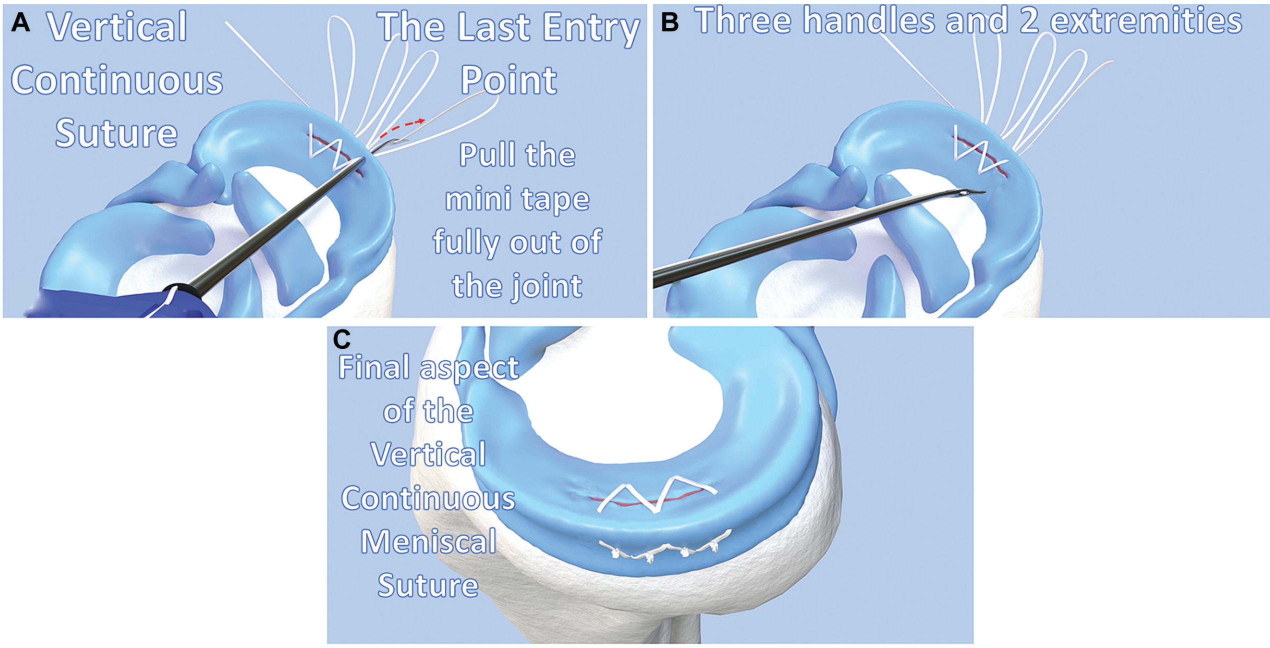

Figure 4. Schematic model of continuous vertical meniscal suture. (A) The mini tape of the meniscal suture is pulled out of the joint, removing it from the lumen of the device. (B) Final configuration of a suture with 4 points, with 3 loops and 2 ends of the mini tape suture. (C) Final appearance of continuous vertical suture with 4 points (Images adapted with permission from Rocha de Faria, Pavão DM, Cruz RS, et al. Vertical continuous meniscal suture technique. *Arthrosc Tech*. 2020;9(9):e1335-e1340. doi:10.1016/j.eats.2020.05.014 et al).

A continuous vertical inside-out meniscal suture was performed in the CS group as described in our previous study (Figure 4).[26] In the IO group, a traditional vertical inside-out meniscal suture was performed (Figure 1).[23]

For each technique, we performed 4 sutures using suture tapes S-Tape (0.08 × 0.45 mm). Previously, traction tape stitches (0.7 × 1.10 mm) were passed between the suture tapes. The tear was completed edge-to-edge, simulating the most severe meniscal injury. Traction tapes with the same length for all specimens were fixed in a custom device using screws designed to maintain all tapes parallels and in the radial direction (Figure 5). The device was attached to the load cell and fixed to a universal testing machine (ZwickRoell Z2.5TN). The testing machine has a maximum incertainty of ±0.28% in displacement measurement and a loading cell with maximum capacity of 2.5 kN, with an accuracy of ±0.11%.

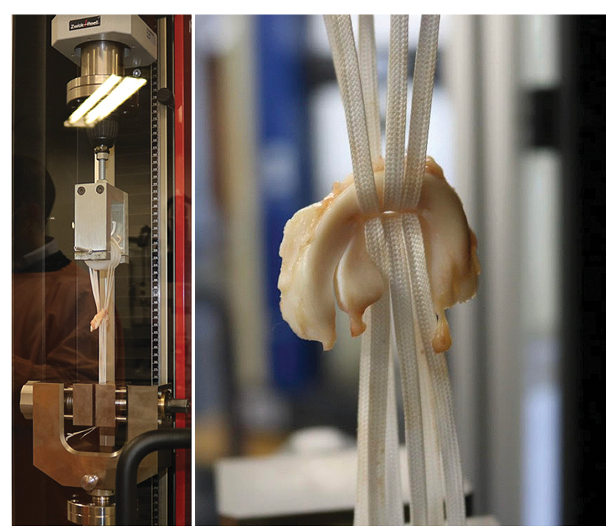

Figure 5. Menisci were prepared for biomechanical analysis on a universal testing machine.

Testing Protocol and Evaluation

Before cyclic loading, a tension preload of 5 N was placed for 30 seconds, followed by 30 loading cycles ranging between 5 and 30 N, performing a triangular waveform at 0.25 Hz in displacement control. This cyclic protocol has been used by other investigators.[6,7,15,16,19] and previous studies showed stabilization of the displacement-versus-time curve between 20 and 30 cycles.[19,6,7,16] Upon completion of cyclic loading, each specimen underwent a load-to-failure test at 5 mm/s. The following biomechanical variables were assessed: (1) the widening gap at the suture after 30 cycles (ie, displacement) was assessed indirectly by subtracting the crosshead displacement from the system compliance measured without the sutured meniscus. (2) Ultimate failure load was considered the maximum force achieved at the load-to-failure phase. (3) System stiffness was measured at the 5th, 30th, and at the load-to-failure cycle, and the construct stiffness

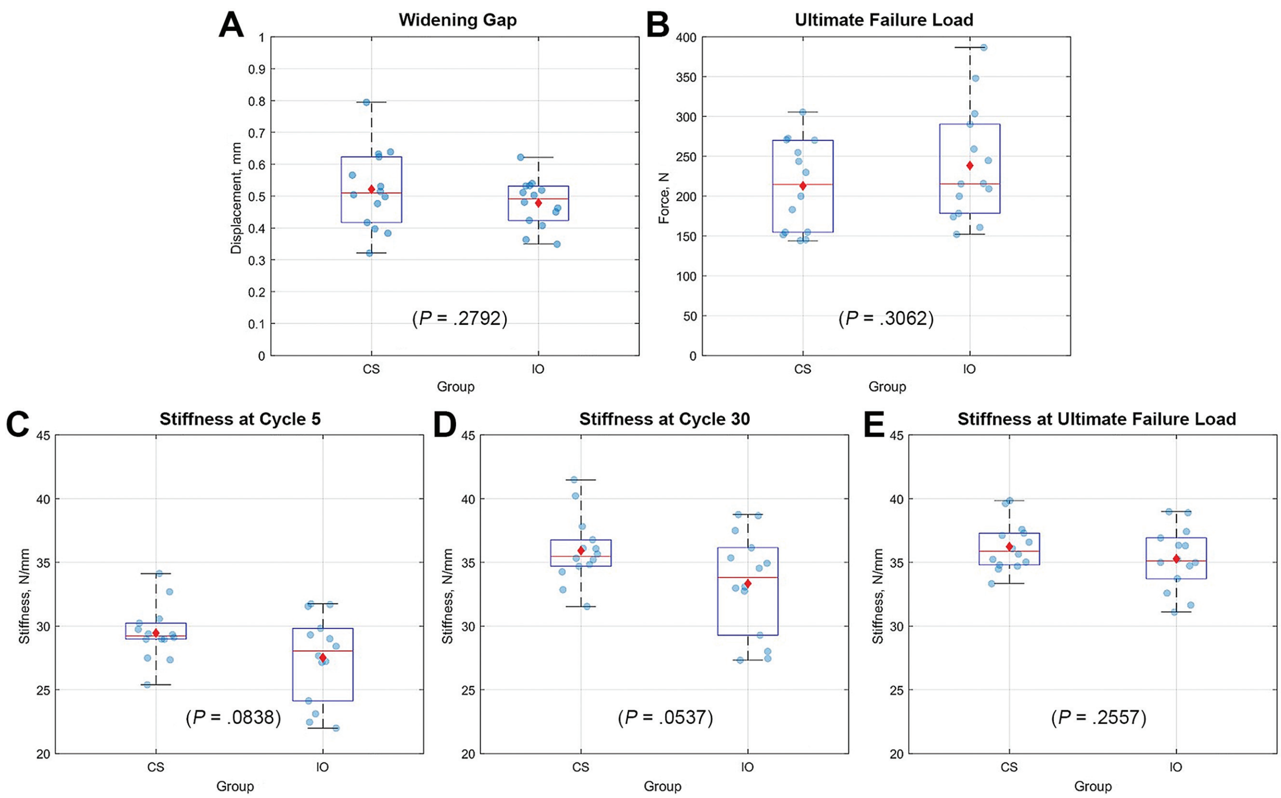

Figure 6. Boxplots showing data for (A) widening at the meniscal repaired site after 30 cycles of preconditioning loading, (B) ultimate failure load at the load-to-failure test phase, and system stiffness (C) at the 5th cycle, (D) at the 30th cycle, and (E) at the ultimate failure load. Circles represent each datapoint, diamonds represents the mean, central horizontal line indicates the median, and bottom and top edges of the box indicate 25th and 75th percentiles, respectively. Whiskers extend to the most extreme datapoints.

was determined from the endpoints of the linear region of the load-versus-displacement curve. Finally, the failure mode was determined by inspecting the samples visually at the end of each test. In this step, the first suture that failed was considered to define the specific failure mode.

Statistical Analysis

The normality of the data distribution for each group was assessed using the Shapiro-Wilk test with a positive outcome. Group variance was analyzed using the *F* test, and we observed that the groups did not differ from each other. Thus, the mean difference was compared using the Student *t* test, assuming equal variance. Considering a 2-tailed alpha of 0.05 for the *t* test with 2 independent samples, we calculated that a sample with 14 specimens per group would be sufficient to obtain 80% power to detect a Cohen $d \geq 1.1$, which we considered sufficient for a preliminary study such as this. The Fisher exact test was used to assess the failure mode for each group. All tests were performed using statistical analysis software (RStudio, Version 1.1.456). Statistical significance was set at $P < .05$.

TABLE 1
Comparison of Widening Gap, Ultimate Failure Load, and Stiffness Between Groups[a]

	CS Group (n = 14)	IO Group (n = 14)	*P**
Widening gap after 30 cycles, mm	0.53 ± 0.12	0.48 ± 0.07	.2792
Ultimate failure load, N	218.2 ± 63.9	238.3 ± 71.3	.3062
Stiffness, N/mm			
At cycle 5	29.4 ± 2.2	27.5 ± 3.4	.0838
At cycle 30	35.8 ± 2.6	33.3 ± 4.0	.0537
At ultimate failure load	36.3 ± 1.9	35.3 ± 2.4	.2557

[a]Data are shown as mean ± SD. CS, continuous suture; IO, inside-out suture.
*Student *t* test.

RESULTS

There were no statistically significant differences between the CS and IO techniques in lesion displacement, system stiffness, or maximum load to failure. The results are shown in Table 1 and Figure 6.

TABLE 2
Comparison of Observed Frequencies for Failure Modes Between Groups[a]

	CS Group (n = 14)	IO Group (n = 14)	P*
Suture breakage	3	2	≥.999
Suture pullout	0	1	≥.999
Knot failure	11	11	≥.999

[a]Data are shown as number of knees.
*Fisher exact test.

The assessment of failure mode indicated that there were 3 main types of failure: suture breakage, suture pull-out, and knot failure. To determine whether there is a significant relationship between these 3 categorical variables, 3 Fisher exact tests were performed with 2 variables each time (resulting in a 2 × 2 contingency table). All 3 tests resulted in *P* values >.05, indicating no significant differences between the CS and IO techniques. The results are shown in Table 2.

DISCUSSION

The most important finding of this study was that there was no significant difference in lesion displacement (widening gap), system stiffness, and maximum load to failure between continuous vertical inside-out meniscal suture and inside-out vertical mattress suture techniques. This demonstrated that the continuous vertical inside-out meniscal suture seems to be similar biomechanically to the traditional meniscal suture considered the gold standard treatment for longitudinal meniscal tears.[10]

Several studies have evaluated the displacement of the lesion, stiffness, and maximum load to failure of different meniscal suture configurations.[††] We analyzed the main studies that examined the repair of longitudinal tears[1,11,12,22,31] and show in Table 3 the groups that obtained the best results as stated by the authors of these studies.

As noted, our study also compared 2 groups with suture tapes passed on both meniscal surfaces. According to Yamakama et al[31], this was the best biomechanical configuration for positioning the threads in the repair of longitudinal tears. Only in the Bachmaier et al[1] study was one All-inside group was considered the best. We performed vertical sutures in both groups, and in the CS group, the positioning of the vertical suture was slightly oblique. We used lower-thickness meniscal suture tapes, with 4 sutures, in both evaluated groups. Compared with the studies shown in Table 3, our study was the one that biomechanically evaluated the highest number of sutures. The widening gap in our study was 0.53 ± 0.12 mm in the CS group and 0.48 ± 0.07 mm in the IO group, one of the smallest compared with the studies above.

Regarding the ultimate failure load, we observed 218.2 ± 63.9 N in the CS group and 238.3 ± 71.3 N in the IO group. These results were superior to the best groups of the studies above. Regarding stiffness, we identified a value of 36.3 ± 1.9 N/mm in the CS group and 35.3 ± 2.4N/mm in the IO group. The study by Yamakama et al[31] did not calculate stiffness, while the research by Iuchi et al[12] presented a stiffness of 79.0 ± 48.0 N/mm. Regarding the failure mode observed in our study, the most common was knot failure, while in the studies evaluated in Table 3, there was variability in failure mode. Only the Yamakama et al[31] study group showed a similar failure mode. We believe that the difference observed between our study and the studies above are due to the number of sutures, with a greater number of sutures providing better biomechanical results.

Recent studies have demonstrated that a more significant number of meniscal sutures is associated with a lower reoperation rate due to meniscal healing.[29,30] According to research by Schleschter et al[29], the mean number of sutures in the patients that did not fail was approximately

[††]References 1, 3-5, 8, 9, 12, 14, 21, 24, 31, 32.

TABLE 3
Summary and Findings From Similar Biomechanical Studies[a]

	Yamakama et al[31] (2021)	Iuchi et al[12] (2017)	Hapa et al[11] (2013)	Naqui et al[22] (2006)	Bachmaier et al[1] (2022)
Best group[b]	Group A (inside-out) meniscus × meniscus	Group 3 (inside-out) meniscus × meniscus	Group 4 (inside-out) meniscus × meniscus	Group vertical PDS (inside-out) meniscus × meniscus	Group soft anchor (all-inside) meniscus × meniscus
Repair configuration	Vertical	Vertical stacked	Horizontal	Vertical	Vertical
Suture	Polyester 2-0	Braided polyester 2-0	UHMWPE 2	PDS 1	UHMWPE 2-0
No. of sutures tested	1	2	1	1	1
Widening gap, mm	0.68 ± 0.26	0.41 ± 0.15	2.9 ± 1.1	25.8 (24.1-28.4)[c]	0.75 ± 0.37
Ultimate failure load, N	59.1 ± 13.6	104.6 ± 12.5	186 ± 28.8	103 (78.1-119.6)[c]	146.8 ± 23.4
Stiffness, N/mm	Not reported	79.0 ± 48.0	11.4 ± 3.0	4 (3.18-4.28)[c]	16.7 ± 0.80
Principal failure mode	Knot failure	Suture breakage	Suture cut through	Device breakage	Suture tearing

[a]Data are reported as mean ± SD unless otherwise indicated. PDS, polydioxanone; UHMWPE, ultrahigh-molecular-weight polyethylene.
[b]As considered by the authors of each study.
[c]Reported as mean values and range.

3 (2.97), and approximately 2 (1.79) in the group that failed to repair.[29]

Nakama et al[21] performed a biomechanical study evaluating 10 pairs of cadaveric knees with bucket-handle tears. The knees were divided into 2 groups: group I had 10 vertical sutures, and group II had 10 vertical crossed sutures. Each knee was evaluated biomechanically in 4 situations: uninjured meniscus, meniscus with unrepaired tears, meniscus sutured only on the femoral surface (single vertical [group I] and crossed vertical [group II]), and meniscus also sutured on the tibial surface with 10 stitches. The biomechanical evaluation measured the femorotibial pressure in the different scenarios described above. The knees were evaluated at different flexion angles (0°, 30°, 60°, 90°, and 120°). The authors observed that femorotibial pressure was restored in all angles studied in both groups. Interestingly, in the double-crossed suture group (femoral and tibial faces), the meniscal contact area and femorotibial pressure decreased compared with the single vertical suture group.[21]

Bachmaier et al[1] published a study that compared 4 all-inside suture devices and 2 types of inside-out meniscal repair, all with vertical stitches in 60 human menisci, divided into 6 groups. Each group corresponded to a device and had an sample size of 10 menisci. Three of the all-inside devices used fixation of their sutures with PEEK (polyether ether ketone) anchors (AIR [Stryker], Fast Fix 360 [Smith & Nephew], or TrueSpan [DePuy Mitek]). One device performed its fixation with soft anchors (FiberStitch; Arthrex). The inside-out devices were the same; however, one used a high-resistance suture wire (FiberWire 2-0; Arthrex) and the other used a meniscus suture tape (Mini SutureTape; Arthrex). Those authors found the best biomechanical results on the FiberStitch device with the shortest gapping formed and the highest force observed after repeated loading. However, it is interesting to note that the inside-out suture device that used the meniscal suture tape presented a similar performance to FiberStitch, with both the stiffness and the load evaluated. Bachmaier et al[1] observed a maximum stiffness of 23.4 N/mm in the FiberStitch load group and 20.6 N/mm in the inside-out MiniTape group, and the maximum load is 146.8 N in the FiberStitch group and 139.4 N in the inside-out MiniTape group. The suture tape used in the Bachmaier et al[1] study was similar to that used in our study. We used a very similar mini suture tape in both groups. We observed a maximum load of 218.2 N in the CS group and 238.3 N in the IO group, most likely higher values because we used 4 sutures, a fact closer to the reality of the meniscal tears found in clinical practice. The Bachmaier et al[1] study found that the new all-inside meniscal suture devices present high-performance biomechanically. However, the inside-out technique using mini suture tapes also presents very similar biomechanical results.[17] Despite these findings, it is important to conduct further comparative clinical studies to establish which method of meniscal repair offers superior outcomes.

Limitations

As a limitation of our study, we cite that the loading direction was nonphysiological. Nevertheless, as a first analysis, we used this biomechanical test to detect the essential effect of the 2 techniques tested and find possible biomechanical differences between them. Another limitation was the use of a porcine model. Despite being similar, there are subtle differences in the histology, texture, and bioconfiguration of the porcine meniscus compared with the human meniscus. However, they are similar in their macromorphology and allow sample homogeneity, and several other studies have already validated these tests performed in different animal models.[9,11,19,22,31] A third limitation was the number of sutures used. The literature remains to be clarified regarding the number of sutures used and the number needed to treat specific injuries. We used 4 sutures in the 2 groups evaluated for 2 cm–long tears. However, we performed sutures only on the proximal meniscal surface.

CONCLUSION

In the current study, a continuous vertical meniscal suture created a beneficial configuration for treating longitudinal meniscal lesions that seems to be biomechanically similar to a traditional vertical suture technique.

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