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Cyclic Displacement After Meniscal Root Repair Fixation

A Human Biomechanical Evaluation

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Background: Recent biomechanical evidence suggests that the meniscus-suture interface contributes the most displacement to the transtibial pull-out repair for meniscal root tears. Therefore, optimization of surgical technique at the meniscus-suture interface may minimize displacement and improve the strength of meniscal root repairs.

Purpose/Hypothesis: The purpose of this study was to investigate the cyclic displacement and ultimate failure loads of 4 different meniscus-suture fixation techniques for posterior medial meniscal root repairs in human meniscus tissue. The hypothesis was that there would be no significant difference between the two simple sutures (TSS) technique and 3 other techniques in cyclic displacement or ultimate failure load.

Study Design: Controlled laboratory study.

Methods: A total of 32 fresh-frozen, human, medial meniscal transplant specimens were randomly assigned to 4 meniscus-suture fixation techniques used for transtibial pull-out repair in posterior medial meniscal root tears (n = 8 per group). The suture techniques studied were (1) TSS, (2) modified Mason-Allen (MMA), (3) single double-locking loop (S-DLL), and (4) double double-locking loop (D-DLL). The menisci were subjected to a cyclic tensioning protocol representative of postoperative rehabilitation (10-30 N for 1000 cycles) and pulled to failure at a rate of 0.5 mm/s.

Results: After 1000 cycles, the TSS group displaced the least (mean ± SD, 1.78 ± 0.64 mm), followed by the MMA (2.14 ± 0.65 mm), D-DLL (2.97 ± 0.57 mm), and S-DLL (3.81 ± 0.78 mm) groups. After 100, 500, and 1000 cycles, suture displacements using the TSS

reported that porcine menisci are significantly stiffer than human menisci, suggesting that results from porcine studies may not be directly generalizable to human tissue and that human menisci may be at risk for increased suture cutout and displacement in comparison to porcine tissue.[3] Therefore, optimization of the transtibial pull-out repair construct should focus on decreasing suture cutout at the human meniscus-suture interface to minimize displacement and preserve the biomechanical integrity of the root repair.[3]

To date, few studies have evaluated the biomechanical properties of specific meniscus-suture fixation techniques currently used for meniscal root repairs. Feucht et al[5] evaluated 4 different meniscus-suture configurations in a porcine model and reported that the two simple sutures (TSS) technique and the modified Mason-Allen (MMA) technique resulted in significantly less cyclic displacement than the horizontal mattress and the 2 modified loop stitches. The generalizability of these findings to human tissue, however, remains unknown.

The purpose of this study was to investigate the cyclic displacement and ultimate failure loads of 4 different, clinically relevant meniscus-suture fixation techniques currently used for meniscal root repairs in a human cadaveric model. The top-performing techniques (TSS and MMA) from a previous porcine study[5] and 2 techniques that have been proposed by industry and taught during instructional courses, using either 1 or 2 double-locking loop (DLL) stitches, were evaluated under a cyclic loading protocol, chosen to replicate a standard postoperative root repair rehabilitation program,[19] followed by pull-to-failure testing. We hypothesized that there would be no significant difference between the 4 suture fixation techniques for cyclic displacement or ultimate failure load.

MATERIALS AND METHODS

Specimen Acquisition

A total of 32 fresh-frozen, human medial tibial plateaus with attached medial menisci of transplant quality (29 male, 3 female) with an average age of 24.3 years (range, 12-35 years) were acquired through the research and development department of an allograft tissue bank (AlloSource). This testing model was chosen because the authors believed it would provide the highest level of standardization since the use of 4 different meniscus-suture techniques precluded the use of matched pair specimens.

Specimen Preparation

The menisci were kept frozen in individually sealed packages until 12 hours before testing. They were subsequently thawed at room temperature and wrapped in saline-soaked gauze before being randomly assigned to 1 of 4 different meniscal suture configuration testing groups (n = 8 per group). The 4 groups included the TSS technique (group 1), MMA technique (group 2), single double-locking loop (S-DLL) technique (group 3), and double double-locking loop (D-DLL) technique (group 4) (Figure 1).

The meniscus-suture configuration techniques were performed by one senior level, board-certified, sports medicine fellowship–trained orthopaedic surgeon (R.F.L.). First, menisci were sharply resected from the bony attachment to the tibial plateau at the posterior root with a scalpel, with care taken to preserve the integrity of the meniscus itself. The needle entry point for each of the 4 different suture configurations was 5 mm from the resected edge of the meniscus, in the center of the meniscus tissue. All techniques used the same No. 2 nonabsorbable sutures (FiberWire; Arthrex Inc) that have been recommended by a previous biomechanical study for use in meniscus tissue.[7]

Suturing Techniques

The 4 suturing techniques are presented photographically in Figure 1. The TSS technique was performed by placing 2 sutures in the meniscus approximately 5 mm apart using a curved tapered needle,[3,5] and this technique was considered to be the clinical standard for repair techniques due to its low level of technical difficulty and promising biomechanical results in resisting displacement.[2,5,6,10,14] The MMA technique was performed by placing a horizontal mattress suture through the meniscus tissue, using a curved tapered needle for each throw, so that the horizontal suture loop was on the superior surface of the meniscus.[5,11] A second suture was then passed through the meniscus, deep, medial, and in the center of the previously placed horizontal mattress suture.[5,11] The MMA configuration chosen for this study replicated the technique from a previous biomechanical study and a technical note.[5,11]

Both of the DLL techniques were performed using a tapered needle to simulate a proposed meniscus-suture fixation technique at the meniscal root. The S-DLL stitch, which is performed using a single suture, was inserted using a suture passer 1 cm from the induced meniscal tear. One end of the suture was inserted from inferior to superior through the meniscus in the posterior aspect of the meniscus tissue. Next, the second end of the suture was similarly inserted 5 mm anterior to the first suture, without pulling tension on the stitch (ie, leaving a loop). The loop was then inserted inferior to superior through the meniscus, approximately 5 mm lateral (toward the root) to the previously placed sutures and centered between them. Both suture ends on the superior surface of the meniscus were then passed through the suture

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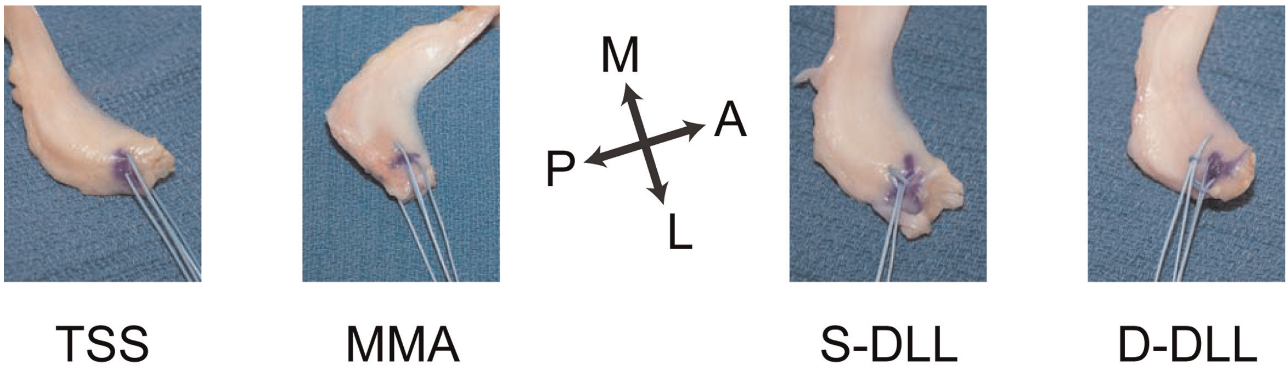

Figure 1. The meniscus-suture fixation techniques. D-DLL, double double-locking loop; MMA, modified Mason-Allen; S-DLL, single double-locking loop; TSS, two simple sutures; M, medial; A, anterior; L, lateral; P, posterior.

loop to create a DLL stitch configuration. For the D-DLL stitch, the first stitch was inserted in the same fashion as above for the S-DLL group. A second DLL stitch, using a second suture, was then inserted 5 mm medial to the first DLL stitch, in the center of the meniscus tissue.

After each meniscal suturing technique was performed, the lengths of the sutures were measured to be 5 cm from the edge of the posterior medial meniscus tissue to a metal rod, as in a previous study.[3] Sutures were tied over a surgical button on the metal rod by use of a surgeon's knot followed by 5 half-hitches on alternating posts. Knot tying was performed in all specimens by the same surgeon to optimize reproducibility. The sutures were then cut approximately 1 cm from the knot, and the anterior root was sharply resected from the bony attachment to the tibial plateau.

Biomechanical Testing

A surgical pen was used to mark the meniscus 1 cm lateral to the previously placed sutures in the midbody of the meniscus. Beyond this location, the anterior horn and midbody of the medial menisci were wrapped with metal wire to ensure that the menisci did not slip during testing.[3,4] The menisci were then rigidly clamped at this location to the actuator of the tensile testing machine (ElecroPuls E10000; Instron). The surgical button of the meniscal repair was placed against the inferior surface of a custom fixture rigidly secured to the base of the tensile testing machine that accommodated the sutures with a 5-mm diameter hole, simulating a common tunnel diameter for a meniscal root repair (Figure 2).[2,3] Measurement error of the testing machine was certified by Instron to be less than or equal to ±0.01 mm and ±0.3% of the indicated force.

All suture configurations were then subjected to the same cyclic tensioning protocol. Specimens were preconditioned for 10 cycles between 1 and 10 N at 0.1 Hz and cyclically tensioned for 1000 cycles between 10 and 30 N at 0.5 Hz.[3] This protocol approximated the tensile forces on the posterior medial meniscal root under neutral rotation, range of motion from 0° to 90° of knee flexion, and 500 N of tibiofemoral load, which are representative of the range of motion and toe-

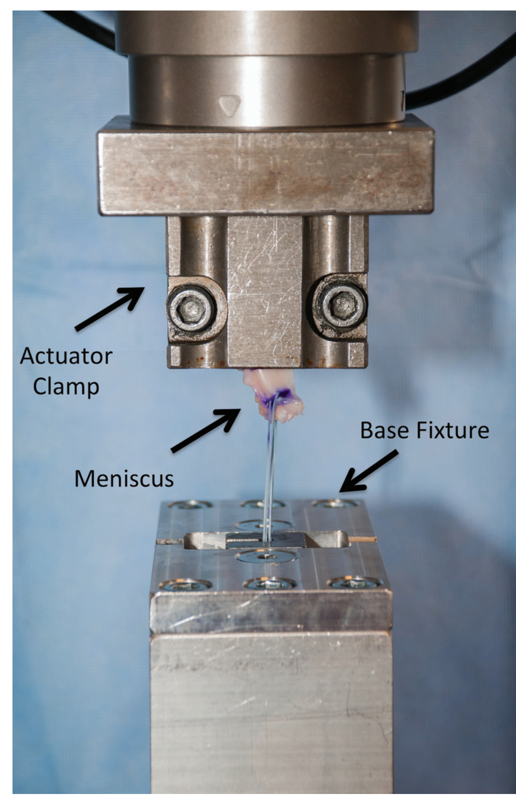

Figure 2. Testing set-up for a right knee medial meniscus. The menisci were inserted in a steel clamp attached to the actuator of the tensile testing machine. The menisci were then secured to a custom fixture, which was rigidly attached to the base of the tensile testing machine. The custom base fixture consisted of an aluminum frame with a slotted steel insert attached to the top of the fixture that provided a rigid surface for the insertion and support of pretied buttons.

touch weightbearing protocols during a standard postoperative rehabilitation program after meniscal root repair.[3,19] Displacements were recorded at the actuator of the tensile testing machine at the conclusion of cycles 1, 100, 500, and

TABLE 1
Cyclic Displacement and Ultimate Failure Load of Meniscus-Suture Fixation Techniques[a]

Group	Displacement, mm				Ultimate Failure Load, N
	1 Cycle	100 Cycles	500 Cycles	1000 Cycles	
TSS	0.53 ± 0.31	1.11 ± 0.47	1.55 ± 0.57	1.78 ± 0.64	192 ± 52
MMA	0.54 ± 0.19 (2.45)	1.31 ± 0.43 (18.0)	1.88 ± 0.59 (21.3)	2.14 ± 0.65 (20.2)	325 ± 77 (69.9)[b]
S-DLL	0.73 ± 0.19 (39.2)	2.09 ± 0.45 (88.3)[b]	3.27 ± 0.67 (111)[b]	3.81 ± 0.78 (114)[b]	217 ± 51 (13.5)
D-DLL	0.61 ± 0.06 (14.7)	1.67 ± 0.24 (50.5)[b]	2.53 ± 0.44 (63.2)[b]	2.97 ± 0.57 (66.8)[b]	320 ± 50 (67.1)[b]

[a]Data are reported as mean ± SD. Values in parentheses are the percentages of greater displacement or ultimate failure load compared with the two simple sutures (TSS) technique. D-DLL, double-locking loop; MMA, modified Mason-Allen; S-DLL, single-locking loop.
[b]$P < .05$ compared with TSS.

1000, similar to a previous study evaluating displacement in meniscus tissue.[3] After cyclic loading, the menisci were pulled to failure at a rate of 0.5 mm/s.[5]

Statistical Analysis

A sample size calculation was conducted assuming moderate standard deviations of 0.5 mm and 0.75 mm for the TSS and D-DDL groups, respectively. Eight specimens per group were sufficient to detect a difference of 1 mm with 80% power, assuming alpha = 0.05. Means with standard deviations of biomechanical measurements were reported, and nonparametric statistical methods were used. Kruskal-Wallis 1-way analyses of variance (ANOVAs) were used to test whether there was an overall effect of configuration on displacement and ultimate failure load. When this overall test was significant, individual comparisons were made between the clinical standard (TSS) and each of the alternative configurations (MMA, S-DLL, D-DLL) with Mann-Whitney U tests. The Holm-Bonferroni method was used to account for these 3 comparisons within each specific measurement. Adjusted P values of less than .05 were considered statistically significant. All statistical analyses were performed by use of SPSS Statistics v20 (IBM Corp).

RESULTS

Cyclic Displacement

Displacements for each of the testing groups after 1, 100, 500, and 1000 cycles (after preconditioning) are noted in Table 1. At testing cycle 1, the overall ANOVA was not significant (P = .083); therefore, individual comparisons were not significant between any of the fixation techniques. At 100, 500, and 1000 cycles, the S-DLL fixation technique resulted in significantly more displacement than the clinical standard of TSS (P = .015, .003, and .003, respectively). Similar trends were noted for the D-DLL configuration, which also resulted in significantly more displacement at 100, 500, and 1000 cycles than the TSS (P = .030, .014, and .010, respectively). The MMA and TSS were not significantly different for displacements at 100, 500, or 1000 cycles (P = .161, .161, and .130, respectively) (Figure 3).

Over the course of testing (after preconditioning), the MMA technique displaced 2.45% greater than the TSS configuration at 1 cycle, and this displacement increased to 20.2% at 1000 cycles. The S-DLL technique displaced 39.2% greater than the TSS at 1 cycle and continued increasing in displacement from the TSS stitch until it reached a 114% increase in displacement at 1000 cycles. Last, the D-DLL configuration displaced 14.7% greater than the TSS technique at 1 cycle and continued increasing to 66.8% at 1000 cycles.

Ultimate Failure Load

There were no specimen failures observed before pull-to-failure testing. All ultimate failure loads are listed in Table 1. In comparison to the TSS configuration, the MMA and D-DLL both resulted in significantly higher ultimate failure loads ($P < .001$ and .004, respectively). The MMA and D-DLL ultimate failure loads were on average 69.9% and 67.1% higher than the TSS technique, respectively. The TSS and S-DLL configurations were not significantly different (P = .574), with the S-DLL resulting in a 13.5% higher ultimate failure load on average. All suture fixation techniques failed because of suture cutout, except 1 MMA suture, which failed because of suture breakage. This failure was noted to occur at 414 N, which was the second highest ultimate failure load in this study (Figure 4).

DISCUSSION

In this study, we disproved our null hypothesis that all meniscus-suture fixation techniques would be indistinguishable for cyclic displacement at 100, 500, and 1000 cycles and ultimate failure load. However, the null hypothesis was verified for the amount of displacement at 1 cycle of tensioning and after preconditioning because no significance was found between groups. We found that the current clinical standard TSS fixation technique was able to significantly resist displacement compared with the S-DLL or D-DLL suturing techniques at 100, 500, and 1000 cycles of cyclic tensioning. The TSS and MMA fixation techniques were not significantly different at any of the measured cycles. The S-DLL technique exceeded the 3-mm threshold for displacement that has been reported to compromise meniscal function in a porcine model,[18] with a mean cyclic displacement of 3.81 mm, while

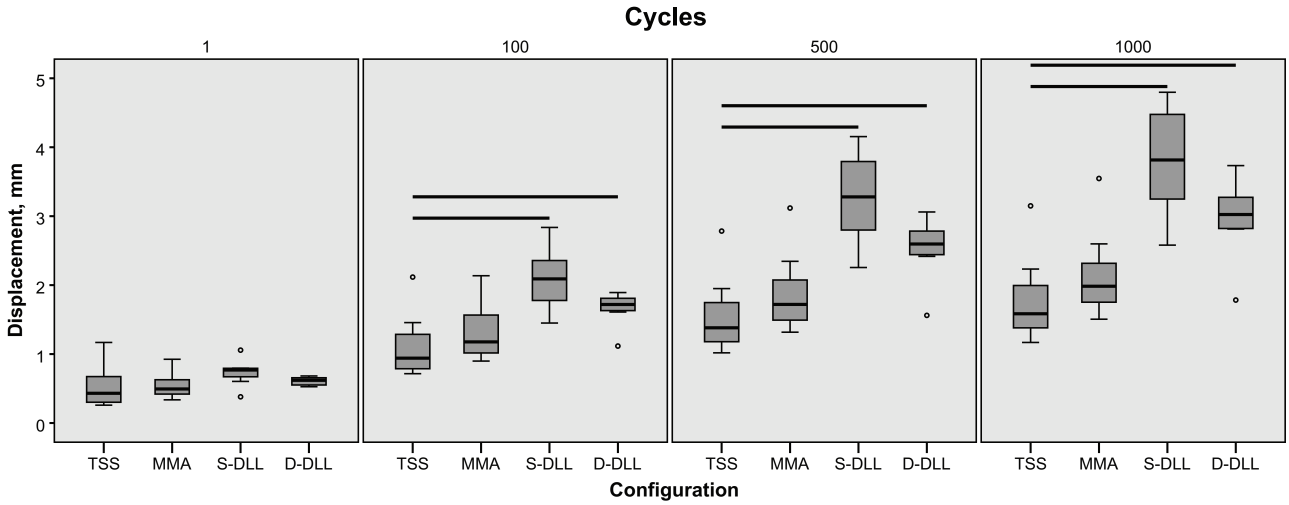

Figure 3. Boxplots demonstrating the cumulative cyclic displacements after 1, 100, 500, and 1000 testing cycles. D-DLL, double double-locking loop; MMA, modified Mason-Allen; S-DLL, single double-locking loop; TSS, two simple sutures. Groups demonstrating significance ($P < .05$) compared with TSS are marked by the overhead bars.

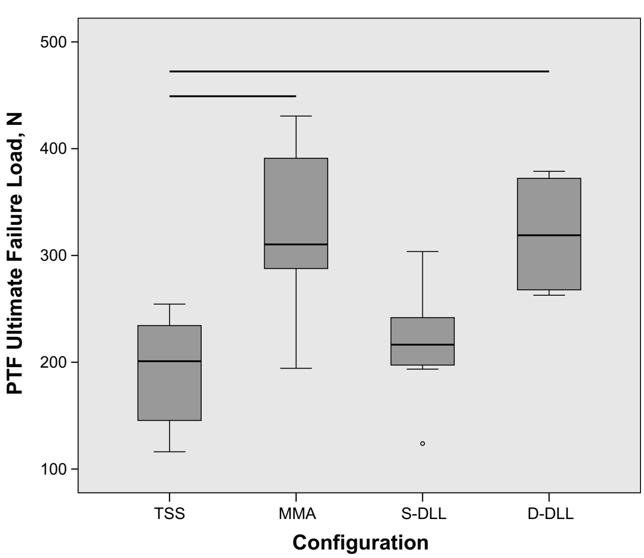

Figure 4. Boxplot comparing ultimate failure loads between the 4 meniscus-suture fixation techniques. D-DLL, double double-locking loop; MMA, modified Mason-Allen; PTF, pull-to-failure; S-DLL, single double-locking loop; TSS, two simple sutures. Groups demonstrating significance ($P < .05$) compared with TSS are marked by the overhead bars.

the D-DLL technique was very close to this threshold (2.97 mm). Last, the MMA and D-DLL techniques demonstrated significantly higher ultimate failure loads than the TSS fixation technique, while the TSS and S-DLL were not significantly different. However, all ultimate failure loads were well above the reported threshold (30 N) for forces on the posterior medial meniscal root during early postoperative rehabilitation.[19] Therefore, the TSS technique, considered to be the least technically difficult to perform intraoperatively and the current standard for root repair, was best able to withstand cyclic loading in a human model. If increased failure load of the repair construct is desirable, the MMA technique, which may be of greater technical difficulty, may also be a viable alternative to resist displacement while enhancing the construct failure load.

In a recent study analyzing the specific components of the transtibial pull-out meniscal root repair technique, porcine menisci displaced approximately 254% and 180% more at the suture-meniscus interface than the button-bone interface or suture elongation components, respectively, using the same cyclic loading protocol as our current study.[3] In addition, the full transtibial pull-out repair construct displaced 3.28 mm in the previous study, which exceeds the threshold of 3 mm that has been reported to compromise native meniscal function in porcine tissue.[3,18] Therefore, minimizing suture cutout at the meniscus-suture interface appears to be the best way to optimize the transtibial pull-out repair technique.

To our knowledge, this study was the first to evaluate different meniscus-suture fixation techniques for meniscal root repair under cyclic loading in a human menisci model. Feucht et al[5] previously evaluated 4 different suturing techniques in a porcine model, but given the increased stiffness of porcine tissue,[16] it was unknown whether the same trends for cyclic displacement and ultimate failure strength would be observed in a human cadaveric model. Under 1000 loading cycles from 5 to 20 N, Feucht et al[5] reported that the TSS (0.60 mm) and MMA (0.88 mm) suture fixation techniques significantly resisted cyclic displacement in comparison to the horizontal mattress suture (1.57 mm) or 2 modified loop stitches (2.05 mm). Therefore, we chose the TSS and MMA suture techniques for this study to evaluate the top 2 performing suture techniques in a human cadaveric model and also to provide a more direct comparison to the literature. Overall, our results were similar to those of Feucht et al,[5] because the TSS and MMA techniques resulted in significantly fewer displacements than the S-DLL and D-DLL suture configurations. Further, there were no significant differences in displacements at 1, 100, 500, or 1000 cycles between the TSS and MMA configurations. As expected, given the use of human menisci in our study rather than stiffer porcine menisci,[16] as well as a higher cyclic loading protocol (10-30 N vs 5-20 N),[5] the overall displacements in our study were greater for both the TSS (1.78 mm) and MMA (2.14 mm) suture configurations compared with displacements in the porcine study after 1000 cycles (0.60 and 0.88 mm, respectively).

Kopf et al[9] previously evaluated the ultimate failure loads of 3 different meniscus-suture fixation techniques in human menisci, but cyclic loading and displacement were not assessed. In their study, all 3 of the evaluated meniscus-suture fixation techniques—the TSS, modified Kessler stitch, and loop stitch—failed at considerably lower forces than any of the techniques in our study. For example, in their study, menisci repaired with a TSS stitch failed at an average of 64 N,[9] as compared with an average of 192 N in our study. We theorize that the menisci used by Kopf et al[9] may have been of older age and potentially compromised tissue quality, yet this is difficult to discern since tissue age was not reported. While we believe it to be of minimal clinical relevance, in our study, as well as those by Kopf et al[9] and Feucht et al,[5] the TSS technique had the lowest ultimate failure load. Nevertheless, the authors believe that all 4 meniscus-suture fixation techniques were more than sufficient to withstand failure during postoperative rehabilitation; a previous study has reported that 30 N is approximately the highest amount of tension that would be present on the posterior medial meniscal root.[18]

Based on the results of this study, the authors reiterate the importance of a slow and careful postoperative rehabilitation program to prevent significant displacement at the root repair site, similar to recommendations in previous studies.[3,5,6,9] Even under a cyclic loading protocol of 1000 loading cycles of 10 to 30 N at 0.5 Hz, chosen to approximate the tensile forces on the posterior medial meniscal root under neutral rotation, a range of motion program from 0° to 90° of knee flexion, and 500 N of tibiofemoral load,[19] a considerable amount of displacement occurred for each meniscus-suture fixation technique. Given that 3 mm of nonanatomic displacement of a meniscal root has been reported to compromise the ability of the meniscus to distribute tibiofemoral loads in a porcine model,[18] displacement approaching this threshold is worrisome after a transtibial pull-out meniscal root repair. In addition, displacement at the meniscus-suture interface is only one component of the transtibial pull-out repair, with suture elongation and the button-bone interface also reported to contribute to displacement in the repair construct.[3] Therefore, it appears that the TSS technique combines the ability to be the less technically difficult procedure and to resist displacement, despite being weaker than other techniques. The MMA technique was able to resist displacement while enhancing the failure load of the repair; however, because of the technical difficulty of this technique in a tight joint space, the significant increase in failure load may limit its clinical relevance. One concerning aspect of the S-DLL and D-DLL techniques is the increased rate and corresponding amount of displacement in comparison to the TSS and MMA techniques over the course of cyclic loading. While displacements of both DLL stitches were not significantly different than those of the TSS technique after the first cycle, displacements of the D-DLL and S-DLL continued to increase approximately twice as fast compared with the TSS or MMA techniques through cycle 1000; however, between 500 and 1000 cycles, the rates of elongation decreased for all techniques (Table 1). These findings suggest that both iterations of the DLL stitches may not be truly "locking" until well into cyclic loading, which may potentially compromise healing in a clinical setting.

The results of our study suggest that suture configurations of a similar technique but with more sutures (eg, the D-DLL in comparison to the S-DLL) may better resist displacement, corroborating a previous study in the literature.[15] However, our results also indicate that techniques that are less invasive and require less penetration of meniscus tissue, such as the TSS technique, may be better able to resist displacement than those that require more invasion of meniscus tissue, such as the D-DLL technique. This is consistent with the findings of another study, which also reported that the TSS resulted in the least amount of displacement.[5] Therefore, we recommend that investigators carefully consider these counterbalancing factors when designing and optimizing meniscus-suture fixation techniques.

An in vitro investigation of a complex biomechanical system carries some inherent limitations. The biggest limitation of this study was the inability to incorporate effects associated with gradual healing that would likely occur over the course of a typical 6- to 8-week partial weightbearing rehabilitation program.[2] In addition, while previous studies have typically used a porcine model because of the difficulty in standardizing tissue quality across human specimens,[3,5-7,15,18] we believe that the differences between the 2 tissues warranted an investigation in human tissue. Note, however, that the potential confounding factor of human tissue quality variability was minimized by obtaining specimens with an average age of 24.3 years (range, 12-35 years) and of transplant quality. Another limitation is that the meniscus tissue used in this study was likely younger than a majority of patients treated clinically, potentially underestimating the amount of displacement in older, degenerative meniscus tissue. Last, in quantifying displacement as changes in actuator position, the observed displacement is representative of the potential displacement of the full testing construct, including the steel fixtures rigidly attached and connected in series from the actuator to the testing machine base. However, the strong and rigid attachments, inherent stiffness (steel), and low forces these fixtures were subjected to during cyclic loading suggest that their contributions to the observed meniscus-suture displacement were negligible.[3]

CONCLUSION

The TSS and MMA fixation techniques were better able to resist displacements compared with the S-DLL and D-DLL stitch configurations. All techniques had ultimate failure loads above the currently accepted rehabilitation force threshold. The TSS fixation technique combines the lowest technical difficulty and the ability to resist displacement at time zero. The MMA technique, although more technically challenging, may provide an alternative means to resist displacement while enhancing the failure load.

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