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Biomechanical Evaluation of the Transtibial Pull-Out Technique for Posterior Medial Meniscal Root Repairs Using 1 and 2 Transtibial Bone Tunnels

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Background: Current methods of the transtibial pull-out meniscal root repair significantly displace under cyclic loading in porcine models but have not been evaluated in human models. One potential explanation for the displacement is that a single transtibial tunnel may not fully restore the attachment of the entire posterior medial meniscal root.

Purpose/Hypothesis: The purpose of this study was to biomechanically evaluate the transtibial pull-out technique in a human cadaveric model using either 1 or 2 transtibial bone tunnels. The hypothesis was that a transtibial pull-out technique using 2 transtibial bone tunnels would confer superior biomechanical properties in comparison to an iteration using 1 transtibial bone tunnel.

Study Design: Controlled laboratory study.

Methods: Ten matched pairs of male human cadaveric knees (average age, 52.7 years) were randomly assigned (1 each of the pair) to 2 groups consisting of a transtibial pull-out technique using either 1 or 2 transtibial bone tunnels. The knees were cyclically loaded for 1000 cycles from 10 to 30 N at 0.5 Hz, representing the loads experienced during a typical meniscal root repair postoperative rehabilitation program, and then pulled to failure at a rate of 0.5 mm/s.

Results: Differences between 1- and 2-tunnel repair groups were neither statistically nor clinically significant with respect to displacement or ultimate failure load. On average, the 1- and 2-tunnel repair groups resulted in 3.32 mm and 3.23 mm of displacement, respectively, after 1000 testing cycles. At 1, 100, 500, and 1000 testing cycles, displacement was not significantly different between groups ($P > .799$). The 2-tunnel repair technique resulted in a 10.2% higher ultimate failure load (135 N vs 123 N); however, this was not significant ($P = .333$).

Conclusions: Similar biomechanical properties were seen between transtibial pull-out repairs using either 1 or 2 transtibial bone tunnels in a human cadaveric model. Both repair groups exceeded the 3-mm threshold for nonanatomic displacement.

Clinical Relevance: This study indicates that a newly proposed iteration of the transtibial pull-out repair technique using a second transtibial tunnel, which theoretically restores more of the posterior medial meniscal root, was almost identical to the current clinical standard involving a single transtibial tunnel. As the importance of repairing meniscal root tears is increasingly recognized, further studies on new iterations of both techniques are warranted to minimize the risk of displacement caused by early motion in the initial postoperative rehabilitation period.

Keywords: meniscal root; posterior root; root tears; transtibial pull-out repair; transtibial bone tunnel

Root tears of the posterior meniscal roots have been reported to result in abnormal tibiofemoral contact mechanics[1,11,14,16,20] and often result in meniscal extrusion and increased articular cartilage degeneration of the ipsilateral compartment.[6,13] Posterior root tears of the medial meniscus are becoming increasingly recognized, with a recent report that posterior root tears account for up to 21.5% of medial meniscal tears.[7]

An increased recognition of the prevalence of tears and biomechanical importance of the meniscal roots has prompted a recent emphasis on repairing these tears.

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The transtibial pull-out repair method, in which sutures are passed through the meniscal tissue adjacent to the root tear and then pulled through a transtibial tunnel and secured over the tibia, has gained popularity due to its ability to restore the tibiofemoral contact pressures and areas to the intact knee at time zero.[1,2,11,14,16,20] However, a recent study demonstrated that the current iteration of the transtibial pull-out technique, which uses a single transtibial tunnel, resulted in approximately 4 times the displacement of the native porcine menisci (0.5 mm compared with 2.2 mm) under cyclic loading.[5] In addition, Cerminara et al[3] reported 3.28 mm of displacement under cyclic loading representative of postoperative rehabilitation in a porcine model, which exceeds the threshold of 3 mm that has been reported to compromise meniscal function in a porcine model.[22] Currently, the transtibial pull-out technique has not been evaluated in a human model under cyclic displacement, and given the reports that porcine meniscal tissue is approximately twice as stiff as human tissue,[19] it is unknown whether these reported levels of displacement underestimate what would be seen in humans biomechanically and clinically.

One theorized explanation for the suboptimal performance of the transtibial pull-out repair is that the use of a single transtibial tunnel, as currently performed, does not incorporate the supplemental fibers of the posterior medial meniscal root.[4,8] These fibers, termed the shiny white fibers,[4,8] are located on the posteromedial aspect of the root and have been reported to account for 46.5% of the area and 37.4% of the strength of the native posterior medial meniscal root.[4] As a result, Ellman et al[4] proposed that multiple bone tunnels may be necessary to account for these fibers and improve the biomechanical properties of the transtibial pull-out technique.

Therefore, the purpose of this study was to perform a biomechanical evaluation of the single transtibial bone tunnel iteration of the transtibial pull-out technique in a human model. In addition, the evaluation of a novel modification of the transtibial pull-out technique using 2 transtibial bone tunnels was then conducted to determine if it conferred superior biomechanical properties in comparison to the iteration using 1 transtibial bone tunnel. It was hypothesized that the technique using 2 transtibial bone tunnels would result in significantly decreased displacement and increased ultimate failure load in comparison with the contralateral, matched knee using a single bone tunnel.

METHODS

Specimen Preparation

Ten matched pairs of fresh-frozen male cadaveric knees (average age, 52.7 years [range, 36-65 years] and average body mass index, 22.5 [range, 15.5-32.3]) with no visual signs of meniscal damage, cartilage degeneration, or any other defects were used. The knees were randomly assigned into 1- and 2-tunnel groups by alternating between right and left knees for each group to account for random variability between matched pairs of knees. One knee from each matched pair was assigned to the 1-tunnel group and the other matched knee to the 2-tunnel group. All knees were dissected free of all skin, cruciate and collateral ligaments, and the patella, and the femur was disarticulated from the knee. Next, each tibia was potted distally with poly(methyl methacrylate) (PMMA; Fricke Dental International Inc) in a cylindrical mold up to a point approximately 4 cm distal to the most proximal aspect of the tibial tuberosity to isolate tensioning on the meniscal roots.[4]

Figure 1. The transtibial pull-out repair technique using a single transtibial bone tunnel (the clinical standard). Two No. 2 nonabsorbable sutures were passed through the meniscal root and then pulled through the transtibial bone tunnel drilled at the center of the entire posterior root of the medial meniscus. The sutures were then secured over a surgical button on the anteromedial tibia.

Surgical Techniques

The posterior medial meniscal root and its supplemental shiny white fibers were sectioned from its attachment site.[4,8] For the 1-tunnel group, a single 2.4-mm transtibial tunnel was drilled using a drill sheath (Smith & Nephew) in the middle of the entire posterior medial meniscal root, including the central and supplemental fibers.[4,8] Two No. 2 nonabsorbable sutures (Ultrabraid; Smith & Nephew) were passed through the meniscal root 5 mm medial to its transection (Figure 1). The sutures were placed into a looped nitinol wire and passed down the tunnel (Figure 2A) and firmly manually tensioned and tied by the senior author (R.F.L.) to a 4 × 12-mm surgical fixation button (Endobutton; Smith & Nephew) over the anteromedial tibia using a surgeon's knot followed by 5 half hitches on alternating posts over the surgical fixation button.

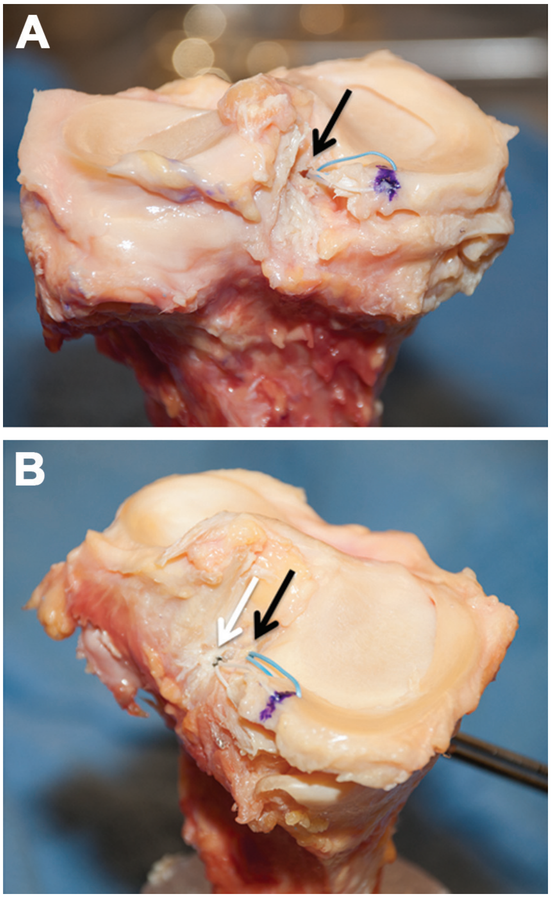

Figure 2. Photographs demonstrating the different methods of passing the sutures between the groups with 1 and 2 transtibial bone tunnels. (A) In the 1-tunnel group, 2 sutures were passed through the center of the entire medial meniscal root using a 2-simple-sutures technique and a single transtibial bone tunnel (black arrow). (B) In the 2-tunnel group, the first transtibial tunnel was placed at the middle of the central main attachment fibers of the posterior medial meniscal root (black arrow), and a single (blue) suture was passed through this bone tunnel. A second transtibial tunnel (white arrow) was reamed parallel and 5 mm posterior to the first tunnel to account for the attachment area of the supplemental shiny white fibers. A single (white) suture was then passed through this bone tunnel.

Figure 3. The newly proposed transtibial pull-out repair technique using 2 transtibial bone tunnels. One suture was passed through the center of the entire meniscal root, while a second was passed through the attachment of the shiny white fibers. Both sutures were then shuttled through their respective bone tunnels and secured over a surgical button on the anteromedial tibia.

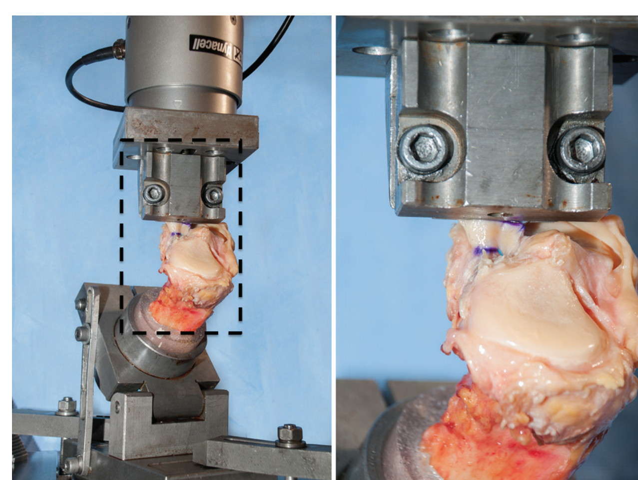

Figure 4. The biomechanical testing setup. The potted knees were secured in a custom fixture and rigidly secured to the base of a dynamic tensile testing machine. The meniscal root was then fixed in line with the circumferential fibers in a clamp attached to the actuator of a dynamic tensile testing machine.

For the 2-tunnel group, the first transtibial tunnel was drilled in the same manner as the 1-tunnel group; however, it was placed at the middle of the central main attachment fibers of the posterior medial meniscal root.[2,4,8] The second transtibial tunnel was then drilled parallel and 5 mm posterior to the initial tunnel with the help of a drill guide (Smith & Nephew) and in the middle of the shiny white supplemental fiber attachment area (Figure 3).[4,8] The sutures in the most anterior portion of the meniscal tissue were then shuttled through the most anterior transtibial bone tunnel, while the sutures from the most posterior portion of the meniscal tissue were pulled through the most posterior transtibial bone tunnel (Figure 2B). The sutures were then both tied to the same

TABLE 1
Cyclic Displacement and Ultimate Failure Load of 1 and 2 Transtibial Tunnel Techniques[a]

	Displacement, mm				
Group	1 Cycle	100 Cycles	500 Cycles	1000 Cycles	Ultimate Failure Load, N
One tunnel	1.27 ± 0.49	2.37 ± 0.62	3.02 ± 0.72	3.32 ± 0.77	123 ± 49
Two tunnels	1.26 ± 0.50	2.28 ± 0.64	2.92 ± 0.65	3.23 ± 0.68	135 ± 42

[a]Data reported as mean ± standard deviation. No significant differences were noted between any testing group.

surgical fixation button using the same knotting technique as the 1-tunnel technique over the anteromedial surface of the tibia.

Biomechanical Testing

Before biomechanical testing, the medial menisci were sectioned in half. A surgical pen was used to mark each root at a distance of 1 cm from its bony attachment. Proximal to this location, the transected medial menisci were inserted into a custom clamp, and metal wire was wrapped around the midbody of the menisci according to a previous technique to prevent slippage of the meniscal tissue.[3,4] The knees were rigidly secured in a custom fixture and securely clamped to the base of a dynamic tensile testing machine (ElecroPuls E10000; Instron) to prevent any movement during biomechanical testing. Measurement error of the testing machine was verified by Instron to be less than or equal to ±0.01 mm and ±0.3% of the indicated force. The meniscal root was then clamped 1 cm from its bony attachment in line with the circumferential fibers, which is believed to be the most physiological method for biomechanical testing (Figure 4).[4,5,10] The menisci were preconditioned for 10 cycles from 1 to 10 N at 0.1 Hz to minimize creep within the meniscal fibers.[3] After preconditioning, the menisci were cyclically loaded for 1000 cycles from 10 to 30 N at 0.5 Hz. This loading protocol has been used by a previous study to represent the tensile forces that the posterior medial meniscal root may experience under neutral rotation, a range of motion from 0° to 90°, and 500 N of tibiofemoral load,[3] which we believe to be a representative range of motion and partial weightbearing seen in a postoperative rehabilitation regimen after meniscal root repair.[3,23] The menisci were then subsequently pulled to failure at a rate of 0.5 mm/s.[4] Cyclic displacement at the completion of 1, 100, 500, and 1000 cycles and ultimate failure load were recorded. Displacement was measured at the testing machine actuator as done in a previous study evaluating meniscal displacement.[3]

Statistical Analysis

Informed by data from the literature about possible effects, an a priori sample size calculation was made. Ten matched pairs were found to be sufficient to detect a 20% decrease in displacement between the 1- and 2-tunnel repair techniques. A 4-mm displacement after 1000 testing cycles of the 1-tunnel repair method was based on the assumption that the displacement seen by Feucht et al[5] (2.2 mm) for the transtibial pull-out repair would be close to twice the displacement due to a slightly higher cyclic loading protocol in our study and the decreased stiffness of human tissue.[19] Thus, we powered the study to detect a 0.8-mm difference between techniques. A moderate standard deviation of 0.7 mm was assumed, with an α of 0.05 and requiring 80% power. The Wilcoxon signed-rank test was used for comparison of matched pairs. The level of statistical significance was set at $P < .05$. All statistical analyses were performed using SPSS version 20 (SPSS Inc).

RESULTS

Cyclic displacements at the completion of 1, 100, 500, and 1000 cycles are listed in Table 1. No significant differences were found after any testing cycle (P = .959, .878, .799, and .799, respectively). After 1000 testing cycles, the 1- and 2-tunnel techniques resulted in a mean of 3.32 and 3.23 mm of displacement, respectively (2.8% difference). With regard to the ultimate failure load, the 2-tunnel technique failed at a level (135 N) approximately 10.2% higher than the 1-tunnel group (123 N); however, this difference was not significant (P = .333). All specimens failed due to suture cutout through the meniscal tissue.

DISCUSSION

We believe that the most interesting finding of this current study was that the 1- and 2-tunnel iterations of the transtibial pull-out repair resulted in 3.32 mm and 3.23 mm of displacement after cyclic loading in a human model, respectively. Both iterations of the transtibial pull-out repair exceeded the current recommended 3 mm of displacement that has been reported to compromise meniscal function in a porcine model.[22] We theorize that the observed displacement in our study may partially explain the controversial results of clinical studies using the transtibial pull-out repair.[9,12,15,21] While clinical outcomes have been reported to improve significantly after transtibial pull-out repair of posterior root tears of the medial meniscus using a single transtibial bone tunnel,[9,12,15,21] there is conflicting evidence on the ability of the transtibial pull-out repair to decrease meniscal extrusion[12,15] and stimulate healing of the meniscal tissue on second-look arthroscopy.[12,21] As a result, we recommend that further studies investigate the ways to minimize displacement of the transtibial pull-out repair for meniscal root tears.

In addition, we hypothesized that a transtibial pull-out technique using 2 transtibial bone tunnels would confer superior biomechanical properties in comparison to an iteration using a single transtibial bone tunnel; in contrast, we found that the 1- and 2-tunnel iterations were not significantly different in terms of displacement at 1, 100, 500, or 1000 cycles or ultimate failure load. It was theorized that the second bone tunnel would incorporate more of the supplemental shiny white fibers into the medial meniscal posterior root repair, thereby more closely approximating the native meniscal root.[4] As reported by Ellman et al,[4] the shiny white fibers are responsible for a significant amount of the native medial meniscal posterior root attachment area (38.8%) and strength (47.8%); therefore, a second transtibial bone tunnel was thought to be a potential method for decreasing displacement and increasing the strength of the repaired meniscal root. Nevertheless, given the novelty of the 2-tunnel technique of the transtibial pull-out repair, which has not been previously reported in the literature, the authors propose that future studies investigate different iterations of this technique.

Previous studies have evaluated the transtibial pull-out repair with a single transtibial bone tunnel, but all previous studies used porcine models or did not utilize physiologic methods of applying loads. We found 3.32 mm of displacement after 1000 cycles for the 1-tunnel group in this current study when tensioning in line with the circumferential fibers of the posterior medial meniscal root. In a porcine model, Feucht et al[5] also evaluated the transtibial pull-out repair technique with a single bone tunnel and a similar physiologic method of applying tension; however, the authors did use a slightly lower cyclic loading protocol (5-20 N for 1000 testing cycles) and reported an average of 2.2 mm of displacement in a porcine model. We believe that it is reasonable to assume that the slight increase in displacement in our study is due to a combination of the decreased stiffness of human menisci compared with porcine menisci and the slightly higher force cyclic loading protocol in our study. In addition, other recent studies have evaluated the transtibial pull-out repair technique, but due to differences in testing technique, comparisons to our current study are difficult. Röpke et al[18] used a sawbones construct, had a lower loading protocol (1-10 N for 100 cycles), and applied the load via the tibial side of the repair; therefore, we believe their finding of 3.8 mm of displacement cannot be directly compared with our study. Another study evaluated the cyclic displacement of the transtibial pull-out technique in a porcine model using the same loading protocol as our study and found a similar amount of displacement (3.28 mm).[3] Since the purpose of the previous study was to isolate the individual displacements of each component of the transtibial pull-out repair, the load was applied in line with the sutures and button on the anteromedial tibia. We believe that this may change the amount of displacement in comparison with our more physiologic method in which the force was applied in line with the circumferential fibers of the meniscal root.

According to Stärke et al,[22] 3 mm of displacement in a porcine model is sufficient to compromise the ability of the menisci to transmit tibiofemoral loads.[22] Given that both the 1- and 2-tunnel techniques surpassed the 3-mm threshold for displacement, we believe that this study conveys the importance of a careful progression of a postoperative meniscal root repair rehabilitation program.[2,3,5,10] With that being said, porcine menisci differ in stiffness, size, and insertion geometry of the roots in comparison with humans, and they can only be used as a relative comparison.[17,19] A similar study in human tissue could add valuable information to the literature by providing a displacement threshold that may be more relevant to human menisci.

In our study, the ultimate failure loads for both the 1-versus 2-tunnel groups were not significantly different. In addition, because porcine meniscal tissue is significantly stiffer than human menisci,[19] it is not surprising that the ultimate failure loads of both repairs were lower than those found by Feucht et al[5] in a porcine model. The average ultimate failure loads for the 1- and 2-tunnel groups were 123 N and 135 N, respectively, in our study, whereas Feucht et al reported an ultimate failure load of 180 N for the transtibial pull-out method in a porcine model. However, the mean ultimate failure loads for both repair techniques are well above the upper threshold of tensile forces (30 N) that would be present on the medial meniscal posterior root during postoperative rehabilitation after a root repair.[23]

Evaluating further potential improvements for both the 1- and 2-tunnel methods is recommended. Increased space between transtibial tunnels could be a future direction that could possibly stabilize the root attachment site more effectively. In addition, an increased number of sutures and/or different suture materials could also decrease the displacements of each technique. It should be noted that the 2-tunnel method seemed to be "more stable and secure" than the 1-tunnel repair when the meniscal root was manually manipulated. We hypothesize that this observation, coupled with the additional bone tunnel, could stimulate more healing at the tissue-bone interface if the meniscal tissue is held firmly in place across a wider surface area. However, this hypothesis cannot be evaluated in vitro; therefore, animal or clinical outcomes studies could elucidate whether 2-tunnel repairs have better healing responses than 1-tunnel repairs, especially with the use of imaging or second-look arthroscopic verification.

Some limitations to our study should be taken into consideration. Our study was completed in vitro, which does not take into account biological healing responses over the 6- to 8-week rehabilitation protocol.[2] Our testing method applied force in line with the meniscal root fibers, which simulated a shear-like mechanism that has been hypothesized to simulate the mechanism of root tears in humans.[4,10] 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 their contributions to the observed meniscus-suture displacement were negligible.[3]

CONCLUSION

Similar biomechanical properties were measured for the transtibial pull-out repair using either 1 or 2 transtibial bone tunnels after 1, 100, 500, or 1000 testing cycles. Both repair groups exceeded the currently recommended 3-mm threshold for displacement, indicating that future studies should aim to decrease the amount of displacement in both iterations of the techniques. Last, no significant differences in ultimate failure loads between the 1- and 2-tunnel repair techniques were observed in this study.

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