Original Research

Knotless Anchor Fixation for Transosseous Meniscal Root Repair Using Suture Tape Is Inferior Compared With Button or Screw Fixation

A Biomechanical Study

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Background: A 2 mm–wide ultrahigh-molecular-weight polyethylene (UHMWPE) tape improves the contact pressure at root repair sites compared with high-strength suture and provides a stronger repair construct. UHMWPE tape is commonly used in rotator cuff repair, and fixation is often achieved with knotless suture anchors. The optimal method for tape fixation for meniscal root repair has not been established.

Hypothesis: The use of suture anchors for the tibial fixation of 2-mm UHMWPE tape transosseous root repairs will lead to better biomechanical performance compared with other fixation methods.

Methods: The medial meniscal posterior root attachment in 25 porcine knees was divided, and a standardized transtibial root repair was performed using 2-mm UHMWPE tape. The testing was performed by cyclic loading followed by load to failure. Tibial fixation was randomized to 5 tibial fixation types: (1) cortical fixation button, (2) pound-in suture anchor with screw-down interference suture locking, (3) tap-in suture anchor with inner locking plug, (4) postscrew, and (5) postscrew and washer.

Results: There was no difference in displacement during cyclic loading between tibial fixation groups except for a highly significant difference in the maximum load at failure. Repairs in both suture anchor fixation groups all failed by tape slippage at relatively low loads (median, 145 and 116 N, respectively). Repairs tied over a cortical button, postscrew, or screw and washer failed by tape breakage at loads of 431, 405, and 528 N.

Conclusion: For meniscal root repairs with 2-mm UHMWPE tape, use of suture anchors offers weaker fixation compared with tying over a button or postscrew/washer. While suture anchor fixation may be adequate for nonweightbearing postoperative protocols, it may not allow for more accelerated weightbearing.

Keywords: tibial fixation; knotless anchors; mechanical testing; failure load; meniscal root repair

The integrity of the meniscal root attachments is critical to normal meniscal function, preventing meniscal extrusion and allowing the dissipation of axial load.[3,12,15] It has been demonstrated that meniscal root tears affect the overall function of the mensicus and result in biomechanical consequences similar to subtotal meniscectomy.[2] Transosseous meniscal root repair can restore the load-bearing function of the menisci[14]; however, the strength of a medial meniscal posterior root repair is weaker than the native root attachment at the time of surgery.[11,17,24]

Theoretically, repairs with better construct strength are less likely to fail. Weightbearing during postoperative rehabilitation results in compressive forces that act to extrude the meniscus and cause displacement in the repair construct. Clinical studies[1,16,22] of meniscal root repairs using sutures have shown better healing rates at second look, with periods of nonweightbearing exceeding 6 weeks. Malposition of the meniscal root by 3 mm compromises meniscal function[30]; yet, some biomechanical studies[8,28] of meniscal root repair constructs, using No. 2 suture, have found displacement in excess of 3 mm with cyclic loading,

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suggesting a requirement to optimize the biomechanical properties of transtibial meniscal root repair.

In shoulder rotator cuff repair, the use of a 2-mm tape with knotless fixation has been shown to be advantageous over suture, with better failure loads and improved footprint contact pressure at the repair site and when compared with the use of suture.[9,23] Recent studies have also demonstrated that the use of 2 mm–wide ultrahigh-molecular-weight polyethylene (UHMWPE) tape provided superior pull-out strength, compared with No. 2 suture, in a meniscal root repair model. When the repair location was optimal in the meniscus, the mean maximum failure loads were 298.5 N for tape compared with 146.8 N for No. 2 suture of the same material.[27]

Studies have shown that for No. 2 suture repairs, displacement of the repaired meniscal root with cyclic loading tends to occur at the meniscus-suture interface, with failure occurring by suture cutout of the meniscus.[8] If the repair strength in the meniscus were to be optimized with the use of 2 mm–wide UHMWPE tape, it is possible that repair displacement could be minimized, and patients may not require a protracted period of postoperative nonweightbearing. This would, however, require fixation at the anterior aspect of the tibia to also have adequate strength to withstand physiological loads.

Commonly, tibial fixation for meniscal root pull-out repairs is achieved by tying the ends of the No. 2 suture either over a cortical button at the anterior tibial cortex[16,20,21] or over a postscrew and washer,[13,22,29] which may additionally compress the suture against the anterior tibia. The optimum method for the fixation of tape at the anterior tibial cortex is unknown. Some surgeons currently advocate knotless fixation for meniscal root repairs. As far as we are aware, this has not yet been evaluated biomechanically.

Given the apparent advantages of using tape in transosseous meniscal root repair, we wished to evaluate different fixation methods at the anterior tibial cortex, under both cyclic and load-to-failure conditions, to determine the optimum fixation method in terms of resistance to cyclic loading, displacement, and ultimate load at failure. We hypothesized that the use of suture anchors for knotless fixation of 2 mm–wide UHMWPE tape within a meniscal root repair would lead to better biomechanical performance compared with tying the tape over a postscrew alone, a postscrew with a washer (additionally compressing the tape against the anterior cortex of the tibia), or tying the tape over a button.

METHODS

The aim of this study was to replicate the surgical technique of transosseous meniscal root repair as closely as possible and perform testing representative of the physiological failure mechanism. Fresh-frozen adult porcine stifle (knee) joints, obtained from a local authorized supplier, were used for this study. Because this study used material generated as waste from food production, no ethical approval was required. Similar porcine models of meniscal root repairs have been used for biomechanical studies.[8,10,27,28,31]

Specimen Preparation

In total, 35 porcine knees were thawed for 24 hours at 4°C. A careful sharp dissection was used to remove the femur and soft tissues proximal to the menisci, including all extra-articular skin and muscle as well as the attachments of the anterior and posterior cruciate ligaments and medial and lateral collateral ligaments to leave the tibial plateau with meniscal root attachments intact. The posterior medial meniscal root attachment was then divided.

Anterior Tibial Cortex Fixation

A 4.5-mm transosseous tunnel was drilled from the anterior tibial cortex to the medial meniscal posterior root repair site to mimic in vivo clinical surgical repair in patients as described previously.[26,27] Before drilling, to standardize tunnel length, a Vernier caliper was used to measure the distance between the posterior root attachment and the position of the aperture of the tunnel at the anterior medial tibia at 45 mm.

A 2 mm–wide UHMWPE tape, hereafter termed "tape" (UltraTape; Smith & Nephew), was then looped around a 4.5-mm rod positioned at the root attachment site and the 2 free ends shuttled down the transtibial tunnel. The rod was used to standardize the repairs and avoid possible variation in thickness of the menisci between specimens.

The tape/sutures were then tensioned and secured with one of the fixation techniques listed below. All repairs were performed by the senior surgical author (J.R.R.). Five specimens were randomly allocated to each of the 5 types of anterior cortex fixation devices (Figure 1):

1. Endocortical Fixation Button 4.0 × 12 mm (Smith & Nephew)
2. Multifix S Ultra 5.5-mm pound-in knotless suture anchor (Smith & Nephew)

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Ethical approval was not sought for the present study.

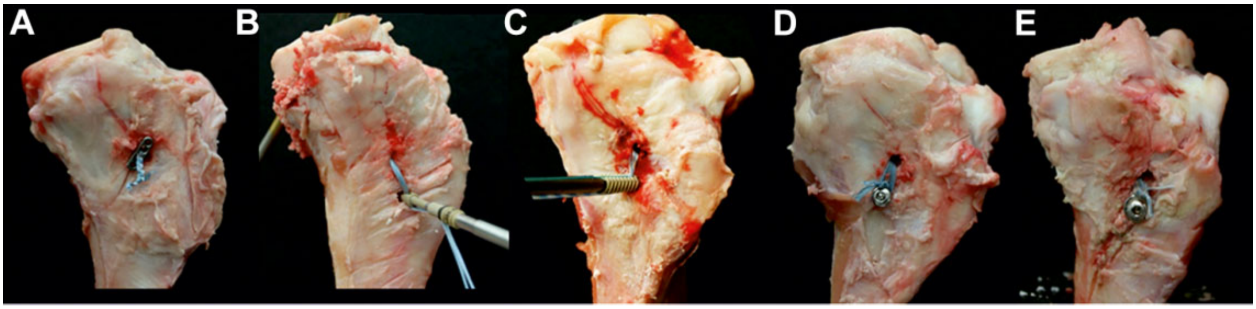

Figure 1. The 5 fixation types tested: (A) Endocortical Fixation Button 4.0 × 12 mm, (B) Multifix S Ultra 5.5-mm knotless suture anchor, (C) Footprint Ultra PK Suture Anchor 5.5 mm, (D) postscrew: 3.5-mm cortex screw, and (E) screw/washer: 3.5-mm cortex screw with washer.

3. Footprint Ultra PK 5.5-mm tap-in suture anchor 5.5 mm (Smith & Nephew)
4. Postscrew: 3.5-mm cortex screw S.T. (Stryker)
5. Screw/washer: 3.5-mm cortex screw S.T. with washer (Stryker)

In the Endobutton group, the tape was passed through the middle 2 holes of the 4-hole surgical button using a surgeon's knot followed by 5 half-hitches on alternating posts. The sutures were then cut approximately 10 mm from the knot.

In the postscrew group, a 2.5-mm bicortical drill hole was made in the anteromedial tibia 12 mm distal to the aperture of the transtibial tunnel. The 3.5-mm cortex screw was placed so that it emerged from the posterolateral cortex of the tibia to ensure bicortical fixation. Using the screw as a post, the ends of the tape were then passed around the screw, tensioned, and tied, using a surgeon's knot followed by 5 half-hitches on alternating posts.

In the screw/washer group, the screw was placed as per the postscrew group, the tape was tensioned and tied, and then the screw and washer were then advanced to ensure the washer compressed the tape against the anterior medial cortex of the tibia.

The suture anchors were implanted according to the manufacturer's instructions. We selected 2 types of anchors with different tape/suture locking mechanisms to determine whether this influenced biomechanical performance. The Multifix S Ultra 5.5 Suture Anchor is a pound-in anchor that has a screw-down mechanism at the proximal end of the anchor that provides interference fixation of the tape against bone. The Footprint Ultra PK Suture Anchor 5.5 mm is a tap-in anchor with offset barbs designed to improve the pull-out strength from the bone. An internal locking plug within the anchor is designed to secure sutures/tape within the eyelet, independent of the bone quality.

Mechanical Testing

After fixation, the 4.5-mm rod was removed and the tape pushed distally into the transtibial tunnel. The proximal-posterior 20 mm of the medial tibia were then removed with a saw to facilitate location within the testing fixture (Figure 2); this was removed to allow mounting in a materials test machine. The distal part of each specimen was potted in a custom pot using a low melting point alloy (Woods Metal 70°C; Lowden Ltd). The tibial diaphysis was scored with a rasp to improve bonding with the Woods Metal. Each potted tibia was then mounted in a specially designed rig that allowed adjustment of the orientation of the specimen within the materials testing machine. The rig was secured to a materials testing machine (series 5965 with 1 kN load cell and Bluehills 3 software; Instron) such that the tibial tunnel through which the tape/sutures passed was vertically below a mandrel mounted to a crosshead. The proximal loop of tape/suture was then positioned over the mandrel.

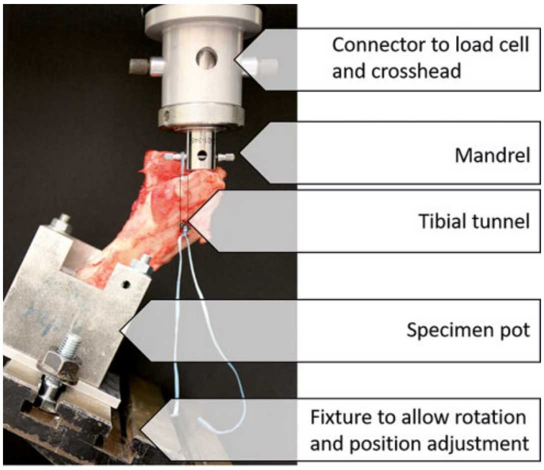

Figure 2. Test arrangement. The transosseous tunnel was oriented to allow the tape or suture to be pulled parallel to the transosseous tunnel and to the axis of the load cell.

Mechanical testing was performed at room temperature. Each specimen was initially pretensioned to 2 N and then conditioned by 20 cycles of loading from 5 to 10 N at a rate of 0.36 mm/s. After conditioning, each specimen was cyclically tensioned for 1000 cycles between 10 and 30 N at 0.5 Hz. A similar testing protocol has been used in other studies evaluating meniscal root repair techniques[8,11] and was selected to approximate the tensile forces on the posterior medial

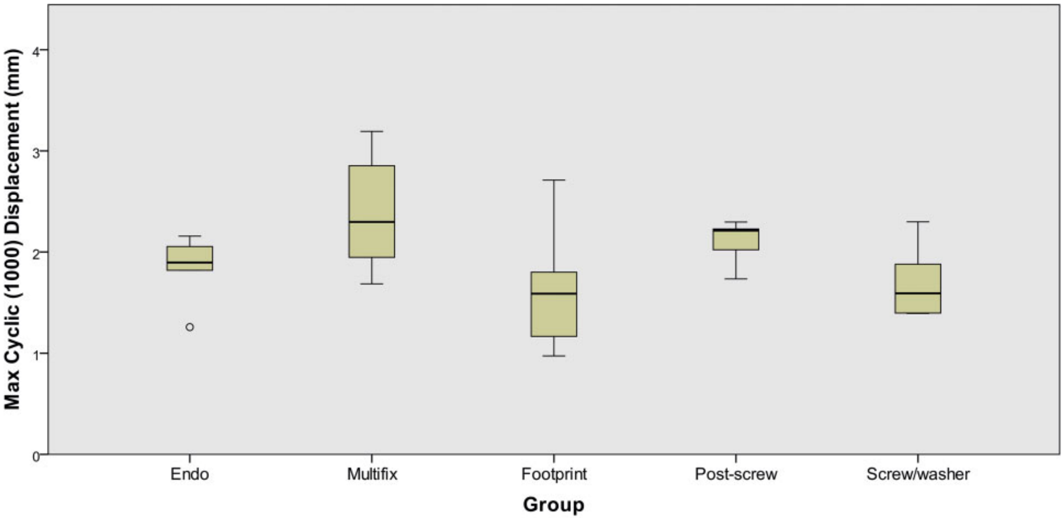

Figure 3. Box and whisker plot of maximum displacement during 1000 cycle loading. Data outside of 1.5× interquartile (IQ) range marked as outliers. A line across the box indicates the median. The circle are outliers with values between 1.5 and 3 times the IQ range, i.e., beyond the whiskers.

meniscal root under neutral rotation, range of motion from 0° to 90° of knee flexion, and 500 N of tibiofemoral load, similar to in vivo loads during the early postoperative period.

After 1000 cycles, each specimen was loaded to failure by applying displacement at a rate of 0.5 mm/s. Load and displacement data were captured continuously at 100 Hz.

Statistical Analysis

A custom routine was written in Matlab (R2017b; The Mathworks Inc) to analyze the data from the testing and automatically extract the variables. The key variables analyzed were the maximum displacement/elongation during cyclical loading as an indicator of optimum repair and the maximum failure load as an indicator of repair strength.

Statistical analysis was performed using SPSS (Version 24; IBM). Nonparametric statistical tests were performed using the Kruskal-Wallis test to examine differences in the key variables over all the 5 groups of fixation type used with the tape and the Mann-Whitney *U* test between pairs of fixation types. The key variables were described by the median and the 95% CI of the median; in addition, variation in key variables was further described by range.

RESULTS

The cyclic loading protocol gave rise to displacement of the crosshead, with the majority of the displacement occurring during the first 200 cycles, after which the rate of displacement decreased. In all cases, the displacement versus number of cycles had an asymptotic appearance. While the pattern of displacement was similar for all 5 groups during the cyclic loading, there were differences in the maximum displacement after 1000 cycles and the variability between groups (Figure 3 and Table 1). Repairs in the Footprint and the screw/washer groups had the lowest median values (1.6 mm) for maximum displacement with cyclic loading, followed by the Endobutton group (1.9 mm); higher values were recorded for the postscrew (2.2 mm) and Multifix (2.3 mm). The differences in maximum displacement during cyclic loading were not statistically significant (Kruskal-Wallis, $P = .164$). The greatest variability in the maximum displacement was seen for the Footprint group (range, 0.9-2.7 mm) and Multifix group (range, 1.69-3.19 mm). The other groups had a markedly lower variability; the lowest variability was observed for the postscrew group (range, 1.74-2.30 mm) and that for the Endobutton (range, 1.26-2.16 mm) and screw/washer (range, 1.39-2.30 mm) was slightly higher.

During load-to-failure testing, there were 2 different patterns of load versus displacement observed. The Endobutton, postscrew, and screw/washer groups all displayed a linear increase in load with displacement followed by a sudden drop after failure of the tape. In these groups, a distinct rupture of the tape was observed. The Footprint and Multifix groups had an initial linear increase in load with displacement, reaching a maximum value and then reducing with an oscillatory pattern. In all Footprint and Multifix specimens, failure occurred by tape slippage as it worked free of the fixation device, slipping through the tunnel, leaving the free end of the tape undamaged after the failure test.

There was a highly significant difference (Kruskal-Wallis, $P = .001$) in the maximum load at failure between the 5 tape/fixation device groups (Table 1, Figure 4). The screw/washer group had the highest median value for the maximum failure load of 528 N (95% CI, 490-542 N), followed by the Endobutton group with a failure load of

TABLE 1
Summary of Key Variables From 1000 Cycle Loading and Loading to Failure

Group	Median (95% CI)	Mean ± SD (range)
Maximum cyclic (1000) displacement, mm		
Endobutton	1.90 (1.82-2.16)	1.84 ± 0.35 (1.26-2.16)
Multifix	2.30 (1.95-3.19)	2.40 ± 0.62 (1.69-3.19)
Footprint	1.59 (1.17-2.71)	1.65 ± 0.68 (0.9-2.71)
Postscrew	2.21 (2.02-2.30)	2.10 ± 0.23 (1.74-2.30)
Screw/washer	1.59 (1.40-2.30)	1.71 ± 0.38 (1.39-2.30)
Maximum load, N		
Endobutton	431.10 (425.36-456.70)	432.60 ± 16.25 (412.62-456.70)
Multifix	145.42 (100.31-179.41)	133.59 ± 36.56 (92.24-179.41)
Footprint	115.97 (109.47-130.58)	112.91 ± 14.85 (90.14-130.58)
Postscrew	405.45 (403.99-501.83)	414.63 ± 92.11 (271.70-501.83)
Screw/washer	528.40 (489.89-541.53)	507.99 ± 42.62 (441.30-541.53)
Displacement at maximum load, mm		
Endobutton	11.98 (8.88-14.71)	11.23 ± 2.71 (8.13-14.71)
Multifix	11.25 (7.74-39.66)	17.80 ± 13.84 (7.10-39.66)
Footprint	7.17 (3.79-13.34)	6.91 ± 4.09 (2.96-13.34)
Postscrew	17.69 (14.09-22.20)	17.58 ± 4.39 (12.33-22.20)
Screw/washer	13.71 (12.23-48.45)	20.07 ± 16.18 (8.51-48.45)

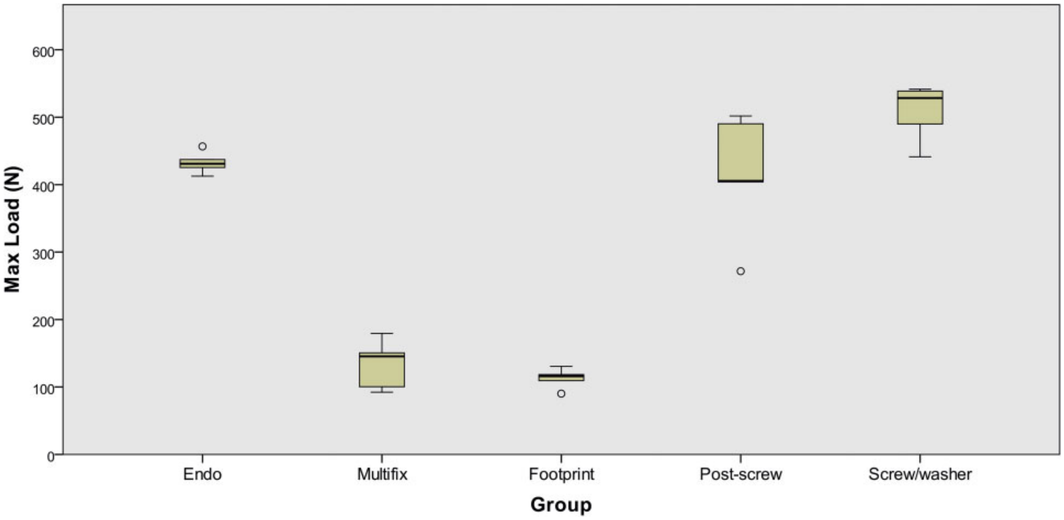

Figure 4. Maximum failure load by material/fixation device group. The box represents the interquartile (IQ) range which contains the middle 50% of the records. The whiskers are lines that extend from the upper and lower edge of the box to the highest and lowest values which are no greater than 1.5 times the IQ range. A line across the box indicates the median. The circle are outliers with values between 1.5 and 3 times the IQ range, i.e., beyond the whiskers.

431 N (95% CI, 457-433 N); this was marginally higher than the postscrew group, which had a median failure load of 405 N (95% CI, 404-502 N). The Multifix and Footprint groups had markedly lower failure loads, with median values of 145 N (95% CI, 100-179 N) and 116 N (95% CI, 109-131 N), respectively.

Performing paired comparisons, there was no significant (Mann-Whitney U, $P = .347$) difference in maximum failure load between the repairs in the Footprint and Multifix groups. The Endobutton, postscrew, and screw/washer groups all had significantly higher failure loads than repairs using both the Footprint and the Multifix suture anchors (Mann-Whitney U, $P = .009$). Repairs in the screw/washer group had a significantly greater failure load than the Endobutton (Mann-Whitney U, $P = .016$), but the differences between the screw/washer and postscrew were not significant (Mann-Whitney U, $P = .076$), neither were those between the postscrew and the Endobutton (Mann-Whitney U, $P = .602$).

The differences in displacement at maximum failure load did not reach significance between fixation devices (Kruskal Wallis, $P = .056$; Figure 5).

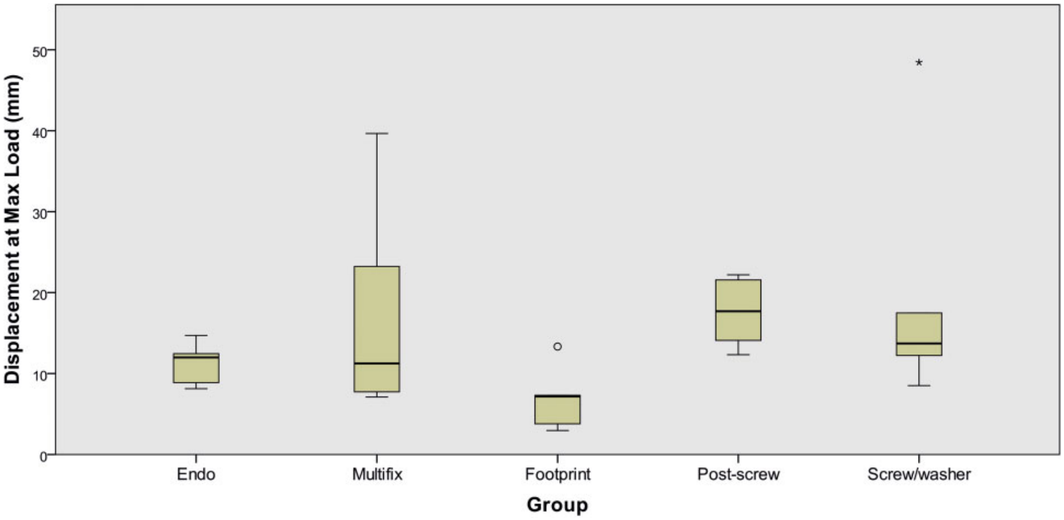

Figure 5. Displacement at maximum failure load by material/fixation device group. The box represents the interquartile (IQ) range which contains the middle 50% of the records. The whiskers are lines that extend from the upper and lower edge of the box to the highest and lowest values which are no greater than 1.5 times the IQ range. A line across the box indicates the median. The circle are outliers with values between 1.5 and 3 times the IQ range, i.e., beyond the whiskers. Asterisks are extreme outliers cases with values more than 3 times the IQ range.

DISCUSSION

The primary aim of our study was to assess the optimum fixation method for transosseous meniscal root repair using 2 mm–wide UHMWPE tape. The most important finding was that, in our meniscal root repair model, knotless suture anchor fixation of the tape failed at significantly low median loads (145 N Multifix and 116 N Footprint) than when the tape was secured by tying over a cortical fixation device (528 N screw/washer, 431 N Endobutton, and 405 N postscrew).

Studies using porcine models of transosseous medial meniscal root repair, using No. 2 suture, have shown the displacement of the repair when subject to cyclic loading, representative of postoperative rehabilitation. In these studies, sutures were fixed by knotting them over a cortical fixation device, and most of the displacement was reported to occur at the meniscus-suture interface[8] because of suture cutout of the meniscus. The amount of displacement that has been reported (between 2.2[10] and 3.3 mm[8]) could lead to a poorly functioning meniscal root repair, resulting in altered tibiofemoral contact mechanics similar to the unrepaired state.[18]

Previous authors[8,19] have suggested that the focus of optimization of meniscal root repair should be aimed at reducing the displacement at the meniscus-suture interface. Although more complex suture repair patterns (such as modified Mason-Allen and locking suture configurations) may improve maximum failure load,[17,19] they can be technically more challenging to perform, entailing longer surgical time,[4] and may be prone to even greater displacement compared with simple sutures.[19] Transosseous meniscal root repair with 2-mm UHMWPE tape has been shown to increase the repair strength in the meniscus, with ultimate failure loads of 298 N[27] reported in a porcine model compared with those for No. 2 suture of 58[24] to 180 N[10] in porcine studies and 64[17] to 169 N[11] in human cadaveric studies. The failure load of 2-mm UHMWPE tape in the meniscus exceeds the maximum failure loads for tibial fixation using suture anchors that we found in the present study: 116 to 145 N for the 2 devices we tested. Although these values are higher than the tensile forces that are likely to act on posterior root repairs in the early postoperative period with toe-touch weightbearing (60.1 ± 20.2 N),[31] they might potentially compromise a more accelerated postoperative protocol with earlier full weightbearing.

The use of tape for meniscal root repair is increasingly being advocated, with some surgeons recommending fixation at the anterior tibial cortex with a suture anchor. To our knowledge, the displacement of tape at the bone-fixation interface in a meniscal root repair model has not been previously been evaluated in the literature. Knotless suture anchor fixation of the tape is commonly used in shoulder surgery for repairs of the rotator cuff.[5,6,23,25] Improved pull-out strength has been achieved using a second row of anchors[7]; load sharing between the 2 rows of anchors is being proposed as the mechanism for this. The failure mechanism of tape and suture slippage through the single knotless anchor at relatively low yield loads, seen in our study, is supportive of this. Failure in all-suture anchor specimens was by tape slippage as opposed to tape breakage that occurred in all the Endobutton, postscrew, and screw/washer specimens; similarly, suture slippage was the failure mechanism for the suture + Multifix specimens, compared with suture rupture for the suture + Endobutton specimens.

The 2 types of knotless suture anchors used in this study have different methods of fixation of the tape. The Footprint Ultra PK suture anchors have an internal plug to secure the tape and the Multifix S Ultra anchors rely on interference compression of the tape between the threads of the suture anchor and the surrounding bone. These fixations depend upon friction, and if the tape repair is loaded such that the frictional forces resisting tape motion are overcome, tape slippage will occur. Our findings are also in accordance with those of Wieser et al,[32] who showed that suture slippage through a single-suture anchor occurs at relatively lower loads (66-109 N) compared with anchor pullout (156-269 N) for the devices they tested, because of low static friction between the suture and anchor. The increased number of fixation devices used in rotator cuff surgery acts to share the loads applied to the repair construct, reducing the loads acting on the tape fixed by any single anchor. In meniscal root repair, a single anchor is used to fix 1 or 2 pieces of tape that are passed through the anchor. In addition, the tape ends are shuttled down the transosseous tunnel, possibly resulting in the tape being coated with bone marrow fat, leading to a reduction in the coefficients of friction between the tape, bone, and anchor.

Some authors have suggested that tying the tape over a screw and washer may be advantageous in that the washer may be used to compress the tape against the anterior cortex of the tibia to provide some further interference fixation of the tape as opposed to tying the tape over a postscrew alone.[26] This has not been previously tested biomechanically. We found that the use of a washer did not confer any advantage in resistance to cyclic loading. Although the displacement was lower in the screw/washer group (1.6 mm) compared with the postscrew group (2.2 mm), this difference did not reach statistical significance. With load-to-failure testing, it was noted that in some specimens where a postscrew or screw/washer was used, at high loads, the screw began to cut through bone proximally. This mechanism may have resulted in the increased displacement seen at ultimate failure, although this did not reach statistical significance and is of doubtful clinical significance as screw cutout occurred at loads in excess of tape cutout from the meniscus.[27]

Limitations

Biomechanical studies using cadaveric porcine tissue do have limitations. Although young porcine knees have been used as reasonable surrogates for human knees and are an accepted model for the study of meniscal root repair,[8,24,27,28] they are not the same and surgical results may differ. However, porcine tibiae have been shown to have biomechanical properties similar to human tibiae and have the advantage of standardizing tissue and bone quality.[8] It should be highlighted that we studied 2 specific designs of suture anchor that can be used for knotless fixation, and extrapolating our findings to other designs may not be accurate. However, the work by Wieser et al[32] has shown slippage occurring in other designs of suture anchor with a standard suture material.

The number of loading cycles we used in this study (1000) is relatively short, and there may have been further displacement occurring beyond this. However, in all of our tests, we noted that the displacement versus number of cycles had an asymptotic appearance, and it is likely that any further displacement would be small. Additionally, testing with cadaveric material beyond 1000 cycles would not account for the biological healing that is likely to have begun.

In this study, displacements were measured through changes in actuator position. Therefore, displacement in the full test construct was measured. It is possible that displacement in the fixtures may have accounted for some of the displacement seen; however, contribution to the displacement is likely to be negligible, given that the fixtures were made of steel and were fixed securely to the baseplate of the materials testing machine.

CONCLUSION

In this study, we found that when using a 2 mm–wide UHMWPE tape for transosseous meniscal root repair, tying the tape over a cortical fixation button appeared to give the most reproducible biomechanical behavior, but tying over a screw or screw/washer would also be reasonable. Use of a single knotless anchor may not provide sufficient strength to allow an earlier return to weightbearing in the postoperative period.

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