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The strength of transosseous medial meniscus root repair using a simple suture technique is dependent upon suture material and position.

James R. Robinson[1,2], MB BS MRCS FRCS(Orth) MS

Evelyn G. Frank[3], Dipl.-Wirt.-Ing.

Alan J. Hunter[3], BE (Hons I), PhD, MIEEE, MIOA

Paul J. Jermin[1,4], MBChB (Hons), MRCS (Ed), FRCS (T&O)

Harinderjit S. Gill[3] , BEng, DPhil, FIPEM

1. Avon Orthopaedic Centre, Bristol, UK. 2. International Knee and Joint Center, Abu Dhabi, UAE. 3. Department of Mechanical Engineering, University of Bath, Bath, UK. 4. The Robert Jones & Agnes Hunt Orthopaedic Hospital, Oswestry, UK.

Abstract

Background: Use of a simple suture technique in transosseous meniscal root repair is potentially advantageous. It can provide equivalent resistance to cyclic load and is less technically demanding to perform than more complex suture configurations, yet maximum yield loads are lower. Various suture materials have been trialed for repair but it is currently not clear which is optimal in terms of repair strength. Meniscal root anatomy is also complex; consisting of the ligamentous mid-substance (root ligament), the transition zone between the meniscal body and root ligament; the relationship between suture location and maximum failure load has not been investigated in a simulated surgical repair.

Hypotheses: A) Using a knotable 2 mm wide ultra-high molecular weight polyethylene (UHMWPE) braided tape for trans-osseous meniscus root repair with a simple suture technique will give rise to a higher maximum failure load than a repair made using size No. 2 UHMWPE standard suture material for simple suture repair. B) Suture position is an important factor in determining the maximum failure load.

Study Design: Controlled Laboratory Study

Methods: Part A: The posterior root attachment of the medial meniscus was divided in 19 porcine knees. The tibias were potted and repair of the medial meniscal posterior root was performed, closely replicating single-tunnel, trans-osseous surgical repair commonly used in clinical practice, using a suture passing device to place 2 simple sutures into the posterior root of the medial meniscus. 10 tibias were randomised to repair with No. 2 suture (SUTURE group), 9 for repair with 2 mm wide knotable braided tape (TAPE group). The repair strength assessed by maximum failure load measured using a materials testing machine.

Micro CT scans were obtained to assess suture positions within the meniscus. The wide range of maximum failure load appeared related to suture position.

Part B: 10 additional porcine knees were prepared. Five were randomised to the SUTURE group and five to the TAPE group. All repairs were standardised for location, placing repair in the body of the meniscus.

A custom image registration routine was created for co-registering all 29 menisci, which allowed the distribution of maximum failure load versus repair location to be visualised with a heat map.

Results: Part A **-** Higher maximum failure load was found for the TAPE group (Mean = 86.7 N, 95% CI 63.9 N to 109.6 N) compared to the SUTURE group (Mean = 57.2 N, 95% CI 30.5 N to 83.9 N). The 3D micro CT analysis of suture position showed that the mean maximum failure load for repairs placed in the meniscal body (Mean = 104 N, 95% CI 81.2 N to 128.0 N) was higher than those placed in the root ligament (Mean = 35.1 N, 95% CI 15.7 N to 54.5 N).

Part B - Mean maximum failure load was significantly greater for the TAPE group, 298.5 N (p=0.016, Mann-Whitney U, 95% CI 183.9 N to 413.1 N), compared to that for the SUTURE group, mean = 146.8 N (95% CI 82.4 N to 211.6 N).

The visualisation with the heat map revealed that small variations in repair location on the meniscus were associated with large differences in maximum failure load; moving the repair entry point by three millimetres could reduce the failure load by 50%.

Conclusions: The use of 2 mm braided tape provided higher maximum failure load than the use of a No.2 suture. The position of the repair in the meniscus was also a highly significant factor in the constructs' properties.

Clinical Relevance: Gives insight into material and location for optimal repair strength.

Key Terms: Meniscal root repair; suture material; biomechanical testing; repair location

What is known about this subject: The material used for meniscus root repair has an influence on repair strength, established by non-physiological loading tests. Collagen fibre orientations vary within the meniscus, leading to differences in repair strength for varying repair locations.

What this study adds to existing knowledge: Using an experimental technique that replicates the surgical repair process and applied loading in a physiological direction this study has shown that 2 mm tape has a higher repair strength than No. 2 suture material. For the first time a heat map of repair strength as a function of repair location is presented to guide the surgeon.

Introduction

The anatomy of the posterior meniscal root attachments is complex; consisting of the ligamentous mid-substance (root ligament), the transition zone between the meniscal body and root ligament, and the bony insertion of the root ligament onto the tibial plateau. [2, 12, 27] The root attachments prevent extrusion of the meniscus with joint compression, [2, 10, 12] allowing the menisci to dissipate axial loads through the distribution of hoop stress in the circumferential collagen bundles and thus reduce peak loads in the articular cartilage. [10, 13, 17, 24, 27, 32] The strength of medial meniscus posterior root repair is weaker than the native root attachment at time of surgery for both common methods of meniscal root repair: trans-osseous tunnel suture repair and suture anchor repair. [8] Trans-osseous tunnel repair has garnered favour as it does not require posterior portals and tran-osseous drilling may be advantageous in enhancing meniscal healing with cells from the bone marrow entering the intra-articular space. [8] Surgeons commonly use two simple sutures in the meniscus as this configuration has been reported to combine the lowest technical difficulty with while resisting cyclic displacement at time zero over more complex suture patterns. [21] However, for simple vertical sutures, maximum yield loads at failure are low: Kopf et al. [16] reported a mean ultimate yield load of 64.1 ± 22.5 N for two No. 2 sutures, and Mitchell et al. [28] 96.2 ± 51.4 N for two No. 0 sutures. However, Feucht et al. [9] showed a failure load of 169.0 ± 43.4 N for a single No.2 suture using the same material (FiberWire, Arthrex, Naples, FL). This disparity in failure loads is unexplained, yet all well below the maximum failure load of native posterior root attachment of the medial meniscus, 678 ± 200 N. [16]

More complex suture repair patterns (such as modified Masson-Allen and locking suture configurations) may improve maximum failure load [16, 21] but can be technically challenging to perform with longer surgical time [3, 21] and may be prone to increased displacement compared with simple sutures. [21, 22]. The comparative biomechanical properties of several different single vertical sutures has been previously investigated in lateral porcine menisci [9], with the authors concluding that none of them provided superior properties. Biomechanical studies have shown that shoulder rotator cuff repairs with a wider tape in place of a No. 2 suture had higher maximum failure load. [23] However, fixation of tapes and sutures for the rotator cuff repairs was performed using knotless suture anchors, while for trans-osseous meniscal root repair the sutures are usually tied over a post screw [25] or button. [20, 22] Previous investigations of direct pull out strength of a single 2 mm tape [9], in simple suture configuration, in porcine lateral menisci showed a tendency towards increased displacement over suture. However, in that study the tape was used in conjunction with knotless fixations and it is possible that the increased displacement seen was due to knot slippage. It has also been suggested that the low yield loads seen in some studies with simple sutures might result from the relative disparity between the diameter of No. 2 suture and the larger 2 mm hole made in the meniscus by the suture passing devices commonly used in meniscal root and rotator cuff repair[16]. Wider tape better fills the hole, better distributing pressure and has been shown to increase rotator cuff repair strength. [5]

Given the apparent advantages of a simple suture technique in terms of simplicity and reduced displacement, the purpose of this study was to evaluate the biomechanical properties of trans-osseous tunnel, simple suture, medial meniscus root repair using a knotable 2 mm wide tape compared to No. 2 suture to ascertain whether the use of knotable tape might perhaps offer the best combination of strength, resistance to displacement and speed of execution.

We hypothesized that, in a porcine model, the use of knotable tape to repair the posterior medial meniscus root would lead to higher yield loads at ultimate failure than suture. However, when the initial experiment produced highly variable yield loads, we speculated that the position of the suture / tape in the meniscus root attachment effected the biomechanics of the repair. This led us to perform a second experiment in which we hypothesized that there might be a link between suture position and meniscal root repair strength.

Method

The key principal in 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 were used for this study, obtained from a local authorised supplier. As this study used material generated as waste from food production no ethical approval was required.

Specimen Preparation and Root Repair

The stifle specimens were thawed for 24 hours at 2°C. The femur and soft tissue were then carefully removed proximal to the menisci, leaving the meniscal root attachments undamaged and meniscal-tibial fibres intact. The posterior medial meniscus root attachment was divided flush with its attachment to the tibia so as to leave the transition zone and root ligament intact.

A trans-tibial meniscal root repair was then performed mimicking in vivo clinical surgical repair in patients previously described. [20, 30] A 3.8 mm diameter trans-tibial tunnel was drilled from the posterior medial meniscus root attachment to the anteromedial cortex of the tibia. A suture passing device (FirstPassST, Smith & Nephew, Andover, MA) was used to pass suture material, through the root attachment (Figure 1). The sutures material was then shuttled down through the trans-tibial tunnel. The normal surgical process used by the senior surgical author is to pass the first suture through the meniscus root, pull the meniscus back into position using this suture and then pass a second suture in a more postero-medial position. This process was followed in the repairs performed in the first part of this study (Part A). The position of the sutures was not standardised, with the senior surgical author aiming to place the two sutures or tapes in a vertical, simple suture configuration, medial to the position in which the meniscus root had been divided. In Part A, 19 porcine specimens were randomised to receive a repair either using a traditional UHMWPE suture (n=10, No.2 UltraBraid, Smith & Nephew, Andover, MA) hereafter termed SUTURE or using a knotable, 2 mm UHMWPE braided tape (n=9, UltraTape, Smith & Nephew, Andover, MA) hereafter termed TAPE.

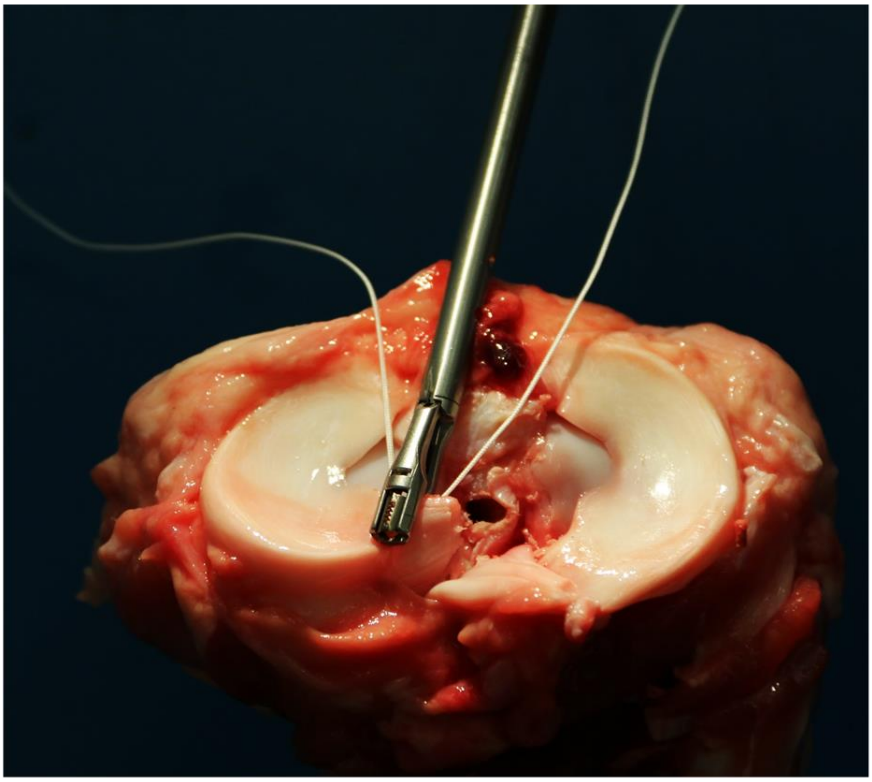

Figure 1: A suture passing device (FirstpassST, Smith and Nephew, Andover, MA), typically used in shoulder rotator cuff repair, was used to pass either No. 2 Suture (Ultrabraid, Smith and Nephew Andover, MA) or 2 mm knotable tape (UltraTape, Smith and Nephew, Andover, MA) for the posterior horn root repairs. Repairs were made with either two No. 2 sutures (SUTURE) or two knotable 2 mm tapes. As per clinical surgical repair, the first suture/tape was passed into tissue of the root attachment and then shuttled down a trans-osseous tunnel drilled to the root attachment. Traction on this suture allowed the meniscus to be controlled and held more firmly allowing a second suture/tape to be passed through the meniscus medial to the first. This suture/tape was then also passed down the trans-osseous tunnel, to allow the free ends to be attached to the mandrel of the Instron tensile testing machine.

In Part B the menisci were marked medial to the border of the transition zone between body and root ligament according to clinical judgement based on literature. [9, 15, 28] Care was taken to ensure that sutures/tape were placed in line with this mark to ensure that sutures were placed in the body of the meniscus. Care was taken not to over reduce the meniscus when fixed to the mandrel of the Instron testing machine.

Mechanical Testing

After surgical repair, the distal part of each tibia specimen was positioned into a custom pot using a low melting point alloy (Woods Metal 70°C, Lowden Ltd., Lower Moor, UK). Each potted tibia was then mounted inverted in a specifically designed rig that allowed adjustable positioning. The rig was secured to a material test machine (Series 5965 with 1 kN load cell, Instron, High Wycombe, UK) such that the tibial tunnel through which the sutures passed was vertically below a mandrel mounted to the crosshead (Figure 2). The sutures were securely knotted around the mandrel. Care was taken to ensure that the meniscus was repaired to its anatomical position (the meniscus was reduced back to where it had been sectioned) and that it had not been over reduced prior to testing. Each specimen was initially pre-tensioned to 2 N and then conditioned by 20 cycles [16] loading from 5 to 20 N at a rate of 0.36 mm/s. [8] After conditioning, each specimen was loaded to failure, by applying displacement at a rate of 0.5 mm/s. [8] Load and displacement data were captured continuously at 10 Hz; the maximum failure load, as per Kim et al. [15], was used as the indicator of repair strength.

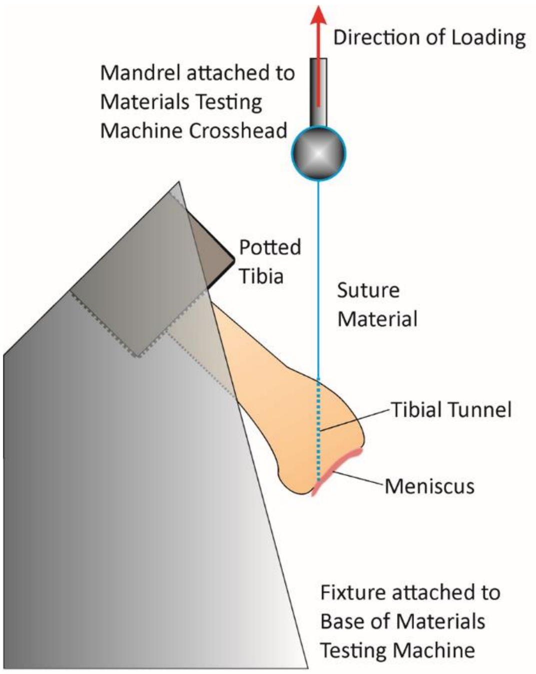

Figure 2: Experimental setup. The trans-osseous tunnel was orientated to allow the TAPE or SUTURE to be pulled parallel to the trans-osseous tunnel and to the axis of the load cell.

3D Scanning

Following the mechanical testing performed in Part A, we noted large variability in maximum failure load for both TAPE and SUTURE repairs. This led us to hypothesise that the position of the repair in the meniscus was important in determining the repair strength. In Part B menisci were scanned using a microCT scanner (Nikon X-Tek, XT H 225 ST, Shinagawa, Japan). The reconstructed scan data were used to establish the suture locations. The mode of failure from the mechanical testing was, in all specimens, by the sutures cutting out of the meniscus lateral to the 0.9 mm hole made by the suture passing device. The entry point into the meniscus of the most posteromedial suture (this was the second suture inserted) was classified as being in the: i) Root Ligament [RL], ii) Transition Zone [TZ] or iii) the substance of the meniscus [BODY] (Figure 3). Entry point classification was performed blinded (EGF) to the Instron data. The ICC for repeated blinded evaluation within an examiner was 0.98 (95%CI 0.95 to 0.99).

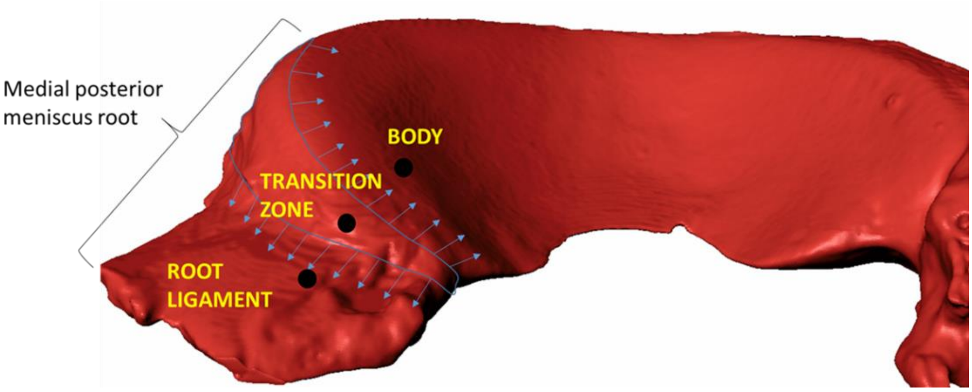

Figure 3: A 3D reconstruction from a microCT scan of a representative meniscus showing the suture/tape entry locations that were analysed.

Analysis

A custom Matlab (version 2013, The MathWorks Inc, MA, USA) script was used to extract the maximum failure load from the Instron data and the extension at maximum load. The difference in maximum failure load was then examined grouped by either suture material (SUTURE or TAPE, Mann-Whitney U) or suture entry location (RL, TZ or BODY, Kruskall-Wallis). All statistical analyses were performed using SPSS (v22, IBM SPSS Statistics, Armonk, New York, USA). A p-value of 0.05 or less was considered significant.

Part B

The results from Part A displayed considerable variability, which appeared to be related to the location of the sutures. Part B repeated the study protocol of Part A using five fresh frozen porcine stifle joints for the SUTURE group and five for the TAPE group. For Part B, care was taken to ensure the suture entry points were in a similar location in the meniscus for each specimen (BODY); the intention was to provide a comparison between SUTURE and TAPE repair while controlling for suture location. The menisci were marked medial to the border of the transition zone between body and root ligament; the mark was placed as close as possible to the midline of the meniscus. Care was taken to ensure that sutures/tape were placed in line with this mark to ensure that sutures were placed in the body of the meniscus and avoided the transition zone and root ligament parts of the root attachment. After the mechanical testing, a 3D high-resolution laser scan (CMS108Ap, Hexagon Metrology, Telford, UK) of each meniscus was performed to ascertain the achieved location of the suture entry points in the body of the meniscus. The Instron data were processed in the same way as that from Part A with identical analysis.

Image Analysis

The experimental method allowed the maximum failure load to be determined for each specimen, and for Part A considerable variation in repair location was noted between specimens. Given that there was anatomical variation between specimens, we developed a method, based on Delauney triangulation, [11] to map locations on any meniscus specimen to a chosen reference meniscus specimen. This allowed all the maximum failure loads to be plotted at each respective repair location mapped onto a single reference meniscus. To aid visualisation these plotted data were represented as a heat map, showing the variation in maximum failure load as a function of repair location. The method is described below:

Digital photographs of each dissected meniscus laid flat were taken (EOS 80D, Canon, Tokyo, Japan). The outer edge of the meniscus body was traced onto each image, with the repair material insertion points marked by yellow dots. The distribution of insertion positions over the meniscus specimens was mapped to a single reference specimen, chosen to be a good representation of a nominal meniscus shape. Transformations to the chosen reference meniscus were achieved with a two-stage process. The anatomic coordinate frame was marked in each image, with coloured dots placed in the most anterior (magenta), posterior (green) and medial (cyan) aspects of each meniscus. An initial coarse transformation was applied to align the three dots corresponding to the anatomical frame locations with the matching locations in the image of the reference meniscus; the dots were automatically detected using colour-based segmentation. This initial alignment was then followed by a finer transformation using automated warping of the meniscus outline to the outline of the reference meniscus based on Delauney triangulation. [11] Automated detection of the yellow dots in the warped images then gave the location of the repair for each meniscus specimen mapped onto the reference meniscus. The corresponding maximum failure load values were plotted over the reference meniscus outline and cubic interpolation was used to generate the heat map where high maximum failure loads were represented as hot (red) and low maximum failure loads represented as cold (blue).

All image processing was performed using custom routines written in Matlab.

Results

Part A

During the cyclic loading performed to condition the specimens, the average displacement was 1.65 mm (95% CI 1.39 to 1.91 mm); there was no difference between the TAPE and SUTURE material in the displacement during conditioning (p=0.756, Mann-Whitney U). The maximum failure load for the repairs made using the TAPE material was approximately 52% greater than that for the SUTURE material (Figure 4), this was significant (p=0.043, Mann-Whitney U). Considerable variability in maximum failure load was observed (Figure 4), the range was from 55.3 to 136.5 N for the TAPE group and from 13.7 to 143.0 N for the SUTURE group.

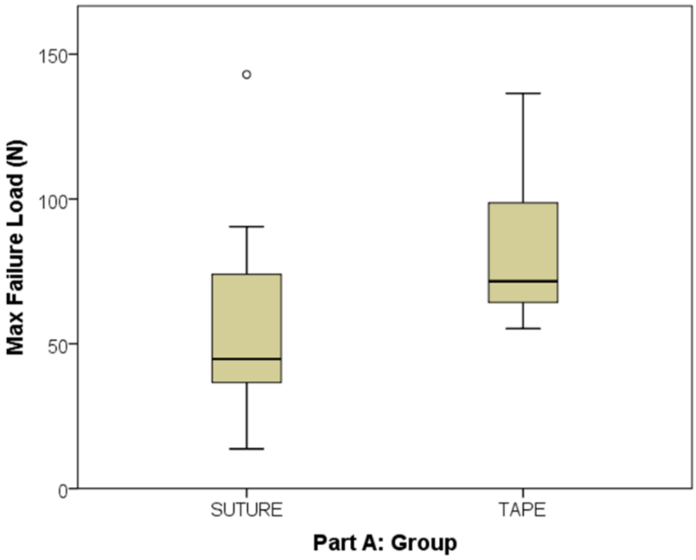

Figure 4: Maximum failure load for Part A, SUTURE (n=10) versus TAPE (n=9) groups. The circle represents an outlier greater than the third quartile (Q3) + 1.5 times the interquartile range).

The maximum displacement at maximum load was not significantly (p=0.079, Mann-Whitney U) different between suture material groups; it was 6.6 mm (95% CI 3.0 to 10.2 mm) for the SUTURE group and 8.3 mm (95% CI 5.7 to 10.9 mm) for the TAPE group.

The 3D analysis showed that the distribution of entry point locations was not even between the SUTURE and TAPE groups, with four of the SUTURE group having RL entry points compared to one for the TAPE group; additionally, only three of the SUTURE group had BODY entry points compared to five of the TAPE group. For the whole group of Part A specimens, the maximum failure load was significantly different (p=0.001, Kruskal-Wallis) between the entry point location groups (Figure 5). Maximum failure load was highest for the BODY location, 104 N (95% CI 81.2 to 128.0 N), and lowest for the RL location 35.1 N (95% CI 15.7 to 54.5 N).

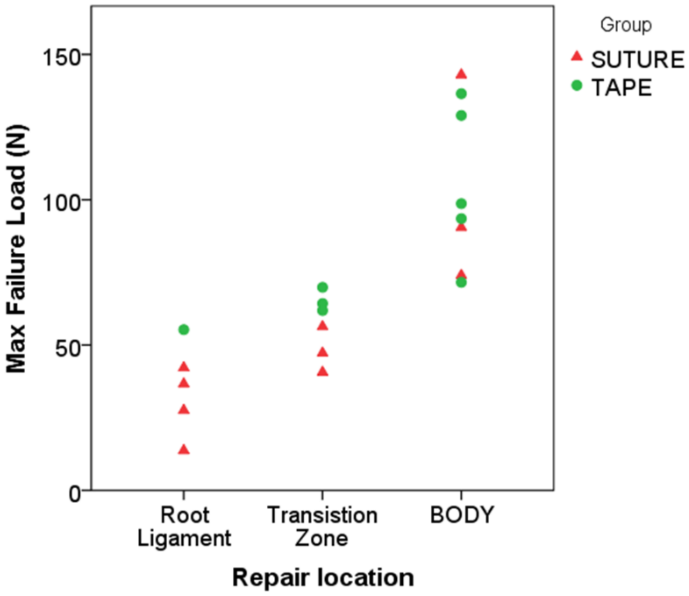

Figure 5: Effect of suture/tape entry location on maximum failure load for Part A.

Part B

The 3D reconstructions confirmed that all second suture entry points for all specimens in Part B were located at the BODY location. The maximum failure load values for both repair material groups were substantially higher than had been observed for Part A. The maximum failure load was significantly (p=0.016, Mann-Whitney U) greater for the TAPE group, approximately double, compared to that for the SUTURE group (Figure 6).

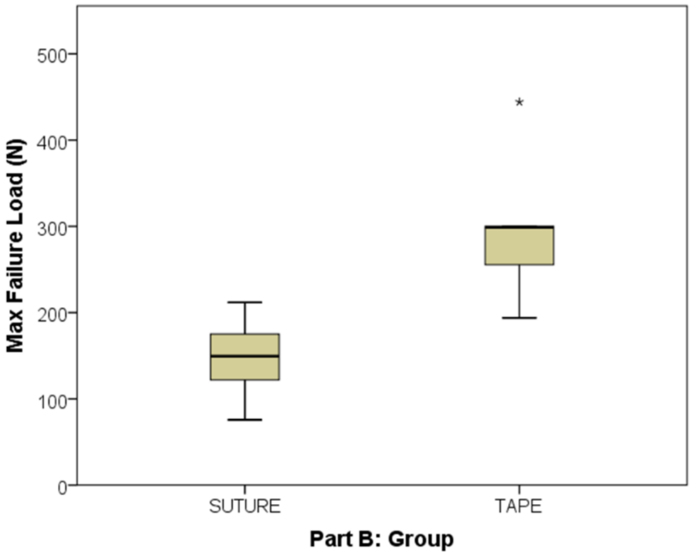

Figure 6: Maximum failure load for Part B, SUTURE (n=5) versus TAPE (n=5) groups. The asterix represents an extreme outlier value (three times the inter quartile range from either the first quartile [Q1] or the third quartile [Q3]).

Image Processing

The registration procedure was able to successfully register all specimens to the reference specimen. The mapping between suture insertion point and maximum failure load indicated that small variations in suture insertion point could result in a relatively large reduction in failure strength (Figure 7). Highest maximum failure loads were found for insertion points within the body of the meniscus to either side of the central part of the transition zone.

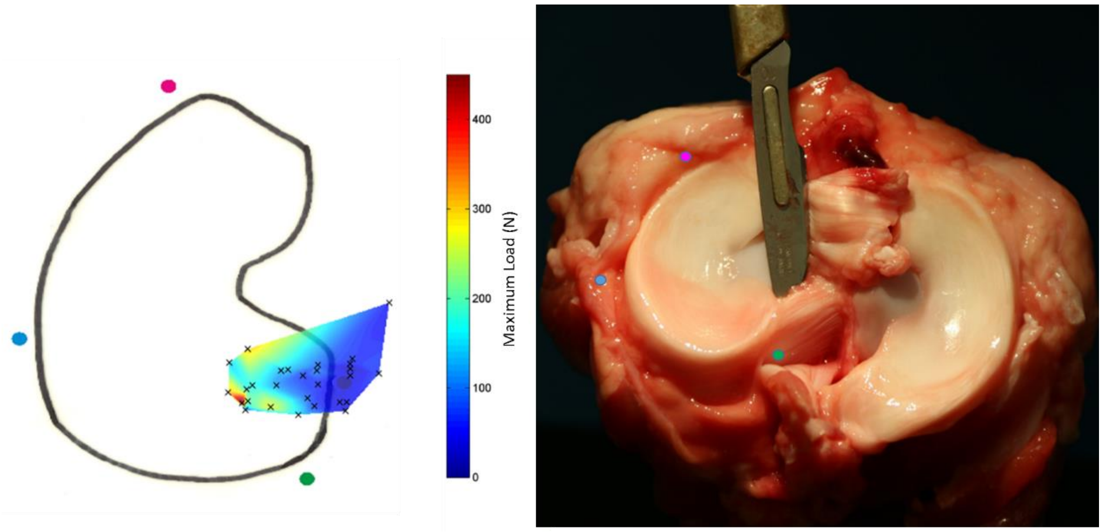

Figure 7: Heat map of maximum failure load as a function of suture/tape entry location (points shown as crosses) generated from all 29 specimens based on image registration and warping to a representative meniscus; the image on the right shows a photograph of the tibial plateau to allow orientation of the heat map. For initial registration coloured dots were placed in the most anterior (magenta), posterior (green) and medial (cyan) aspects of each meniscus; the image of the tibial plateau on the right has the same locations marked to clarify position of heat map. The heat map was generated based on cubic interpolation. Small variations in suture insertion point were found to result in a large difference in maximum failure load. Highest failure loads were found for insertion points within the substance of the body of the meniscus to either side of the central part of the transition zone.

Discussion

The primary aim of our study was to assess whether posterior meniscal root repair using knotable 2 mm ultra-high molecular weight polyethylene tape provided superior initial fixation strength compared to repair with No.2 suture with comparable extension at failure. The study confirmed this to be the case. The study also showed that the location of suture or tape within the posterior root attachment was a much more important determinant of maximum failure load. Feucht et al.[8, 9] tested the pullout strengths of single, vertical sutures, of different material in lateral porcine menisci. In this previous study a 2 mm tape (Fibertape, Arthrex, Naples, FL, USA), was found to have a higher load to failure than No. 2 PDS (Ethicon, Somerville, NJ, USA) but not No. 2 Fiberwire (Arthrex, Naples, FL, USA) or No. 2 Ethibond (Ethicon, Somerville, NJ, USA . However, higher displacement was noted with tape repairs. They concluded that none of the evaluated suture materials provided clearly superior properties in load-to-failure testing. The tendency for the higher displacements seen with the 2 mm Fibertape repairs may be related to the tape that was tested (Fibertape), which is usually used for knotless fixation in shoulder surgery and not normally knotted. In their experimental setup the free ends of the tapes/sutures were tensioned and tied to the platen of the materials testing machine with a knot stack. The increased displacement seen in the repairs may have resulted from knot slippage.

The findings of our study, that the position of the repair influences strength, may explain the variation in root repair strength reported in the literature. Previous studies have reported mean yield loads for meniscal root repair using simple sutures varying from 58 N [28] to 180 N [8] in porcine studies and from and 64 N [16] to 169 N [9] in human cadaveric studies. Examination of the available images published in these studies show that different suture locations were used in the meniscus. The variation of suture position between studies may account for these somewhat disparate results. The findings of our study support this. For example, Kopf et al. [16] found low pull-out strengths for simple meniscal root sutures (mean 65 N). However, the figure from Kopf et al.'s study showing an example of a simple suture posterior meniscal root repair demonstrates a repair location in the transition zone of the root attachment. In our study, we found that repairs in the root ligament and transition zone had similar low mean yield load, 57 N. In studies where suture placement was standardised, results between different suture materials were consistent with Feucht et al. [9] finding similar suture construct strengths of 146 ± 21 N using Ethibond suture and 169.0 ± 43.4 N using FibreWire.[9] Figures from the Feucht et al. studies demonstrate a repair location within the substance of the meniscal body. In the second part of our study (Part B) the repair location was standardised, and sutures/tape were implanted in the meniscus substance, tape repairs were found to be twice as strong as suture repair with mean maximum yield load of 298.5 N (TAPE) compared to 146.8 N (SUTURE).

The heat map generated from the image analysis (Figure 7) shows the sensitivity of failure load to small variations in suture insertion point. Of note the strongest repairs were found to occur on either side of the main transition zone. The collagen fibres in the root ligament are mostly orientated parallel to the direction of the root ligament, and this parallel fibre orientation continues into the body of the meniscus.[32] Repairs located within the transition zone where the fibres are predominately parallel have approximately half the strength of those outside this area. The gradient of maximum failure load is very steep in the latero-posterior portion of the medial meniscal root adjacent to the transition zone. Polarized light microscopy [6] and optical projection tomography [2] of the meniscus the has shown that the principal orientation of the collagen fibres in the substance of the meniscus is circumferential. In the outer third of the meniscus the circumferential collagen fibres are organised in fascicles. These are parallel to the fibres in the transition zone and root ligament and are ideally orientated to resist hoop stresses that occur when the meniscus is exposed to axial load. The arrangement however offers little resistance to pull-out sutures. In the mid zone of the meniscus body there are increasing numbers of radially disposed fibres [6] and the collagen fibrils take on a more woven appearance. [2] This fibre orientation is likely to contribute to the increased ultimate yield load for repairs where the suture location is in the substance of the meniscal body as shown in the heat map. Kim et al. [15] reported that vertical sutures placed in the red-white zone of the meniscus had a higher pull out strength than those placed in the red-red zone when pulled in the direction of the root, however, the strength of a surgical trans-osseous repair was not tested.

Feucht et al. [9] suggested that low yield loads seen in for simple sutures in their models of meniscal root repairs using simple sutures might result from the relative disparity between the diameter of No. 2 suture and the larger 2 mm hole made in the meniscus by the suture passing devices commonly used in meniscal root repairs.

The findings of this study have potentially important implications for surgery and post-operative rehabilitation. For the root repairs performed in our study, it must be noted that even when repair location was optimal, the mean maximum failure load for a simple suture technique shown in our study (for TAPE = 298.5 N and SUTURE = 146.8 N for tears in the meniscus substance) remain significantly lower than the strength of native root 594 ± 241 N [16] but, reassuringly, are higher than the maximum tensile forces found acting on the posterior root repairs in vitro human models (60.1 ± 20.2 N). [33] Meniscal root tears types have been previously classified by LaPrade et al. according to their morphology. [18] Degenerative complete radial tears 0 mm to 9 mm (LaPrade type 2) from the medial meniscus posterior root tibia attachment site are common.[18, 30] The findings of this study suggest that for medial root tears more adjacent to the attachment site (LaPrade 2A and 2B) the surgeon should still make an effort to ensure that sutures/tapes are passed medial to the transition zone and ensure that the body of the meniscus has been penetrated by the suture. Whilst is may be technically easier at surgery to place suture closer to the tear, our data suggests that surgeons should be careful to avoid placing sutures in the transition zone and particularly into the root ligament parts of the meniscus root attachment (56.7 N mean yield load in the transition zone and 35.1 N in the root ligament.). The effect of tear proximity to the suture insertion site on repair strength is unknown and remains an area for further study.

With respect to rehabilitation, weight bearing the knee results in compressive forces which act to displace/extrude the meniscus and any repair construct. The optimal post-operative rehabilitation protocol after a root repair is currently unknown. Studies have shown better healing rates at second look with periods of non-weight exceeding 6 weeks,[1, 14, 16, 27, 34] therefore many would advocate a conservative rehabilitation. If our load to failure is optimised with correct placement and use of a tape, it is possible that we may not need such a protracted period of non-weight bearing. However, it is worth noting that the best repairs we achieved in this study were still below the strength of a native root. We would, therefore, advocate a cautious post-operative rehabilitation, which has already been shown to have superior outcomes clinically.[30]

Transosseous simple suture repair has gained popularity due to its ability to restore the tibiofemoral contact pressures and areas to the intact knee at time zero.[4, 19, 26, 29, 31] However, concerns have been raised about fixation strength.[16, 28] Laprade et al. [20] suggested that different suture materials or the use 2 transosseous tibial tunnels could be advantageous if the meniscal tissue could be held firmly in place across a wider surface area, improving the stability and pressure distribution and thus stimulating more healing at the tissue-bone interface. Their study of single and double tunnel repairs found that ultimate failure loads for both were similar however the double tunnel repairs seemed more stable and secure. Our study found that that the ultimate failure loads for tape repairs were higher than those using suture and that the tape appeared to have the effect of distributing pressure more evenly lying the meniscus flat at the repair tissue-bone interface; an effect that has been previously observed in rotator cuff repair.[5] The evaluation of possible improved meniscus-bone healing is an area for in vivo or animal studies employing second look arthroscopy.

Limitations

The limitations of our study are: although using young porcine menisci has been accepted as a reasonable surrogate to human menisci, they are not the same and results may differ. However porcine menisci have been shown to have similar biomechanical properties to human menisci and are an accepted model for the study of meniscus root repair. [9, 15, 28] Whilst the morphology of the porcine medial meniscus is different, corresponding to the porcine tibiofemoral articulation, the anatomy of the posterior medial root attachment is similar to the human consisting of the transition zone between the body of the meniscus and the root ligament that attaches to bone. The heat map analysis is based on the co-registration of 29 images with relatively sparse load data at some locations. However, the analysis is unique and offers insight into the optimal placement of surgical repairs. We observed a non-significant difference ($p=0.07$) between the SUTURE and TAPE groups in the maximum displacement at maximum load, an increased sample size may have shown this difference to be significant.

Our study is unique in that it closely replicates a surgical repair. Most similar studies place the dissected meniscus directly in a clamp and apply pressure directly to this. By testing a surgical transosseous repair, we feel that our findings will be more representative of what happens in patients.

Our root tears were caused by clean, sharp dissection; often medial root tears can be degenerate in nature and may behave differently when loaded.

Our tests utilised highly specialised materials and extrapolating this data to other forms of tape may be inaccurate. The tape used in this study may be knotted, other tapes however are designed for knotless fixation. For trans-osseous pull-out suture repair, the usual fixation method is that the tape/suture is tied over a post or button. If using a tape that is designed to be knotless, this may affect the maximum failure load significantly. In our practise, we tie over a small fragment screw with a washer, which is then tightened against the anterior cortex of the tibal to provide additional interference fixation; we did not investigate the effect of different fixations at the anterior tibial cortex and this is an area of further work. It has been reported that displacement of the repaired meniscal root with cyclic loading occurs at the meniscus-suture interface rather than at the site of fixation on the anterior tibia. [7] The effects of the use tape on meniscus-suture interface displacement are another area for further investigation.

Conclusion

The findings of both arms of our study provide valuable evidence for clinicians undertaking meniscal root repairs; importantly this study is unique in that it closely replicates a whole surgical repair rather than considering a dissected meniscus held in a clamp. By testing a surgical transosseous repair, our findings will be more representative of what happens in patients. Repair with knotable 2 mm tape had approximately double the strength of suture. The location of the repair was found to be important, repairs located in the substance of the meniscus were significantly stronger than those in the transition zone and root ligament.

Figure captions:

Figure 1. A suture passing device (FirstpassST, Smith and Nephew, Andover, MA), typically used in shoulder rotator cuff repair, was used to pass either No. 2 Suture (Ultrabraid, Smith and Nephew Andover, MA) or 2 mm knotable tape (UltraTape, Smith and Nephew, Andover, MA) for the posterior horn root repairs. Repairs were made with either two No. 2 sutures (SUTURE) or two knotable 2 mm tapes. As per clinical surgical repair, the first suture/tape was passed into tissue of the root attachment and then shuttled down a trans-osseous tunnel drilled to the root attachment. Traction on this suture allowed the meniscus to be controlled and held more firmly allowing a second suture/tape to be passed through the meniscus medial to the first. This suture/tape was

then also passed down the trans-osseous tunnel, to allow the free ends to be attached to the mandrel of the Instron tensile testing machine.

Figure 2. Experimental setup. The trans-osseous tunnel was orientated to allow the TAPE or SUTURE to be pulled parallel to the trans-osseous tunnel and to the axis of the load cell.

Figure 3: A 3D reconstruction from a microCT scan of a representative meniscus showing the suture/tape entry locations that were analysed

Figure 4: Maximum failure load for Part A, SUTURE (n=10) versus TAPE (n=9) groups. The circle represents an outlier greater than the third quartile (Q3) + 1.5 times the interquartile range).

Figure 5: Effect of suture/tape entry location on maximum failure load for Part A.

Figure 6: Maximum failure load for Part B, SUTURE (n=5) versus TAPE (n=5) groups. The asterix represents an extreme outlier value (three times the inter quartile range from either the first quartile [Q1] or the third quartile [Q3]).

Figure 7: Heat map of maximum failure load as a function of suture/tape entry location (points shown as crosses) generated from all 29 specimens based on image registration and warping to a representative meniscus; the image on the right shows a photograph of the tibial plateau to allow orientation of the heat map. For initial registration coloured dots were placed in the most anterior (magenta), posterior (green) and medial (cyan) aspects of each meniscus; the image of the tibial plateau on the right has the same locations marked to clarify position of heat map. The heat map was generated based on cubic interpolation. Small variations in suture insertion point were found to result in a large difference in maximum failure load. Highest failure loads were found for insertion points within the substance of the body of the meniscus to either side of the central part of the transition zone.

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