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Structural Properties of the Meniscus Roots

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Background: Current surgical techniques for meniscal root repair reattach the most prominent, dense portion of the meniscus root and fail to incorporate recently identified peripheral, supplemental attachment fibers. The contribution of supplemental fibers to the biomechanical properties of native meniscus roots is unknown.

Hypothesis/Purpose: The purpose was to quantify the ultimate failure strengths, stiffness, and attachment areas of the native posterior medial (PM), posterior lateral (PL), anterior medial (AM), and anterior lateral (AL) meniscus roots compared with the most prominent, dense meniscus root attachment after sectioning of supplemental fibers. It was hypothesized that the ultimate failure strength, stiffness, and attachment area of each native root would be significantly higher than those of the respective sectioned root.

Study Design: Controlled laboratory study.

Methods: Twelve matched pairs of male human cadaveric knees were used. The 4 native meniscus roots were left intact in the native group, whereas the roots in the contralateral knee (sectioned group) were dissected free of all supplemental fibers. A coordinate measuring device quantified the amount of tissue resected in the sectioned group compared with the native group. A dynamic tensile testing machine pulled each root in line with its circumferential fibers. All root attachments were preconditioned from 10 to 50 N at a rate of 0.1 Hz for 10 cycles and subsequently pulled to failure at a rate of 0.5 mm/s.

Results: Supplemental fibers comprised a significant percentage of the native PM, PL, and AM meniscus root attachment areas. Mean ultimate failure strengths (in newtons) of the native PM, PL, and AM roots were significantly higher than those of the sectioned state, while the ultimate failure strength of the native AL root was indistinguishable from that of the sectioned state.

Conclusion: Three of the 4 meniscus root attachments (PM, PL, AM) contained supplemental fibers that accounted for a significant percentage of the native root attachment areas, and these fibers significantly contributed to the failure strengths of the native roots.

Clinical Relevance: These supplemental fibers are not routinely reattached during root repair surgery, suggesting that current techniques fail to reattach the biomechanically relevant attachments of native meniscus roots.

Keywords: meniscus root; root repair; meniscal repair; posterior meniscus root, medial meniscus; lateral meniscus

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Meniscal root tears are defined as avulsions of the anterior or posterior meniscus horn attachments from the tibial plateau or radial tears adjacent to the root itself. [5,19,20] After posterior root tears of the medial and lateral menisci, there is a significant increase in tibiofemoral contact pressure concomitant with decreased contact areas, [2,13,19,20,22] with one study reporting that posterior root tears simulate a state of total meniscectomy.2 Therefore, the current treatment of choice for meniscal root injuries is primary repair by use of either a transtibial bone tunnel or a suture anchor for fixation of the root to bone. [7,14,16,21]

The literature suggests that existing surgical techniques for meniscal root repair fail to restore the biomechanical properties of repaired meniscus tissue to its native state at time zero. [6,7,8,18] Feucht et al[7] reported that neither the transtibial pullout nor suture anchor technique was able to adequately restore biomechanical properties of the native posterior medial (PM) meniscal root. Both repair techniques demonstrated a significantly higher displacement during cyclic loading and lower maximum load and stiffness during load-to-failure testing compared with the native PM meniscal root. [7]

The reasons for this discrepancy are unknown, but one plausible explanation not previously considered is that current techniques reattach only the most prominent, dense portion of the meniscal root and fail to incorporate peripheral, less dense, supplemental attachment fibers. These supplemental fibers are not reattached surgically for 2 reasons: (1) They are recently defined structural attachments, and (2) their importance and function have yet to be elucidated. For example, a large posterior-based sheet of supplemental tissue, termed the “shiny white fibers” (SWFs), has recently been identified as a supplemental fiber expansion of the posterior horn of the medial meniscus. [3,10] The SWFs extend posterior and distal to the main meniscal root attachment and are located just proximal to the tibial attachment of the anterolateral bundle of the posterior cruciate ligament (PCL) (Figure 1A). [3] They are not considered part of the central root attachment because they are not part of the dense root insertion into the tibia. Current repair techniques for PM meniscal root tears fail to incorporate the SWFs, potentially contributing to decreased stability after root repair, abnormal load distribution within the meniscus, and altered tibiofemoral contact mechanics.[6,7]

Similar to the SWFs of the medial meniscus, a large band of tissue has been found to course from the posterior lateral (PL) meniscal root attachment to the lateral aspect of the medial tibial eminence (Figure 2A), [10,19] yet it is unknown whether these fibers provide significant strength and stiffness to the native root. In addition, both anterior root attachments (ie, anterior medial [AM] and anterior lateral [AL] roots) may contain previously undefined supplemental fibers that adhere to adjacent bone or neighboring tissues. If supplemental fibers are indeed found to exist within the anterior roots, their incorporation into routine root repairs may allow for improved restoration of meniscal root function.

The purpose of this study was to quantify the attachment areas, ultimate failure strengths, and stiffness of the 4 native meniscal roots (with supplemental fibers left intact) compared with the most prominent, dense meniscal root attachment after sectioning of the supplemental fibers (sectioned group), thereby simulating the attachment area of the surgically repaired root. It was hypothesized that the ultimate failure strengths, attachment areas, and stiffness of the native meniscal roots would be significantly higher than those of the roots after sectioning of the supplemental fibers.

MATERIALS AND METHODS

Specimen Preparation

Twelve matched pairs of male human cadaveric knees (average age, 54.9 years [range, 40-61 years]; mean body mass index [BMI], 24.2 [range, 13.6-40.0]) without any previous meniscal injury or gross evidence of cartilage degeneration were used in this study. One additional matched pair was excluded before testing because of meniscal and cartilage degeneration. Institutional review board approval was not required because the use of cadaveric specimens is exempt at our institution. An a priori power analysis was performed using data from the literature and after pilot testing and updated again after testing of the first 3 matched pairs of knees. Conservatively allowing a 10% increase in variability, we found that 10 matched pairs were sufficient to detect a 25% decrease in failure load between groups with 80% power. Ultimately, testing of 12 matched pairs was planned to hedge against the possibility of specimen failure. Each knee was dissected free of all skin, muscles, and cruciate and collateral ligaments, and the femur, fibula, and patella were removed from the tibia, exposing the medial and lateral menisci on the tibial plateau. In one matched knee, the native meniscal roots were left intact (native group), while the roots in the contralateral matched knee were dissected free of all supplemental fibers (sectioned group), as determined by a visually and palpably apparent decrease in fiber density compared with the most prominent, dense portion of each root.

To quantify the amount of tissue resected in the sectioned group compared with the native group and to ensure consistency between specimens, a coordinate measuring device (MicroScribe MX Series; GoMeasure3D, Amherst, Virginia, USA), with a single point repeatability of 0.126 mm, was used to measure the attachment areas, as previously described.[10] The same individual (M.B.E.) performed data collection for all specimens, and another individual (M.T.R.) was present for landmark confirmation during all measurements to ensure interrater reliability. For each specimen, a local coordinate system was built using the most medial, lateral, anterior, and posterior points located on the tibial plateau. The periphery of each native root attachment was divided into 4 quadrants and measured with 16 data points distributed evenly (4 per quadrant) by use of a needle-point stylus attached to the coordinate measuring device. Quadrants were used to optimize consistency and validity of footprint measurements. These peripheral data points were then used to calculate the meniscal footprint area using Heron's formula.[10] For each paired knee, the PM (Figure 1), PL (Figure 2), and AM (Figure 3) meniscal roots were measured in the native knee and compared with the sectioned, dense area of each respective root in the sectioned knee.

In contrast to the PM, PL, and AM roots, a considerable portion of the footprint of the anterior root of the lateral meniscus (AL) was concealed by fibers of the anterior cruciate ligament (ACL). Although the ACL has been reported to have an intimate relationship with the AL root,[4,17] we are unaware of any study describing the extent to which the AL root traverses under the ACL (Figure 4). Further, we found no significant distinction between dense, prominent fibers and less dense, supplemental fibers attaching to bone for the AL root. Therefore, we chose to assess whether the fibers from the overlying ACL contributed to the biomechanical properties of the AL root. Sectioning down to bone at the overlap area was avoided because it was theorized that this would have resulted in a variable amount of detachment of the AL root attachment fibers among the tested specimens. In the sectioned knee only, the total area of the ACL tibial attachment was measured and then transected off the lateral meniscus attachment so that the entirety of the AL root attachment could be visualized and measured (Figure 4). Standard system software (MicroScribe Utility Software, version 6.0; Revware Inc, Raleigh, North Carolina, USA) was used to operate the MicroScribe system and export the 3-dimensional coordinates of the measured data points to Microsoft Excel (Microsoft Corp, Redmond, Washington, USA).

Biomechanical Testing

Each tibia was then potted distally in a cylindrical mold with polymethylmethacrylate (PMMA; Fricke Dental International Inc, Streamwood, Illinois, USA) up to a point approximately 4 cm distal to the most proximal aspect of the tibial tuberosity to minimize bending of the tibial diaphysis and isolate tensioning on the meniscal roots. For biomechanical testing, tibias were secured in a custom fixture and rigidly clamped to the base of a dynamic tensile testing machine to prevent motion during testing (ElecroPuls E10000; Instron, Norwood, Massachusetts, USA). The medial and lateral menisci were transected in half to allow for insertion of meniscal tissue into a custom-made clamp. Each root was then marked with a surgical marking pen at a distance of 1 cm from its bony attachment. Proximal to this location, metal wire was wrapped around the meniscal tissue to prevent slippage of the tissue within the clamp or damage to the meniscal fibers. This technique was developed during pilot testing. The meniscal root was then clamped 1 cm from its bony attachment and aligned such that the force vector was in line with the circumferential fibers, simulating a shear-type mechanism, similar to the technique used by Kopf et al[18] (Figure 5, A and B). Pilot studies confirmed that the distance of 1 cm was adequate for the tensile testing machine to induce a bony avulsion directly and consistently at the bony root attachment rather than within the meniscal fibers themselves or at the clamp (Figure 5C), which is consistent with prior literature.[18] All roots were preconditioned from 10 to 50 N at a rate of 0.1 Hz for 10 cycles and subsequently pulled to failure at a rate of 0.5 mm/s, similar to previous studies evaluating meniscal root failure strengths.7,18 Throughout testing, specimens were repeatedly sprayed with normal saline (0.9% sodium chloride) to prevent the desiccation of meniscus tissue.

Statistical Analysis

The Wilcoxon signed rank test was used for comparison of matched pairs. The level of statistical significance was set at $P < .05$. Data are presented as mean with 95% confidence intervals (95% CI). All statistical analyses were performed using SPSS Statistics, version 20 (IBM Inc, Armonk, New York, USA).

RESULTS

Root Attachment Areas

The MicroScribe was used to measure and calculate the attachment areas of each root, and results are demonstrated in Table 1. For the PM meniscal root, the mean difference in attachment area between the native and sectioned root (ie, after removal of SWFs) of 26.4 mm^2 reveals that the SWFs accounted for 38.8% of the native root area. The supplemental medial fiber expansion of the PL root accounted for 30.7% of the native root attachment area, and the supplemental fibers of the AM root accounted for 43.9% of the native root area. With regard to the AL meniscal root, the ACL tibial attachment area measured 141.6 mm^2 (95% CI, 121.8-161.4), whereas the AL root attachment after removal of the overlying fibers of the ACL had an attachment area of 99.5 mm^2. There was considerable overlap between these 2 structures with a mean area of 44.6 mm^2 (95% CI, 32.4-56.7), which constituted 31.6% of the ACL and 44.0% of the AL root areas.

Ultimate Failure Strengths

All meniscal failures were at the bone-meniscus junction, with a small bony avulsion of the meniscal root tissue off bone (Figure 5C). No difference between failure mechanisms was observed between the native and sectioned groups. The ultimate failure strengths of the native versus sectioned roots are reported in Table 1. After sectioning of the supplemental fibers of the PM root, the mean difference in ultimate failure strength of 245.9 N reveals that the SWFs accounted for 47.8% of the native root strength. Similarly, the supplemental medial fiber expansion of the PL root provided an average of 17.6% of the native PL meniscal root strength, and the supplemental fibers of the AM root accounted for 28.4% of the native AM root strength. In contrast, strength testing of the AL root demonstrated a mean difference of only 44.3 N between the native and sectioned state, revealing that the soft tissue fibers attaching from the AL meniscal root to the overlying ACL accounted for only approximately 6.79% of the native meniscal strength.

Stiffness

Sectioning of the supplemental fibers resulted in a significant reduction in stiffness for only the PM and AM roots (Table 1). Our results reveal that the SWFs of the PM root accounted for approximately 34.2% of the stiffness of the native PM root, and the supplemental fibers of the AM root accounted for 16.9% of the stiffness of its native root. In contrast, the stiffness did not significantly differ between native and sectioned states for the PL and AL roots (Table 1). The supplemental fibers of the PL root accounted for only 8.9% of the native root stiffness, whereas the supplemental fibers of the AL root accounted for only 9.5% of the native root stiffness.

DISCUSSION

The findings from this study demonstrate that 3 of the 4 meniscal root attachments (PM, PL, and AM) contain supplemental fibers that significantly contribute to the native attachment areas and strengths of each root. Additionally, supplemental fibers of the AM and PM roots contributed significantly to the stiffness of the native roots. From a clinical perspective, failure to incorporate biomechanically relevant supplemental fibers into meniscal root repairs may be one important reason why current techniques fail to adequately restore the biomechanical properties and function of native meniscal roots.[6,7,8,18]

To date, few studies have evaluated the biomechanical properties of native meniscal roots.[6,7,8,18] Kopf et al[18] reported that the AL (692 N) and AM (407 N) roots demonstrated the highest and lowest mean ultimate failure strengths, respectively. Hauch et al[9] reported that the AL (625 N) and the PL (330 N) roots were the strongest and weakest roots, respectively. The strongest and weakest native roots in our study were the AM (655.6 N) and PL (509.0 N) roots, respectively. One possible explanation for these differences is the quality of the meniscal tissue. In-house pilot studies revealed a wide range of meniscal tissue quality; therefore, we decided to include only relatively young, male specimens and to use matched pairs to minimize confounding variables. In the 2 previous studies noted.[9,18] the authors did not control for age or sex with their specimens, which may explain, at least in part, the differences between the 2 studies.

Interestingly, differences in ultimate failure strengths between the 4 roots may be related to mobility differences within the menisci themselves.[4,23] For example, Benjamin et al[4] reported that the anterior roots had a significantly greater thickness of uncalcified fibrocartilage than did their posterior root counterparts, thereby increasing anterior root mobility and potentially ultimate failure strengths compared with the posterior roots. Our findings indicate that increased mobility may indeed be related to the higher ultimate failure strength observed for both anterior roots compared with the posterior meniscal roots (Table 1). Kopf et al[18] were also the first to compare native root strength versus repair strength after various suture fixation techniques, and they found that none of their tested suture fixation methods (ie, 2 simple sutures, modified Kessler stitch, or loop stitch) adequately restored the strength of the native meniscal roots. Two recent studies by Feucht et al[6,8] corroborate these findings with similar results in a porcine model using different suture fixation techniques.

Hauch et al[9] were the first to compare the stiffness of the meniscal roots. Just as in our study, they reported the highest stiffness for the AL root (219 N); however, they reported that the PL root had the lowest stiffness (130 N),[9] as compared with the PM root in our study. Feucht et al[7] recently evaluated the stiffness of the native meniscal roots compared with repaired states; the investigators reported that the native PM root had a significantly higher stiffness than the repaired state when either the transtibial pullout repair or suture anchor repair was used in a porcine model. The authors did not evaluate the other 3 meniscal roots. Nevertheless, their findings are consistent with the results from our study because the native PM root demonstrated a significantly higher stiffness than did the sectioned state. Villegas and Donahue[24] used scanning electron microscopy to evaluate the collagen structure of each human meniscal attachment and hypothesized that the meniscal roots with the least amount of crimping or length would result in the stiffest meniscal roots. These investigators reported no significant differences between the 4 attachment sites for crimp angle or length but suggested that further research into collagen structure may help to identify reasons for differences in stiffness. In a quantitative study on the structure and function of the meniscal attachments, Abraham and Donahue[1] reported that the PM meniscal root was significantly more compliant than others, consistent with the findings from our study. This increase in tissue compliance (ie, lack of stiffness) may be an etiological factor for the increased prevalence of PM root tears compared with others seen clinically.

The anatomic features of the attachments of supplemental posterior meniscal fibers have only recently been described in the literature.[3,10,19] Johannsen et al[10]reported that the central, most dense portion of the PM meniscal root averages only 30 mm^2, compared with a 47-mm^2 attachment area of the SWFs. When the SWFs were included in the investigators' measurements of the PM root area, the total area of the native root averaged approximately 77 mm^2, which is consistent with findings of previous studies[11,17] but considerably larger than the average tunnel or anchor size used in current root repair techniques. [15,16,18] Our results reveal that the average area of the native footprint of the PM root was 68.0 mm^2, similar to the overall area as defined by Johannsen et al,[10] with the footprint of the central root and SWFs averaging 41.6 mm^2 and 26.4 mm^2, respectively. Given that the SWFs account for 37.4% of the native root surface area and 46.5% of its native strength, based on our findings, inclusion of these fibers may be necessary to restore the biomechanical properties of the PM root.

Similar to the SWFs of the medial meniscus, the expansile supplemental fibers of the PL meniscal root are not reattached surgically, yet these supplemental fibers account for more than 25% of the native root attachment area and 18.4% of its native strength. Previous studies on meniscal root structure have reported variable insertional features of the PL meniscal root.[10,15] However, no studies have quantified the attachment areas of the PL supplemental fibers. For example, the reported footprint of the native PL root ranges from 28.5 mm^2 to 115 mm^2 in the literature,[3,11,17] and Johannsen et al[10] suggested that this variability may result from whether the supplemental fiber attachments were included in previous measurements. In our study, the total area of the native PL root was 83.1 mm^2, with an average of 25.9% of this area accounted for by the supplemental fibers. Therefore, incorporation of these fibers is encouraged to help achieve anatomic surgical repair of PL root tears.

The AM meniscal root was found to have a large band of supplemental fibers that extended anteriorly and distally over the edge of the tibial plateau. These fibers were thin, were less dense, and occupied on average 43.9% of the native root attachment area (area of supplemental fibers = 44.7 mm^2; area of native root attachment = 101.7 mm^2). Previous studies have reported the medial meniscal anterior root to have variable attachment areas between 61.4 mm^2 and 139 mm^2, and this wide variability between studies likely is attributable to the incorporation, or lack thereof, of the supplemental fibers in their measurements.[11,17] The most prominent root center, which lies on the anteromedial aspect of the plateau, measured approximately 57 mm^2 in this study and is the most common site for AM root repair. Based on our results, failure to incorporate supplemental fibers into an AM meniscal root repair would neglect biomechanically relevant tissue responsible for 35.1% of the native strength.

In all of our specimens, a sizeable portion of the AL root attachment was concealed by ACL fibers. After resection of the overlying ACL fibers in the sectioned knees, we were able to identify the anatomic footprint of the AL root. Given the overlap and adherence between AL root fibers and overlying ACL fibers, which constituted 31.6% of the ACL and 44.0% of the AL root areas, we sought to reveal whether the adhered ACL fibers accounted for a significant percentage of the strength and stiffness of the native root. Our results indicate that overlying ACL fibers do not add significant strength or stiffness to the AL root, which is intuitive given that these are soft tissue attachments only and no fibers were sectioned directly off of bone. However, the fact that the AL root attachment coursed deep into the ACL in all specimens indicates that further studies are necessary to determine whether this “sectioning” of tissue during ACL reconstruction may lead to lower ultimate failure strengths of the AL root, especially if the tunnel is reamed on the lateral aspect of the ACL attachment.

The biomechanical properties of each repair technique likely play an important role in achieving (or failing to achieve) a successful repair.7′12′14 For example, success of a meniscal root repair seems to be most dependent on the strength of the suture-meniscus interface, which is not as strong as the native root footprint itself.7 Perhaps just as important, based on the results from this study, the failure to restore native strength, attachment areas, and stiffness in previous biomechanical studies6⇓8′18 may be attributable to failure to account for supplemental fibers of the native meniscal roots, thereby failing to restore normal structure and function of each root. From a clinical standpoint, given that most current repair techniques incorporate only one fixation point (ie, bone tunnel or suture anchor), the area of fixation may be too small to achieve adequate fixation. Future repair constructs using a larger fixation area, via either multiple suture anchors or multiple bone tunnels, may potentially account for supplemental fibers and improve the structural and biomechanical properties of meniscal root repairs.

It is important to recognize some limitations of this study. It is an in vitro study at time zero in human cadaveric menisci, failing to simulate in vivo conditions with biological healing and rehabilitative exercises after surgical repair. There was wide variability between specimens with regard to the ACL tibial footprint concealing the AL meniscal root, making it difficult to extrapolate any significant clinical correlation with this root in particular. There was also wide variability of tissue quality between cadaveric specimens. This potential confounding variable was partially accounted for with the use of matched pairs, allowing for comparison between 2 similar tissues of the same donor rather than between different donors. Further, we limited the specimens used in this study to those from younger, male donors (<61 years of age) to optimize meniscal tissue quality. To prevent any additional bias, we also tested 6 right and 6 left intact knees by alternating between specimens. It is difficult to rule out the possibility of bending of the tibia during biomechanical testing, potentially confounding our stiffness data. Although we attempted to minimize bending by encasing as much of the tibial diaphysis as possible and using a custom fixture that prevented motion during testing, it is possible that bending of the tibia may confound the stiffness calculations. However, because we tested specimens with similar bone quality and used a consistent and reproducible potting method, we believe that any error introduced would have been consistent and would not have affected the observed differences between groups. Finally, during biomechanical testing, all specimens were tested in a uniform manner with stress applied in line with the meniscal root fibers, similar to the study by Kopf et al.[18] This simulates a shear-type mechanism, which we believe correlates well with the typical mechanism of a meniscal root tear clinically, but the exact mechanism of root tears remains unknown. Although the mechanism of failure has been reported to result in a bony avulsion in our study and in a previous biomechanical study,[18] the in vivo mechanism may be due to a combination of currently unknown variables that lead to a soft tissue avulsion rather than a bony avulsion. Further research is necessary to help elucidate these differences. Nevertheless, the consistent mechanism of failure noted in our specimens enabled us to control for this potential confounding variable.

The results of this study reinforce the need for further research to identify novel surgical techniques that can restore the native anatomic area, strength, and stiffness of the meniscal roots after repair. Until such studies are completed, however, increased caution is warranted in defining early motion and weightbearing protocols in the postoperative period. Because of the widely reported inherent weakness of surgically repaired meniscal roots using current techniques (ie, suture anchors and/or transtibial pullout), combined with the inherent weakness of the suture-meniscus interface, a conservative postoperative protocol must be followed.[6,7,8,18]

CONCLUSION

This study demonstrates that the supplemental fibers impart significant contributions to the overall native attachment areas and ultimate failure strengths of the PM, PL, and AM meniscal roots. These supplemental fibers are not routinely reattached during meniscal repair techniques, suggesting that current surgical techniques significantly underestimate the biomechanically relevant attachment areas of the meniscal roots. In addition, the AL root was found to have supplemental fibers that adhered to the ACL attachment; however, removal of these fibers did not result in the sectioned state significantly differing from the intact AL root.

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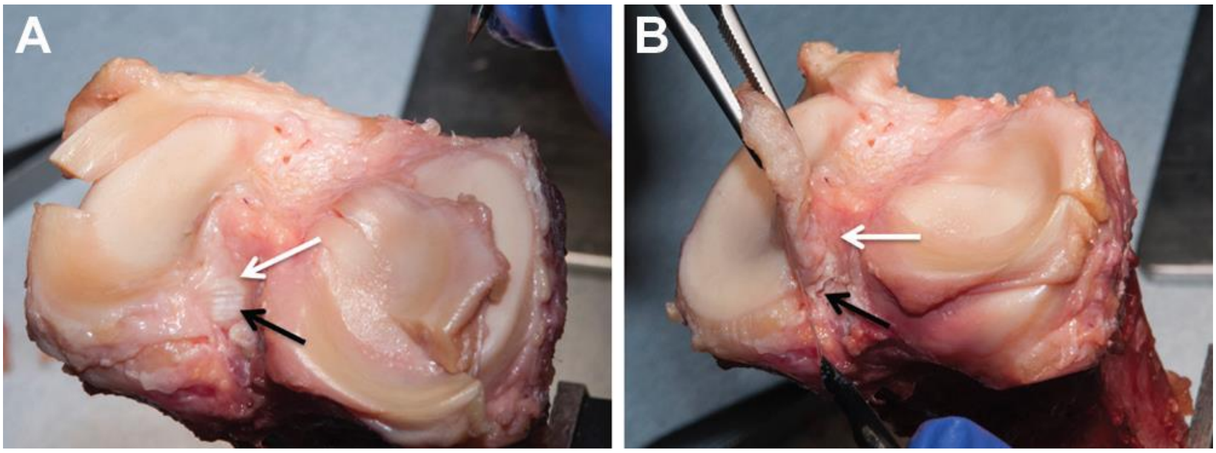

Figure 1.

Photograph depicting (A) an intact posterior medial (PM) root with the central, prominent root (white arrow) and the supplemental shiny white fibers (SWFs; black arrow and white appearance). (B) The sectioned PM root after the removal of the SWFs (white arrow, central root; black arrow, SWFs).

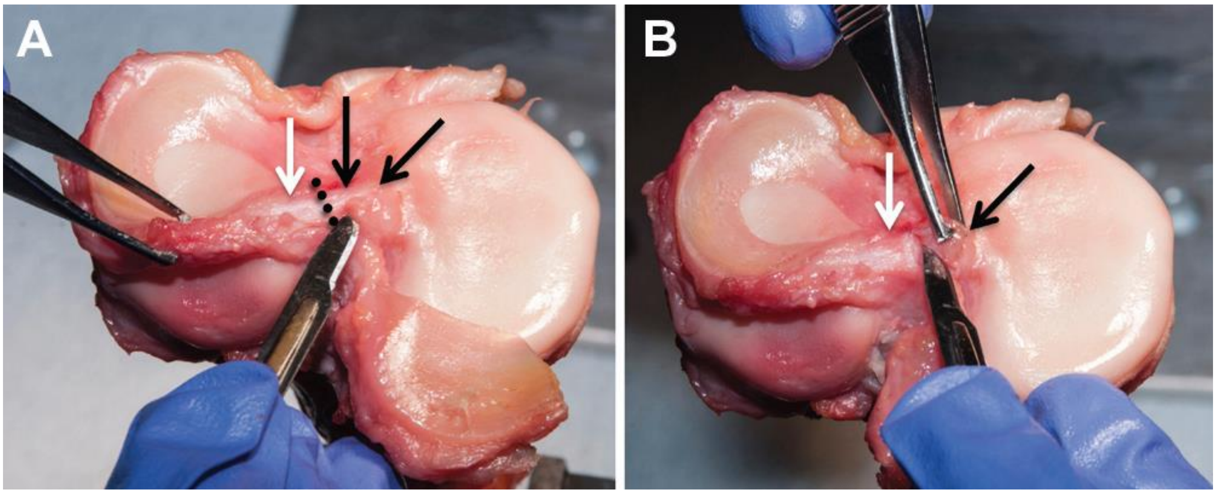

Figure 2.

Photograph displaying (A) an intact posterior lateral (PL) root with supplemental fiber expansion from the central root attachment (white arrow) to the lateral aspect of the medial tibial eminence. The black dotted line reveals the transition point from dense fibers (to left of dotted line) to less dense supplemental fibers (to right of dotted line); black arrows and scalpel outline the supplemental fibers. (B) The sectioned PL root during sectioning of the supplemental fibers (white arrow, central root; black arrow, most anteromedial edge of supplemental fibers).

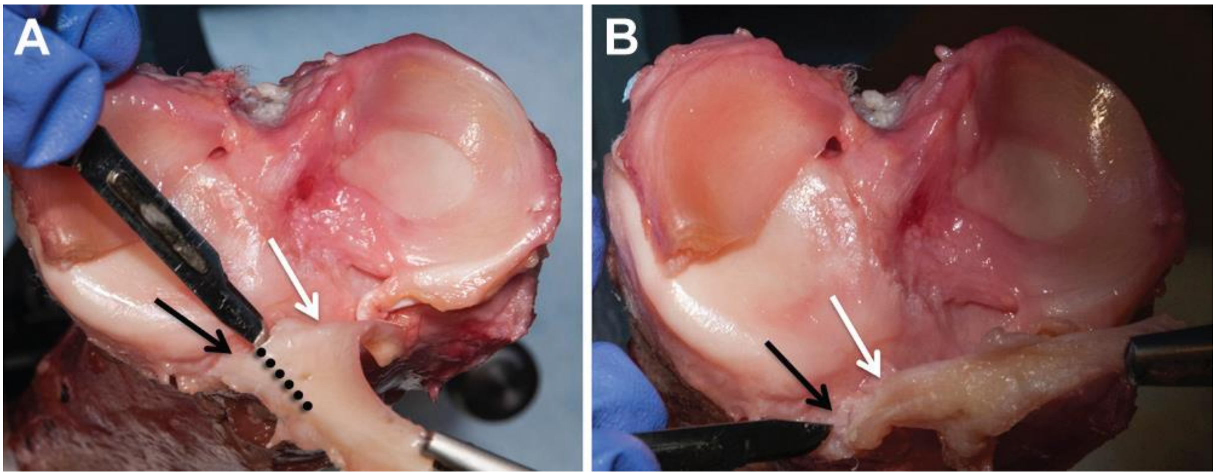

Figure 3.

Photograph demonstrating (A) the intact anterior medial (AM) root with central, prominent root (white arrow) in comparison to the supplemental fibers (black arrow) with visually apparent decreased fiber density. The black dotted line reveals the transition point between supplemental fibers (to left of dotted line) and dense fibers (to right of dotted line). (B) The sectioned AMroot after removal of supplemental fibers (white arrow, central root; black arrow, supplemental fibers).

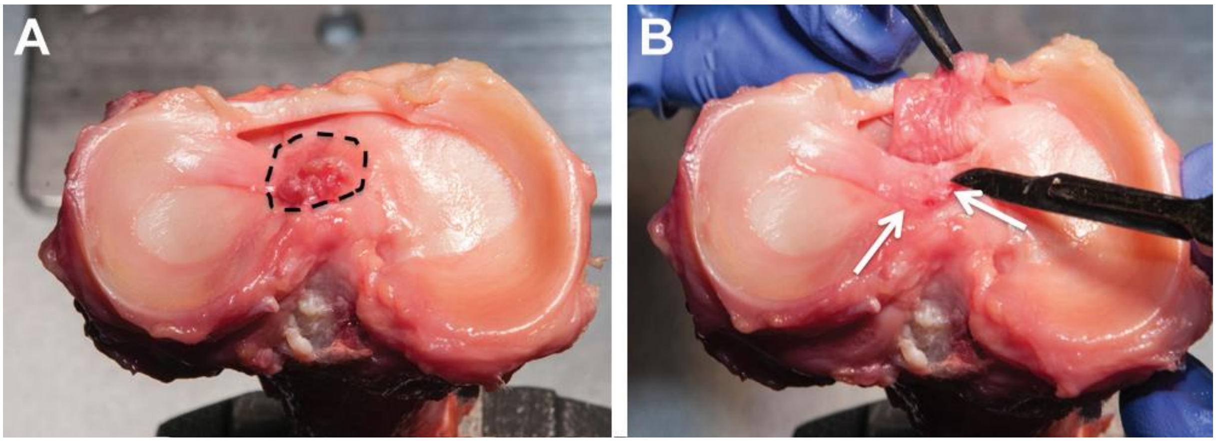

Figure 4.

Photograph depicting (A) the intact anterior lateral (AL) root with the overlying anterior cruciate ligament (ACL) footprint outlined with a dashed line. (B) The sectioned AL root after transection of ACL (reflected off the AL root and held with pick-ups) with footprint of AL root outlined with scalpel and white arrows. The AL fibers, which run parallel with each other, are shown to be visually distinct from the reflected ACL fibers and are almost perpendicular with the ACL fibers.

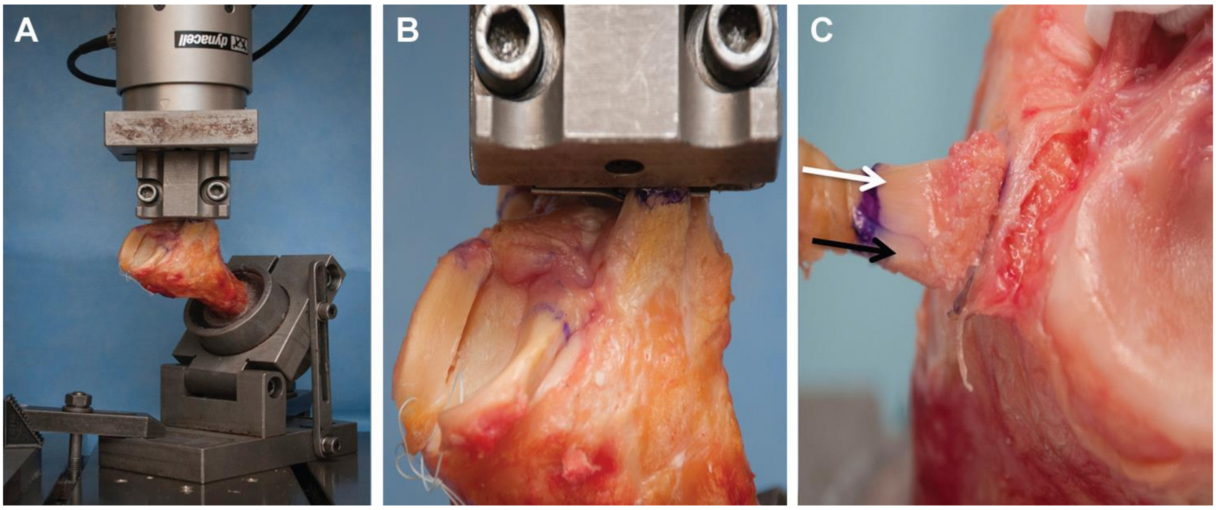

Figure 5.

Testing setup of an anterior medial (AM) root in the dynamic tensile testing machine. (A) The tibia was potted in bone cement and then rigidly fixed in a custom-made fixture that prevented any movement during biomechanical testing. (B) The roots were then aligned with their circumferential fibers and tightly secured in a clamp connected to the actuator of the dynamic tensile testing machine at a distance of 1 cm from the root attachment to the tibial plateau. This distance of 1 cm was marked by use of a surgical marking pen (purple line). (C) The alignment of the root with its circumferential fibers created a consistent bony avulsion failure after pull-to-failure testing. The locations of the central root (white arrow) and supplemental fibers (black arrow) are also indicated in this AM root.

Table 1.

Ultimate failure stregths, stiffness, and attachment areas of native and sectioned meniscal roots[a]

Root	Native[b]	Sectioned[b]	%Δ[b]	*P* Value
Attachment area, mm^2				
AM	101.7 (82.4 to 120.9)	57.0 (49.4 to 64.5)	44.7 (27.3 to 62.0)	.003
PM	68.0 (59.1 to 76.9)	41.6 (35.3 to 47.8)	26.4 (17.6 to 35.3)	.002
AL	99.5 (83.1 to 116.0)	N/A	N/A	N/A
PL	83.1 (63.6 to 102.7)	57.7 (47.3 to 68.0)	25.5 (9.1 to 41.8)	.006
Ultimate failure strength, N				
AM	655.5 (487.2 to 823.8)	469.1 (240.7 to 697.4)	186.4 (65.1 to 307.8)	.019
PM	513.8 (388.4 to 639.1)	267.9 (206.6 to 329.2)	245.9 (155.8 to 335.9)	.002
AL	652.8 (528.2 to 777.3)	608.4 (434.2 to 782.6)	44.3 (–65.4 to 154.1)	.272
PL	509.0 (392.0 to 625.9)	419.4 (288.9 to 549.8)	89.6 (28.6 to 150.6)	.019
Stiffness, N/mm				
AM	124.9 (101.4 to 148.3)	103.7 (75.4 to 132.0)	21.1 (6.3 to 36.0)	.012
PM	122.7 (95.1 to 150.3)	80.7 (71.1 to 90.2)	42.0 (8.4 to 75.7)	.034
AL	151.1 (123.9 to 178.4)	136.8 (108.4 to 165.2)	14.3 (–18.0 to 46.6)	.754
PL	128.7 (104.1 to 153.3)	117.2 (89.8 to 144.7)	11.5 (–6.7 to 29.7)	.209

[a]AL, anterior lateral; AM, anterior medial; PL, posterior lateral; PM, posterior medial; N/A, not applicable.
[b]Data reported as mean (95% confidence interval).