Consequences of Tibial Tunnel Reaming on the Meniscal Roots During Cruciate Ligament Reconstruction in a Cadaveric Model, Part 1

The Anterior Cruciate Ligament

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Background: The current standard for treating complete tears of the anterior cruciate ligament (ACL) is reconstruction, which requires reaming a tibial tunnel. Based on recent anatomic and biomechanical studies, this reconstruction tunnel may cause injuries to the anterior meniscal root attachments.

Purpose/Hypothesis: The purpose was to determine if injuries occurred to the anteromedial (AM) and anterolateral (AL) meniscal root attachments because of reaming a tibial reconstruction tunnel in the anatomic center of the ACL footprint. It was hypothesized that tibial tunnel reaming for ACL reconstruction would result in significant decreases in the attachment area and in ultimate failure strength for the AL root.

Study Design: Controlled laboratory study.

Methods: Twelve matched pairs of human cadaveric knees were tested. One knee from each pair remained intact, while the contralateral knee was reamed with a tibial tunnel for an anatomic ACL reconstruction. The attachment areas of the anterior meniscal roots were measured with a coordinate measuring device before and after tunnel reaming. The anterior meniscal roots were then pulled to failure with a dynamic tensile testing machine.

Results: There was a significant mean decrease in the attachment area for the AL root (%Δ, 38%; 95% CI, 25-51) after ACL tunnel reaming compared with the intact state (P = .003). The mean ultimate failure strength of the native AL root (mean, 610 N; 95% CI, 470-751) was significantly stronger (P = .015) than that of the AL root with a reamed ACL reconstruction tunnel (mean, 506 N; 95% CI, 353-659). Tunnel reaming did not significantly affect the AM root attachment area or ultimate failure strength.

Conclusion: Tibial tunnel reaming during anatomic single-bundle ACL reconstruction significantly decreased the AL meniscal root attachment area and ultimate failure strength. The AM root was not significantly affected by reaming of the ACL reconstruction tunnel. Future studies should investigate the clinical importance of these iatrogenic injuries to the AL root.

Clinical Relevance: The ACL reconstruction tunnels reamed in the center of the ACL tibial footprint caused a significant decrease in the attachment area and ultimate strength of the AL meniscal root attachment. Clinically, repositioning guide pins placed in the lateral aspect of the ACL attachment before tibial tunnel reaming may minimize iatrogenic injuries to the AL meniscal root attachment.

Keywords: meniscal roots; anterior cruciate ligament; medial meniscus; lateral meniscus

Current emphasis has been on the placement of anterior cruciate ligament (ACL) reconstruction tunnels at the center of the anatomic attachments of the ACL.9,22,23,34 However, recent studies have suggested that placement of the tibial tunnel at the center of the ACL footprint may risk damage to the anterior meniscal roots.7,14 These anterior root insertions are in close proximity to the native ACL insertion and have the potential to be disrupted with anatomic ACL reconstruction.5,3,11,12,14,33,34
Recent anatomic and biomechanical studies have reported that the attachment fibers of the anterolateral (AL) meniscal root course deep to a significant portion of the ACL’s tibial attachment fibers. However, previous studies have not investigated whether the biomechanical strength of the insertion fibers of the AL root would be compromised during ACL reconstruction, even when the ACL reconstruction tunnels are reamed anatomically.

Reports have demonstrated increased levels of meniscal extrusion after anterior horn meniscal tears, which was further associated with significantly increased cartilage degeneration. However, the biomechanical importance of the anterior meniscal roots is still poorly understood. While posterior root avulsions of the medial and lateral menisci have been demonstrated biomechanically to result in significant increases in tibiofemoral contact areas and pressures, anterior root tears have not been biomechanically evaluated. Therefore, considering the negative effects on the knee joint after meniscal root injuries, it is important to investigate whether anatomic tibial reaming during ACL reconstruction could inadvertently injure the meniscal attachments, thereby affecting mechanical function. A study by Watson et al first reported on the potential risk of injury to the anterior meniscal roots after reaming of the ACL tibial tunnel; however, they observed an anterior shift in the proximal tibial tunnel aperture caused by bone deflection during antegrade reaming. As a result, there is a need to investigate whether a tunnel precisely placed in the center of the ACL’s tibial footprint results in increased injuries and a decrease in strength of the anterior meniscal roots.

The purpose of this study was to determine if injuries occurred to the anterior meniscal root attachments because of tibial tunnel reaming in the center of the ACL tibial footprint during anatomic ACL reconstruction. It was hypothesized that tibial tunnel reaming during ACL reconstruction would result in significant decreases in the meniscal root attachment area and ultimate failure strength for the AL root. Tibial tunnel reaming was hypothesized to have no effect on the anteromedial (AM) meniscal root attachment area and ultimate failure strength.

MATERIALS AND METHODS

Specimen Preparation

Testing was performed on 12 fresh-frozen matched pairs of human cadaveric knees without any signs of previous meniscal injuries or cartilage degeneration from male donors aged ≤63 years (mean age, 55.8 years; range, 46-63 years). The knees were thawed 24 hours before testing, and the femurs were disarticulated, exposing the menisci and cruciate ligaments. The tibias were potted in a cylindrical mold with polymethyl methacrylate (PMMA; Fricke Dental International Inc). The fibula was disarticulated to allow the tibia to fit within the cylindrical mold. The knees were frequently sprayed with normal physiological saline solution (0.9% sodium chloride) and covered in saline-soaked gauze throughout preparation and testing to prevent desiccation of the meniscal tissue. All knees were used concurrently with part 2 of this study, which evaluated the effect of tibial tunnel reaming during posterior cruciate ligament reconstruction.

Quantification of Area Reduction After Tibial Reaming

Paired knees were randomly and evenly distributed between 2 groups: intact and reamed. Furthermore, left and right knees were also evenly distributed between groups. For both groups, the native tibial attachment footprints of the ACL and anterior meniscal roots (Figure 1) were quantified using a coordinate measuring device (MicroScribe-MX, GoMeasure3D). To assess the coordinate measuring device, the single-point articulation performance test (SPAT) was performed and resulted in a value of 0.115 mm. The SPAT evaluates the performance of articulated arm coordinate measurement machines in accordance with the B89.4.22 American Society of Mechanical Engineers standard and the manufacturer’s recommendations. The SPAT provides information on the level of repeatability obtainable in the study’s testing environment. To identify the fibers of the ACL, a hemostat was used to apply varying levels of tension to the ligament, while observations were made of which fibers became taut, in a similar manner as previous studies. The periphery of each native root attachment was divided into 4 quadrants and measured with 24 evenly distributed data points. Specifically, this technique used a clockface method to obtain data points at the 12-, 3-, 6-, and 9-o’clock positions, with 5 data points collected between each of these positions. This method was chosen to optimize standardization and footprint measurements. After determining the periphery of each meniscal or cruciate ligament attachment, the Heron formula was used to calculate the footprint area for each attachment.

In addition to the aforementioned measurements, the reamed group of knees then had tibial tunnels reamed for an ACL reconstruction. After creation of the ACL tibial tunnels using the technique described below, the coordinate measuring device was again used to measure the attachment areas of the anterior meniscal roots after reaming with 24 data points using the same clockface method described above. These areas were used to determine the percentage of reduction of the meniscal root.
attachment areas after reaming of the tibial tunnels to quantify the amount of meniscal root damage caused by ACL tunnel reaming.

Surgical Technique

All tibial tunnel reamings during ACL reconstruction were performed by 2 fellowship-trained orthopaedic surgeons (M.G.H., R.F.L.) in a repeatable manner. Consistent tunnel positioning was afforded by calculating the anatomic center of the footprint by independently averaging the x, y, and z coordinates of the previously collected ACL peripheral data points. For creation of the anatomic ACL reconstruction tunnels, a 45° tibial ACL aiming guide (Acufex, Smith & Nephew), which is commonly used clinically, was positioned in the center of the ACL footprint. A 2.4-mm guide pin was then drilled inside out with the pin placed at the calculated center of the ACL footprint, as determined using the collected peripheral data points, on the proximal tibia and exiting on the AM aspect of the tibia at a point 4 cm distal to the tibial plateau and 2 cm posterior to the tibial tubercle. The inside-out reaming direction was chosen to standardize the reaming locations by ensuring that the guide pin was drilled directly at the calculated center location and to prevent previously reported deflection of the reamer over the guide pin during antegrade reaming. An 11 mm–diameter reamer (Cannulated Headed Reamer, Arthrex) was used to ream over the guide pin (Figure 3). This diameter was chosen because it is a commonly reported size used for bone–patellar tendon–bone (BTB) ACL reconstruction.

Biomechanical Testing

The menisci were biomechanically tested with a dynamic tensile testing machine (Instron ElectroPuls E10000, Instron). The measurement error of the test frame was calibrated and verified to be less than or equal to ±0.01 mm
and ±0.3% of the indicated force. After reaming of the tibial tunnels and quantification of attachment areas before and after reaming, both menisci were transected at their midpoint. The anterior menisci were clamped with a custom device 1 cm from the root attachment (Figure 4). This distance was chosen to ensure that failure consistently occurred directly at the root attachment. Slippage was monitored visually by marking the tissue with ink at the region where the meniscus exited and interfaced with the clamp. The clamp was rigidly fixed to the actuator of the tensile testing machine. The tibia was oriented in a custom fixture so that the force vector was in line with the circumferential fibers of the meniscus and rigidly fixed to the base of the test frame.

The menisci were preconditioned with sinusoidal cyclic tensile loading between 10 and 50 N for 10 cycles at 0.1 Hz and then pulled to failure at a displacement-controlled rate of 30 mm/min. The ultimate failure load was recorded, and the failure mechanism was observed to ensure that failure consistently occurred at the root attachment.

Statistical Analysis

An a priori power analysis was performed after testing of 3 matched pairs, which determined that a sample size of 12 knees per group would be needed to detect a 20% difference in ultimate failure strength with 80% power. The Wilcoxon signed-rank test was used for statistical comparison of matched pairs. Significance was set at \( P < .05 \). Data are presented as means with 95% CIs. Statistical analyses were performed with SPSS Statistics (v 20, IBM Corp).

RESULTS

Anatomic Measurements

The attachment areas of the anterior meniscal roots before and after reaming are listed in Table 1. The AL root was iatrogenically injured in all 12 of the knees. There was a significant mean decrease in the attachment area for the AL root (mean, 38%; 95% CI, 25-51) after ACL tunnel reaming compared with the intact state \( (P = .003) \). The attachment areas of the AM roots before and after reaming were not significantly different, which was consistent with no injury on visual inspection.

Biomechanical Results

All meniscal roots failed because of a bony avulsion from the tibial plateau. The ultimate failure strengths (N) of the native and reamed anterior meniscal roots are listed in Table 1. The native AL root (mean, 610 N; 95% CI, 470-751) had significantly stronger ultimate failure strength (mean, 19%; 95% CI, 7-31; \( P = .015 \)) than did the AL root with an ACL reconstruction tunnel (mean, 506 N; 95% CI, 353-659). The attachment strengths of the AM roots before and after reaming were not significantly different (\( P = .53 \)).

DISCUSSION

The most important finding of this study was the significant reduction in the ultimate failure strength and attachment area of the AL meniscal root after reaming of a tibial tunnel during anatomic single-bundle ACL reconstruction. The AL root was damaged in all specimens during reaming of ACL tibial tunnels. There was no damage to the AM root during reaming. The locations of the reamed ACL tibial tunnels, set angles of the tibial aiming devices, and reamer diameters were based on the current literature for single-bundle ACL reconstruction. Therefore, the results of this study demonstrate that some current methods for ACL reconstruction could be causing unrecognized iatrogenic damage to the AL meniscal root. While previous methods to reference the location of a tibial tunnel in ACL reconstruction were often based off the posterior cruciate ligament and resulted in tibial tunnels posterior to the anterior horn of the lateral meniscus, current anatomic techniques that use the true center of the ACL as a reference, adjacent to the anterior horn of the lateral meniscus, could be causing unrecognized iatrogenic damage to the AL meniscal root.
meniscus, risk iatrogenic damage to the AL meniscal root attachment.\textsuperscript{7,14,34}

In this study, the finding that anatomic single-bundle ACL reconstruction resulted in significantly decreased AL root attachment area and strength is concerning. However, the authors do not believe that this is a particularly surprising finding, given that recent anatomic and biomechanical studies reported that the ACL has a significant attachment over the AL root that overlaps up to 63\% of the AL root attachment area.\textsuperscript{7,14} In addition, another study reported that, based on the new quantitative understanding of the lateral meniscal attachment, the centers of the AL root and ACL were only 5 mm apart.\textsuperscript{14} Given this close proximity, the present study confirmed that the AL root is at risk of injury when the tibial tunnel is reamed anatomically during ACL reconstruction.\textsuperscript{7,14,34}

The importance of the posterior meniscal roots for joint stability and load distribution is also becoming increasingly recognized,\textsuperscript{1,16,21,29,31} with a posterior medial meniscal root tear reported to result in similar biomechanical consequences as total medial meniscectomy.\textsuperscript{4} Only 1 biomechanical study has evaluated the anterior meniscal roots, and this study reported that supplemental fibers of the AM root significantly contribute to the native attachment area, stiffness, and strength of the AM root.\textsuperscript{7} In this previous study, the native AM root, with an intact, overlying ACL, was also compared with a contralateral, matched knee with the ACL overlap on the AL root removed.\textsuperscript{7} Removal of the ACL did not significantly affect the native stiffness or strength of the AL root. This finding is intuitive, given that no AL tibial attachment fibers were removed.\textsuperscript{7} The present study found that those fibers that run deep to the ACL have a significant role in the function of the AL root and were compromised after tibial tunnel reaming during ACL reconstruction.

Presently, case reports are the only available literature describing anterior meniscal root tears.\textsuperscript{5,15,25} Since iatrogenic injuries to the AM meniscal root attachment during ACL reconstruction have been recently reported,\textsuperscript{15} it is possible that injuries to the AL root are not currently recognized. This absence of documented disruptions in the literature is not surprising, considering that reports of the intimate relationship of the AL root and the ACL are very new.

In addition, studies have reported that concomitant ACL and meniscal injuries resulted in higher rates of osteoarthritis in comparison to isolated ACL injuries.\textsuperscript{19,27,28} Øiestad et al,\textsuperscript{27} in a systematic review, reported a prevalence of knees with osteoarthritis of up to 13\% after isolated ACL injuries and up to 48\% after combined meniscal and ACL injuries for the highest quality studies in their review. While it is impossible to determine retrospectively, it is possible that iatrogenic anterior meniscal root damage after reaming of the ACL tibial tunnel may have an indeterminable role in the prevalence of osteoarthritis after ACL reconstruction.\textsuperscript{19,27,28} Consequently, the effects of iatrogenic damage to the AL root attachment on lateral compartment contact areas and peak pressures should be a concern for future studies.

The findings of the current study suggest that the current standard of reaming in anatomic single-bundle ACL reconstruction may be causing a clinically relevant amount of damage to the AL meniscal root. It is currently unknown whether a decrease in ultimate failure strength of 19\% can lead to in vivo failure of the anterior attachment of the lateral meniscus or increased displacement during compressive loading of the knee; however, it is anticipated that increased recognition of potential iatrogenic injuries during ACL reconstruction will initiate future clinical outcome studies evaluating its effects. In cases in which the guide pin is placed laterally on the ACL tibial attachment during ACL reconstruction, the authors recommend repositioning of the guide pin before reaming. In addition, surgeons should be aware that the AL root may need to be repaired after ACL reconstruction. Probing the AL root to ensure that it is not detached may be necessary to ensure that meniscal extrusion and possible later osteoarthritis are not iatrogenically instigated.

As with any time-zero in vitro study, certain limitations were present. All meniscal roots failed because of a bony root avulsion from the tibia. This failure mechanism suggests that bone density may affect ultimate failure

\textsuperscript{a}Data are expressed as mean (95\% CI). ACL, anterior cruciate ligament; AL, anterolateral; AM, anteromedial.

\begin{table}[h]
\centering
\caption{Ultimate Failure Strength and Area of the Native AM and AL Meniscal Roots and After ACL Tibial Tunnel Reaming\textsuperscript{a}}
\label{tab:1}
\begin{tabular}{lllll}
\hline
Root & Native & Reamed & $\%\Delta$ & $P$ Value \\
\hline
AM & 617 (457 to 778) & 657 (527 to 788) & 14 (–12 to 41) & .53 \\
AL & 610 (470 to 751) & 506 (353 to 659) & –19 (–31 to –7) & .015 \\
\hline
\end{tabular}
\begin{tabular}{lllll}
\hline
Root & Native & Reamed & $\%\Delta$ & $P$ Value \\
\hline
AM & 165 (141 to 188) & 160 (135 to 185) & –3 (–9 to 3) & .21 \\
AL & 146 (128 to 165) & 87 (71 to 104) & –38 (–51 to –25) & .003 \\
\hline
\end{tabular}
\end{table}
strength. These effects were minimized by testing only male specimens ≤63 years of age and using matched pairs, so decreases in root strength could be analyzed relative to the intact contralateral knee. Although this consistent failure mode is not necessarily observed clinically, it ensured that failure was because of disruption of the root attachment caused by tunnel reaming rather than the integrity of the native meniscal tissue. The applied loading conditions did not simulate the shear and compressive forces that the meniscus experiences in vivo. However, tension was applied to the menisci in a consistent manner by pulling in line with the circumferential fibers in the same manner as previous studies.³⁻⁷ In addition, tunnels were drilled retrograde, which is different than the antegrade technique typically performed in vivo. This was performed to optimize the accuracy and repeatability of reconstruction tunnel drilling and prevent bone deflection of the reamer, which could cause nonanatomic positioning of the tibial tunnel during antegrade reaming, as described in a previous study.³² Additionally, retrograde reaming may have prevented incomplete proximal tunnel apertures, which have been reported for antegrade reaming,⁸ thus enabling more uniform measurements to be taken of the root attachments and tunnel aperture in the present study. Lastly, intraobserver or interobserver reliability tests for the collection of area data were not performed. These effects were minimized by using a single investigator during data collection, as reported in previous studies.⁷⁻¹⁴ Finally, an 11 mm–diameter reamer was used for the tibial tunnel according to recent reports⁷ and because it is a frequently used reamer diameter of the senior authors (L.E., R.F.L.) when performing BTB ACL reconstruction. A recent study reported an increased risk of revision in cases involving a hamstring autograft for ACL reconstruction versus a BTB autograft, especially for younger patients (15-19 years).³⁰ Therefore, the use of an 11-mm reamer simulated the authors’ preferred technique for young and active patients. Further studies should investigate the effect of smaller diameter tibial tunnel reamers on the AL meniscal root attachments, including those commonly used for 9 mm–diameter hamstring tendon ACL grafts,²⁰ and double-bundle ACL reconstruction.

**CONCLUSION**

Tibial tunnel reaming in anatomic single-bundle ACL reconstruction significantly decreased the AL meniscal root attachment area and ultimate failure strength. The AM root was not significantly affected by ACL tunnel reaming. Future studies should investigate the clinical importance of these iatrogenic injuries to the AL root.

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