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Intramedullary Tibial Nailing Reduces the Attachment Area and Ultimate Load of the Anterior Medial Meniscal Root

A Potential Explanation for Anterior Knee Pain in Female Patients and Smaller Patients

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Background: Intramedullary (IM) nailing is the treatment of choice among orthopaedic surgeons for tibial shaft fractures. However, because of the close proximity of the nail's insertion site to the anterior medial (AM) meniscal root on the tibial plateau, there is increased risk of iatrogenic injury to the meniscal root during nailing.

Purpose: To quantify the area of the AM meniscal root footprint damaged by IM tibial reaming and determine its subsequent effects on the ultimate failure load in female versus male knees.

Study Design: Controlled laboratory study.

Methods: Twelve matched pairs (6 male and 6 female pairs; average age, 50.2 years) of human cadaveric knees were randomly assigned to native and reamed groups. In the reamed group, knees were reamed within the ''safe zone'' according to current guidelines for IM tibial nail insertion (3 mm lateral to the center of the tibial tubercle and adjacent to the anterior margin of the tibial plateau). The attachment areas and ultimate failure load were quantified and compared with paired knees in the native group.

Results: Intra-articular reaming within the ''safe zone'' for IM tibial nail insertion did not significantly decrease the AM root attachment area or ultimate failure load in male specimens, as only 2 of the 6 knees were damaged by reaming. In contrast, all 6 of the AM roots in the female knees were damaged by reaming, and on average, reaming decreased the female AM root attachment area by 19% and significantly decreased ultimate failure load by 37% (P = .028). There was a strong negative correlation (R^2 = 0.77) between reamed tunnel–AM root overlap area and medial-lateral width in female but not in male knees.

Conclusion: Standard reaming for an IM tibial nail induced significant damage to the AM meniscal root in smaller, female specimens, whereas larger, male specimens were not affected.

Clinical Relevance: These findings may suggest that improvements in current guidelines and surgical techniques are warranted to prevent iatrogenic injury to the AM meniscal root during intramedullary reaming for tibial shaft fractures in females and in smaller patients.

Keywords: medial meniscus; meniscal root; anterior medial meniscus; intramedullary tibial nailing; tibial shaft fracture

Intramedullary (IM) nailing is the treatment of choice among orthopaedic surgeons for tibial shaft fractures, the most common of long bone fractures.[3,4,18,21,29] The use of IM nailing for tibial shaft fractures ensures minimal dissection of soft tissues, sparing of the extraosseous blood supply, lower risk of malalignment, and faster bone union compared with nonsurgical treatment.[5,18,31] Reamed nails typically have faster union times, fewer nonunions or malunions, and a lower likelihood of revision surgeries compared with unreamed nails.[3,10,15]

However, reamed IM tibial nailing is not without concerns due to the high prevalence of anterior knee pain, which has been reported to occur in up to 73% of patients.[9] It is generally accepted that the cause of anterior knee pain after IM nailing is complex and not fully understood and that it most likely involves several factors. These may include reaming-induced intra-articular cartilage damage, retropatellar fat pad fibrosis, patellar tendon scarring,

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malalignment, osteoarthritis, and the presence of a prominent nail tip.[17,35,36] All of these may ultimately lead patients to seek out a sports medicine physician. Interestingly, iatrogenic injury to the anterior medial (AM) meniscal root after IM reaming may be a significant contributor to anterior knee pain postoperatively, yet this potential origin has only recently been elucidated in the literature.[12,19,23]

In a recent case report, disruption of the AM meniscal root was reported after the insertion of a reamed IM nail to treat a tibial shaft fracture.[12] This report, along with 2 recent anatomic studies,[19,23] has raised concerns about whether the currently recommended entry point guidelines for tibial IM nailing overlap with the AM meniscal root footprint. The currently recommended starting point for nail insertion is, on average, 9 mm lateral to the midline of the tibial plateau and 3 mm lateral to the center of the tibial tubercle, corresponding radiographically to a point just medial to the lateral tibial eminence.[18,29,35] Nail insertion at or near this location has been reported to prevent apex anterior and valgus deformities.[6,18] Also, insertion within a "safe zone" that includes this location may reduce the occurrence of iatrogenic damage to important intra-articular knee structures.[2,11,16,18,31,35] Previous studies have reported the frequency of injury to the AM root attachment to be between 5% for unreamed IM nails[35] and 12.5% for reamed IM nails[11] in study groups containing both men and women. However, these studies did not differentiate between male and female groups, and the effects of these injuries on the structural properties of the AM root were not assessed. Increased awareness and understanding of the potential for iatrogenic meniscal root injury have the potential to significantly alter clinical practice patterns.

To our knowledge, it is unknown whether the described safe zone for IM nail insertion compromises the structural properties of the AM meniscal root, namely the overall attachment area and ultimate failure load. Therefore, the purpose of this study was to quantify the area of the AM meniscal root footprint damaged by reaming for an IM tibial nail and determine its subsequent effect on the ultimate failure load of this root in comparing paired knees and female knees versus male knees. It was hypothesized that reaming of the tibia using currently accepted guidelines for nail insertion would significantly weaken the AM root via a decrease in attachment area and failure load in both male and female specimens.

METHODS

Specimen Preparation

Twelve matched pairs (6 male, 6 female pairs) of fresh-frozen human cadaveric knees (n = 24) with no previous meniscal injury or cartilage damage were used in the current study (mean age, 50.2 years; age range, 36-62 years; mean body mass index [BMI], 25.4; BMI range, 13.2-40.8). Institutional review board approval was not required because the use of cadaveric specimens is exempt at our institution. Paired knees were randomly assigned to either the native or the reamed group. Native and reamed knees were dissected free of all skin, muscle, and cruciate and collateral ligaments and were disarticulated from the femur, fibula, and patella. Each tibia was then potted distally in a cylindrical mold with poly(methyl methacrylate) (PMMA; Fricke Dental International Inc) up to a point approximately 4 cm distal to the most proximal aspect of the tibial tubercle to minimize bending of the tibial diaphysis and isolate tensioning of each meniscal root.

Area Measurements

The attachment areas of the AM meniscal roots for both the native and reamed groups were measured using a coordinate measuring device (MicroScribe MX Series; GoMeasure3D) with a single point repeatability of 0.414 mm, as previously described.[13,20,23] The attachment areas of each root were defined using 24 data points distributed evenly along the periphery of the AM meniscal root.[25,26] Specifically, this technique used a clock-face method to collect data points at the 12-o'clock (most anterior), 3-o'clock, 6-o'clock (most posterior), and 9-o'clock positions, with 5 data points taken between each of these positions. This permitted standardization and equal distribution of data points during collection. The Heron formula was used to calculate the attachment area.[30] Additional measurements of the tibial plateau were taken to quantify the medial-lateral width and anterior-posterior length of each specimen.

Surgical Technique

After the AM meniscal root footprint area was measured, the precise location for guide pin placement in the reamed group was established by use of digital calipers (Swiss Precision Instruments Inc; manufacturer-reported accuracy of $\pm$0.03 mm) and physical landmarks based upon previously published guidelines.[18,29,35] This method allowed for standardization between the 12 reamed knees (6 male and 6 female specimens) to verify that the reaming site was placed in a consistent position. The entire width of the tibial tubercle was measured by use of the digital calipers. The currently recommended starting point has been reported to be, on average, 9.1 mm lateral to the midline of the tibial plateau, 3 mm lateral to the center of the tibial tubercle, and adjacent to the anterior margin of the tibial plateau.[18,29,35] To place a guide pin at the recommended location, the width of the tibial

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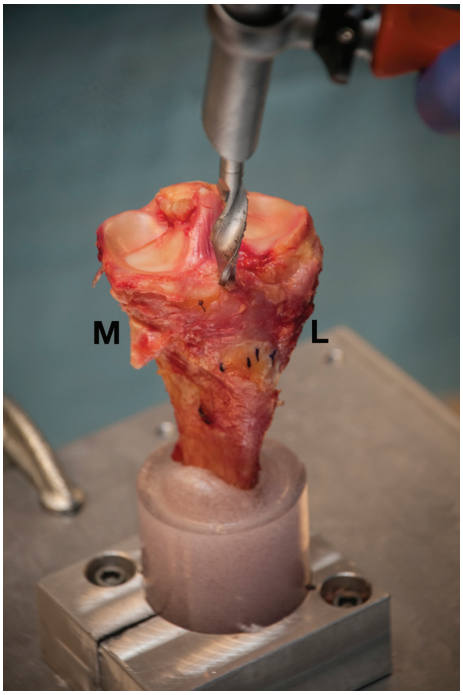

Figure 1. The currently recommended starting point for tibial intramedullary reaming. Before reaming, the location was established and standardized by use of a digital caliper and bony landmarks, and a 3.2-mm guide pin was drilled. A 12.5-mm reamer was placed over the guide pin, and the tunnel was reamed (left knee; M, medial; L, lateral).

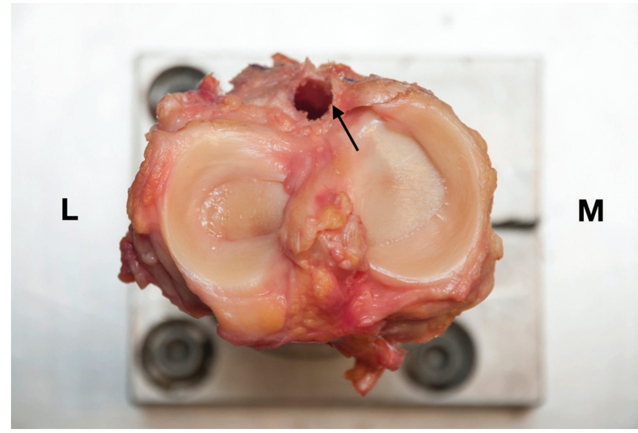

Figure 2. An overhead view of a postreamed female left knee and the corresponding iatrogenic damage (arrow) to the anterior medial meniscal root attachment site (M, medial; L, lateral).

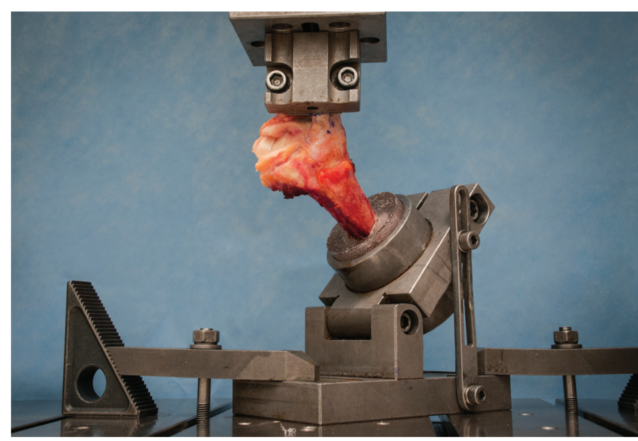

Figure 3. Testing setup for a right knee. Each potted knee was rigidly secured within a custom steel fixture and clamped to the base of a dynamic tensile testing machine. The anterior medial meniscal root was secured to the actuator within a clamp and pulled in line with the circumferential fibers until failure.

tubercle at the distal insertion of the patellar tendon was measured by use of the calipers and marked with a surgical pen, and the midpoint of the tibial tubercle was also marked. The calipers were then used to measure 3 mm lateral to the midpoint of the tibial tubercle. A 3.2-mm guide pin was drilled perpendicular to this location at the edge of the anterior margin of the tibial plateau in line with the tibial shaft, centered in the safe zone as previously described.[18,29,35] A 12.5-mm opening reamer (Trigen Meta-Nail, Tibial Nail System Entry Reamer; Smith & Nephew Inc) was then used to ream over the guide pin (Figure 1). Previous studies and clinical practice suggest that a 12.5-mm diameter reamer is a practical size that allows for the insertion of a standard IM nail.[7,11,15,34] All reaming was performed by a sports medicine fellowship–trained orthopaedic surgeon (M.G.H.). When present, the anterior intermeniscal ligament was preserved and, upon inspection, was not injured during IM reaming. Placement of an IM nail through the reaming site was not performed because the specimens were not full tibias, and we believed that the addition of the nail would neither cause further damage to the AM meniscal root attachment site nor counter the effects of the AM meniscal root.

Postreaming AM Root Measurements

After reaming, the area of the AM meniscal root attachment site was recorded and quantified for the reamed group by use of the coordinate measuring device following the same clock-face method as the prereaming measurement. The outline of the reamed tunnel (Figure 2) was measured by use of 24 data points. Overlap of the AM root and reamed tunnel was then calculated via the Heron formula.[30]

Biomechanical Testing

A custom steel fixture was used to orient and rigidly mount each tibia onto the base of a dynamic tensile testing machine (ElectroPuls E10000; Instron) (Figure 3). Measurement error of the testing machine was certified by Instron to be ±0.3% of the indicated force. In each knee, the medial meniscus was transversely sectioned in half and 24-gauge metal wire was wrapped around the AM meniscus 1 cm from the bony attachment to provide additional interfacial surface area and friction for mechanical interlock once clamped. This technique was adapted from a similar testing protocol performed by Ellman et al[13] and other recent studies.[25,26] Each meniscus was secured in a custom-made steel clamp and pulled in line with its circumferential fibers, simulating a shear-type clinical failure mechanism.[13,22] Each root was 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.[13] The ultimate failure load of each root was calculated in a similar fashion to previous studies that assessed meniscal root failure loads.[14,22]

Statistical Analysis

The nonparametric Wilcoxon signed rank test was used separately for the male and female groups to test whether the reamed specimen produced lower ultimate failure loads than its paired intact specimen. All statistical analyses were performed using SPSS Statistics (v 20; IBM Corp). A P value <.05 was considered statistically significant.

RESULTS

Overlap Area

Average overlap areas of the AM meniscal root and the reaming site for each sex were calculated (Table 1). Only 2 of the 6 male knees had a reduction in AM root attachment area, whereas all 6 female knees had a reduction in AM root attachment area.

Ultimate Failure Load

Ultimate failure loads are listed for both male and female groups in Table 1. The reamed female knees (351 ± 163 N) had significantly lower AM root failure loads compared with the native knees (544 ± 195 N) (P = .028), corresponding to a 37% reduction. There was no significant difference between the male reamed (617 ± 297 N) and native knees (566 ± 276 N) (P = .249). All menisci from male and female knees failed due to bony avulsion from the tibial plateau.

Tibial Plateau Measurements

The average anterior-posterior (AP) proximal tibial plateau length for male knees was 46 ± 4 mm, while the average AP length for female knees was 42 ± 2 mm. There was no apparent correlation between AP length and AM root damage in either sex. The average medial-lateral (ML) width for male knees was 77 ± 2 mm, while the average ML width for female knees was 68 ± 4 mm. Figure 4 depicts the negative correlation (R^2 = 0.77) between total overlap area and ML width in female knees. Only 2 of the 6 male AM roots were damaged, and there was no correlation between ML width and total overlap area as the 2 specimens that were damaged were also 2 of the 4 largest in ML width. All male ML widths were greater than 72 mm.

DISCUSSION

The most important finding of this study was that female knees were susceptible to iatrogenic damage to the AM meniscal root during reaming based on the current recommended guidelines for IM nail insertion. In contrast, male knees were not significantly affected by reaming. This study was the first to quantitatively assess the anatomic and biomechanical effect that reamed tibial nailing has on the structural properties of the AM meniscal root and, perhaps more important, compare these results between human male and female knees.

Based on the findings of this study, it is important for sports medicine physicians to be aware of the possibility of an AM meniscal root tear in both female and smaller patients who have anterior knee pain after intramedullary tibial nailing. In our experience, patients with this injury often have a palpable extruded anterior horn of the medial meniscus and anteromedial joint line pain in response to direct palpation and hyperextension. In these patients, the current standards for IM nailing[18,29,35] place the AM meniscal root at risk for iatrogenic injury. On magnetic resonance imaging (MRI), the axial view may demonstrate the IM nail tunnel location on the tibia at the AM meniscal root attachment, while the sagittal and coronal views may demonstrate AM meniscal root detachment. A definitive diagnosis is obtained via arthroscopic examination and probing. This is important clinically because it may, at least in part, explain the cause of anterior knee pain in some patients after tibial nailing, and care should be taken to ensure slightly more lateral placement of the starting point or the use of smaller diameter entry reamers in these patients. It must be noted, however, that too far of a lateral starting point increases the risk of coronal plane malalignment and varus-valgus malunion.[18] Therefore, a laterally adjusted starting point for female patients may not be optimal for fractures that require precise starting points for anatomic reduction, such as proximal one-third fractures, but may be more clinically relevant for mid-third and distal-third fractures. With regard to the optimal anteroposterior location, placement of the reaming site on the anterior margin of the tibial plateau did not induce iatrogenic articular cartilage injury in either male or female specimens; therefore, we believe that this landmark should continue to be used in all patients.

Injury to the posterior meniscal root attachment sites has been reported to significantly decrease the failure load, function, and tibiofemoral contact mechanics of the menisci.[1,13,24,28,32,33] To date, however, biomechanical effects after anterior meniscal root injury are less understood. In a clinical setting, Costa et al[8] reported that all partial or complete AM meniscal root tears resulted in greater than 3 mm of meniscal extrusion, with a vast majority (89%) of these tears also exceeding 6 mm of meniscal extrusion. These findings, along with reports that greater than 3 mm of meniscal extrusion precedes

TABLE 1
Ultimate Failure Load and Attachment Area of Anterior Medial Meniscal Root Footprint Before and After Reaming[a]

	Ultimate Failure Load, N			Tunnel-AM Overlap		
	Native	Reamed	%Δ	No. Damaged/Total	Area, mm²	% of Native
Male specimens	566 ± 276	617 ± 297	10 ± 18	2/6	2, 28[b]	1, 12[b]
Female specimens	544 ± 195	351 ± 163	–37 ± 10	6/6	19 ± 15	19 ± 16

[a]Data are reported as mean ± SD unless otherwise indicated. AM, anterior medial meniscal root.
[b]Only 2 of 6 specimens were damaged; thus, individual values are presented.

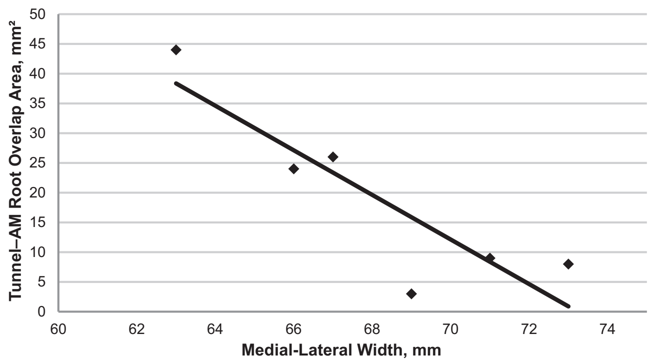

Figure 4. The tibial tunnel and anterior medial (AM) meniscal root overlap area versus tibial medial-lateral (ML) plateau width for female specimens. There was a negative correlation (R^2 = 0.77) between total overlap area and ML width.

degenerative joint disease and can ultimately leave the knee in a functionally meniscal-deficient state,[27] suggest that partial or complete AM root tears may result in persistent anterior knee pain and significantly increase the risk for future osteoarthritis.[8,27] Ellman et al[13] reported that the supplemental fibers of the AM root contribute up to 28.4% of the native root attachment failure load; therefore, the central fibers are the greatest contributor to the native failure load of the AM root. In the present study, the attachment fibers of the AM root were injured in 2 of 6 male knees and 6 of 6 female knees, revealing that complete or partial injury to these central fibers is theoretically possible even when the current recommendations for placing an IM nail are followed. In any circumstance, we believe that placement of the IM nail medial to the aforementioned safe zone should be avoided.

On the basis of the results of this study, we recommend use of radiographic and anatomic tools to identify the proper entry point for tibial IM nail insertion.[19,23] Current guidelines insert the guide pin just medial to the downslope of the lateral tibial eminence on the anteroposterior radiograph and slightly proximal to the anterior articular margin on the lateral view.[2,35] When the same reference points are used, the AM root has been reported to be 17 mm medial to the lateral tibial eminence on anteroposterior radiographs and 4.8 mm posterior to the anterior edge of the tibial plateau on lateral views.[19] Use of these radiographic reference points, as well as open or arthroscopic anatomic references,[23] may help to correctly position the IM nail to avoid iatrogenic meniscal root injury. Further studies should be pursued to help elucidate whether smaller IM nails and/or reamers, or slight lateralization of the entry point in females and in smaller patients, can help mitigate damage to the AM root. Additional studies are recommended to determine whether injury to the AM meniscal root results in abnormal joint contact areas and pressures. Last, future clinical studies are necessary to determine the incidence of anterior knee pain and AM meniscal root injury as a function of tibial width.

Limitations of this study involve using anatomic landmarks for the starting point on an open, dissected knee in the laboratory. In a clinical setting, it is more difficult to place the guide pin in the correct position due to the presence of the patella and other structures of the knee. Nevertheless, an open approach was deemed to be the ideal testing approach because it allowed for the ability to study the best-case scenario if the tunnel was placed correctly in the recommended position. Additionally, the study was conducted in vitro, which does not take healing into consideration for ultimate failure load measurements. The variability of tissue quality could also affect the results; however, the use of matched pairs aged 62 years and younger helped to mitigate this risk.

CONCLUSION

Tibial reaming decreased the AM meniscal root attachment area and significantly decreased ultimate failure load in female but not in male knees, using currently recommended guidelines. On the basis of this study's findings, it is recommended that smaller diameter reamers and, if possible, slight lateralization of the starting point be used for female patients and smaller patients with tibial shaft fractures. Given that the incidence of this iatrogenic injury remains unknown, future clinical studies should be performed to evaluate whether females and smaller patients have a higher risk of AM meniscal root injuries after IM nailing compared with male patients and, as a result, a greater incidence of anterior knee pain.

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REFERENCES

1. Allaire R, Muriuki M, Gilbertson L, Harner CD. Biomechanical consequences of a tear of the posterior root of the medial meniscus: similar to total meniscectomy. *J Bone Joint Surg Am*. 2008;90(9):1922-1931.
2. Althausen PL, Neiman R, Finkemeier CG, Olson SA. Incision placement for intramedullary tibial nailing: an anatomic study. *J Orthop Trauma*. 2002;16(10):687-690.
3. Bhandari M, Guyatt GH, Swiontkowski MF, et al. Surgeons' preferences for the operative treatment of fractures of the tibial shaft: an international survey. *J Bone Joint Surg Am*. 2001;83(11):1746-1752.
4. Bhatia S, Laprade CM, Ellman MB, Laprade RF. Meniscal root tears: significance, diagnosis, and treatment. *Am J Sports Med*. 2014; 42(12):3016-3030.
5. Bone LB, Sucato D, Stegemann PM, Rohrbacher BJ. Displaced isolated fractures of the tibial shaft treated with either a cast or intramedullary nailing: an outcome analysis of matched pairs of patients. *J Bone Joint Surg Am*. 1997;79(9):1336-1341.
6. Buehler KC, Green J, Woll TS, Duwelius PJ. A technique for intramedullary nailing of proximal third tibia fractures. *J Orthop Trauma*. 1997;11(3):218-223.
7. Chalidis BE, Petsatodis GE, Sachinis NC, Dimitriou CG, Christodoulou AG. Reamed interlocking intramedullary nailing for the treatment of tibial diaphyseal fractures and aseptic nonunions: can we expect an optimum result? *Strategies Trauma Limb Reconstr*. 2009;4(2):89-94.
8. Costa CR, Morrison WB, Carrino JA. Medial meniscus extrusion on knee MRI: is extent associated with severity of degeneration or type of tear? *AJR Am J Roentgenol*. 2004;183(1):17-23.
9. Court-Brown CM, Gustilo T, Shaw AD. Knee pain after intramedullary tibial nailing: its incidence, etiology, and outcome. *J Orthop Trauma*. 1997;11(2):103-105.
10. Court-Brown CM, Will E, Christie J, McQueen MM. Reamed or unreamed nailing for closed tibial fractures: a prospective study in Tscherne C1 fractures. *J Bone Joint Surg Br*. 1996;78(4):580-583.
11. Eastman JG, Tseng SS, Lee MA, Yoo BJ. The retropatellar portal as an alternative site for tibial nail insertion: a cadaveric study. *J Orthop Trauma*. 2010;24(11):659-664.
12. Ellman MB, James EW, Laprade CM, Laprade RF. Anterior meniscus root avulsion following intramedullary nailing for a tibial shaft fracture. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(4):1188-1191.
13. Ellman MB, LaPrade CM, Smith SD, et al. Structural properties of the meniscal roots. *Am J Sports Med*. 2014;42(8):1881-1887.
14. Feucht MJ, Grande E, Brunhuber J, et al. Biomechanical comparison between suture anchor and transtibial pull-out repair for posterior medial meniscus root tears. *Am J Sports Med*. 2014;42(1):187-193.
15. Gaebler C, McQueen MM, Vecsei V, Court-Brown CM. Reamed versus minimally reamed nailing: a prospectively randomised study of 100 patients with closed fractures of the tibia. *Injury*. 2011;42(suppl 4):S17-S21.
16. Hak DJ. Intramedullary nailing of proximal third tibial fractures: techniques to improve reduction. *Orthopedics*. 2011;34(7):532-535.
17. Hernigou P, Cohen D. Proximal entry for intramedullary nailing of the tibia: the risk of unrecognised articular damage. *J Bone Joint Surg Br*. 2000;82(1):33-41.
18. Hiesterman TG, Shafiq BX, Cole PA. Intramedullary nailing of extra-articular proximal tibia fractures. *J Am Acad Orthop Surg*. 2011;19(11):690-700.
19. James EW, LaPrade CM, Ellman MB, Wijdicks CA, Engebretsen L, LaPrade RF. Radiographic identification of the anterior and posterior root attachments of the medial and lateral menisci. *Am J Sports Med*. 2014;42(11):2707-2714.
20. Johannsen AM, Civitarese DM, Padalecki JR, Goldsmith MT, Wijdicks CA, LaPrade RF. Qualitative and quantitative anatomic analysis of the posterior root attachments of the medial and lateral menisci. *Am J Sports Med*. 2012;40(10):2342-2347.
21. Katsoulis E, Court-Brown C, Giannoudis PV. Incidence and aetiology of anterior knee pain after intramedullary nailing of the femur and tibia. *J Bone Joint Surg Br*. 2006;88(5):576-580.
22. Kopf S, Colvin AC, Muriuki M, Zhang X, Harner CD. Meniscal root suturing techniques: implications for root fixation. *Am J Sports Med*. 2011;39(10):2141-2146.
23. LaPrade CM, Ellman MB, Rasmussen MT, et al. Anatomy of the anterior root attachments of the medial and lateral menisci: a quantitative analysis. *Am J Sports Med*. 2014;42(10):2386-2392.
24. LaPrade CM, Jansson KS, Dornan G, Smith SD, Wijdicks CA, LaPrade RF. Altered tibiofemoral contact mechanics due to lateral meniscus posterior horn root avulsions and radial tears can be restored with in situ pull-out suture repairs. *J Bone Joint Surg Am*. 2014;96(6):471-479.
25. LaPrade CM, Smith SD, Rasmussen MT, et al. Consequences of tibial tunnel reaming on the meniscal roots during cruciate ligament reconstruction in a cadaveric model, part 1: the anterior cruciate ligament. *Am J Sports Med*. 2014;43(1):200-206.
26. LaPrade CM, Smith SD, Rasmussen MT, et al. Consequences of tibial tunnel reaming on the meniscal roots during cruciate ligament reconstruction in a cadaveric model, part 2: the posterior cruciate ligament. *Am J Sports Med*. 2014;43(1):207-212.
27. Lerer DB, Umans HR, Hu MX, Jones MH. The role of meniscal root pathology and radial meniscal tear in medial meniscal extrusion. *Skeletal Radiol*. 2004;33(10):569-574.
28. Marzo JM, Gurske-DePerio J. Effects of medial meniscus posterior horn avulsion and repair on tibiofemoral contact area and peak contact pressure with clinical implications. *Am J Sports Med*. 2009;37(1):124-129.
29. McConnell T, Tornetta P III, Tilzey J, Casey D. Tibial portal placement: the radiographic correlate of the anatomic safe zone. *J Orthop Trauma*. 2001;15(3):207-209.
30. Nelsen RB. Heron's formula via proofs without words. *The College Mathematics Journal*. 2001;32:290-292.
31. Nork SE, Barei DP, Schildhauer TA, et al. Intramedullary nailing of proximal quarter tibial fractures. *J Orthop Trauma*. 2006;20(8):523-528.
32. Padalecki JR, Jansson KS, Smith SD, et al. Biomechanical consequences of a complete radial tear adjacent to the medial meniscus posterior root attachment site: in situ pull-out repair restores derangement of joint mechanics. *Am J Sports Med*. 2014;42(3):699-707.
33. Schillhammer CK, Werner FW, Scuderi MG, Cannizzaro JP. Repair of lateral meniscus posterior horn detachment lesions: a biomechanical evaluation. *Am J Sports Med*. 2012;40(11):2604-2609.
34. Tabatabaei S, Arti H, Mahboobi A. Treatment of open tibial fractures: comparison between unreamed and reamed nailing a prospective randomized trial. *Pak J Med Sci*. 2012;28:917-920.
35. Tornetta P III, Riina J, Geller J, Purban W. Intraarticular anatomic risks of tibial nailing. *J Orthop Trauma*. 1999;13(4):247-251.
36. Vaisto O, Toivanen J, Kannus P, Jarvinen M. Anterior knee pain after intramedullary nailing of fractures of the tibial shaft: an eight-year follow-up of a prospective, randomized study comparing two different nail-insertion techniques. *J Trauma*. 2008;64(6):1511-1516.