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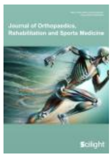

Review

Meniscal Root Tears: Anatomy, Biomechanics, Diagnosis, and Surgical Management—A Comprehensive Review

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Abstract: Background: Meniscal root tears (MRTs), particularly those involving the posterior horns of the medial and lateral menisci, have become increasingly recognized for their significant biomechanical implications and their strong association with the onset and progression of knee osteoarthritis. These lesions disrupt the meniscus's ability to convert axial loads into hoop stresses, leading to extrusion, altered joint mechanics, and accelerated cartilage degeneration. Purpose: This review aims to provide a comprehensive synthesis of current knowledge on the anatomy, biomechanics, epidemiology, clinical presentation, diagnosis, classification, treatment strategies, and surgical outcomes of meniscal root tears. Methods: A narrative literature review was conducted through a non-systematic search of PubMed, Scopus, and Web of Science, including peer-reviewed studies published primarily from 2000 to 2024. Additional landmark articles outside this range were also included for historical or foundational relevance. Selection focused on studies addressing the anatomy, biomechanics, diagnosis, and surgical management of meniscal root tears. Results: MMPRTs are more prevalent than LMPRTs and are typically degenerative in nature, affecting older, overweight females with varus alignment. LMPRTs are more commonly traumatic and frequently associated with anterior cruciate ligament (ACL) injuries. MRI remains the primary imaging modality, although arthroscopy remains the diagnostic gold standard. Surgical repair techniques, particularly transtibial pullout and suture anchor fixation, have demonstrated superior outcomes compared to conservative treatment or meniscectomy. Clinical and functional improvements, as well as reduced progression to osteoarthritis, have been reported, though healing rates vary. Conclusion: MRTs represent a significant clinical entity due to their biomechanical relevance and potential for irreversible joint degeneration. Early recognition and appropriate surgical intervention are effective for preserving joint function and improving long-term outcomes.

Keywords: meniscal root tear; posterior root tear; knee biomechanics; meniscal extrusion; osteoarthritis; arthroscopic repair; transtibial pullout; suture anchor; meniscus anatomy; meniscal healing; meniscectomy

1. Introduction

Meniscal root tears (MRTs), particularly those affecting the posterior horns of the medial and lateral menisci, have increasingly emerged as clinically significant lesions with profound biomechanical consequences. The meniscal roots are essential anchoring structures that transform compressive loads applied to the knee into circumferential (hoop) stresses, facilitating proper load distribution across the joint and contributing to its overall stability and chondroprotection. When these root attachments are disrupted, it leads to meniscal extrusion and altered joint mechanics, resembling the biomechanical deficits observed following a total meniscectomy [1,2].

Among these injuries, medial meniscus posterior root tears (MMPRTs) are more prevalent and typically associated with chronic degeneration, particularly in older women with elevated body mass index (BMI) and varus knee alignment. In contrast, lateral meniscus posterior root tears (LMPRTs) frequently result from acute trauma and are commonly seen in conjunction with anterior cruciate ligament (ACL) ruptures, ramp lesions, or injuries to the meniscofemoral ligaments [1,3,4]. Despite advances in imaging and surgical techniques, MRTs are still frequently underdiagnosed due to their subtle clinical presentation and limitations in imaging sensitivity, especially in detecting lateral root involvement [5–7].

Recent anatomical and biomechanical investigations have improved our understanding of meniscal root morphology, vascularity, and structural integration with adjacent elements such as the joint capsule and posterior cruciate ligament (PCL) [8,9]. These findings have been instrumental in refining classification schemes and surgical repair strategies, such as transtibial pullout and suture anchor fixation, with the goal of re-establishing native biomechanics and minimizing progressive joint degeneration [10–12].

This review consolidates contemporary insights into the anatomy, biomechanics, epidemiology, diagnosis, classification, and treatment of MRTs, with particular focus on recent advancements in surgical management and clinical outcomes.

2. Anatomy and Biomechanics

The knee joint contains two crescent-shaped fibrocartilaginous menisci (medial and lateral) interposed between the femoral condyles and the tibial plateau. The medial meniscus is semi-circular (C-shaped) and measures approximately 27 mm in width and 40.5–45.5 mm in length, whereas the lateral meniscus is more nearly circular (U-shaped), about 26.6–29.3 mm wide and 32.4–35.7 mm long [1,13]. Each meniscus consists of a central body and two horns—anterior and posterior—that anchor to the tibial plateau via the meniscal roots. These roots are composed of a central dense collagen bundle reinforced by additional peripheral fibers known as “shiny white fibers”, which increase the insertion area and enhance tensile strength [1,14]. Several ligaments contribute to meniscal stability: the transverse intermeniscal ligament connects the anterior horns, the medial collateral ligament secures the medial meniscus, and the meniscofemoral ligaments (Humphrey and Wrisberg) reinforce the posterior horn of the lateral meniscus [13].

2.1. Meniscal Vascular Supply

Blood supply to the menisci originates from the genicular arteries, which form a peripheral capillary network. Vascular penetration is limited to the outer 10–25% of the meniscal width. The meniscus is divided into three vascular zones: the red-red (highly vascularized outer third), red-white (intermediate vascularity), and white-white (avascular inner third). Healing potential decreases from periphery to center, making vascularity a crucial factor in determining treatment strategies for meniscal injuries [9].

2.2. Lateral Meniscus Anterior Root

According to LaPrade [15], who included the fibers of the lateral meniscus which run beneath the ACL, the lateral meniscus anterior root (LMAR) has an area of 140.7 mm^2. The distance of the center of the LMAR from the center point of the tibial insertion of the ACL is 5 mm to 7.5 mm, 7.1 mm from the lateral articular cartilage, and 14.4 from the apex of the lateral tibial eminence. There is an overlap of the ACL on the anterior lateral root of about 89 mm^2, corresponding to 63.2% of the LMAR and 40.7% of the ACL tibial footprints [1,16]. This anatomic organization predicts the unavoidable injury of the anterior lateral meniscal root during the reconstruction of the ACL.

2.3. Lateral Meniscus Posterior Root

The lateral meniscus posterior (LMPR) root has an area of 39.2 mm^2, excluding the presence of the supplementary fibers [7]. The distance of the posterior root from the apex of the lateral tibial eminence is 4.2 mm posteromedial, and 1.5 mm posterior. It is placed 12.7 mm anterior to the most proximal margin of the PCL tibial attachment, 4.2 mm medial to the articular cartilage margin of the tibial plateau, and 10.1 mm from the attachment of the lateral meniscus anterior root. However, some fibers of the posterior aspect reach the posterior portion of the lateral aspect of the medial tibial eminence [1,3,12,16].

2.4. Medial Meniscus Posterior Root

The medial meniscus posterior root (MMPR) attaches antero-medial to the posterior cruciate ligament (PCL) on the posterior aspect of the medial tibial intercondylar eminence. The distance between the apex of the medial tibial eminence and the MMPR is 9.6 mm posteriorly and 0.7 mm laterally, while MMPR is 3.5 mm lateral to the medial tibial plateau articular cartilage inflection point and 8.2 mm anterior to the superior aspect of the PCL tibial attachment [3].

It has an area of 30.4 mm^2, whereas its supplementary shiny white fibers extend from 47.3 to 69.6 mm^2 up to 80 mm^2. This is the reason why during a meniscal root repair the placement of the tunnel is influenced by the insertion of the densest fiber and it indicates the use of a 6mm diameter zone [1].

2.5. Medial Meniscus Anterior Root

The medial meniscus anterior root (MMAR) insertion is along the anterior portion of the medial intercondylar eminence and anterior to the apex. It has a mean area of 110.4 mm^2 and a central attachment of 56.3 mm^2. The intermeniscal ligament is not strictly necessary for tibiofemoral contact and meniscal function and as a matter of fact it is present in 70% of knees [3]. The MMAR anatomical location increases the risks for iatrogenic damage during intramedullary tibial nailing procedures [1]

2.6. Biochemical Structure

The meniscus has a great wet weight component, it consists of 72% of water and 28% of organic matter made of ECM and cells (75% collagen, 17% GAGs, 2% DNA, <1% adhesion glycoproteins, and <1% elastin). The previous ratios may change depending on age, injuries, and other clinical conditions [13].

Most of the meniscal dry component is consists of collagen, although it varies in quantity and type depending on the tissue region. The red zone is made of collagen type I (80% of fibrillar component) and type II, III, IV, and XVIII in lesser amount. The white zone has a 70% of collagen component (60% type II and 40% type I). Other than collagen the meniscal fibrillar component is made of elastin, whose biomechanical function is still undetermined,; GAGs (chondoitin-6-sulfatec (60%), dermatan sulfate (20–30%), chondroitin-4 sulfate (10–20%), and keratin sulfate (15%); large proteoglycans such as aggregans and small ones such as buglycan and decorin that are capable of water absorption and tissue support at compression; and adhesion molecules (fibronectin, thrombospondin, and collagen VI) that can link the ECM and cells of the meniscal structure [13].

2.7. Biomechanical Properties

Meniscal role in biomechanics and knee function is manly preventing potential osteoarthritic changes. They can convert the axial loads into radial tangential stress or hoop stress being the shock absorbers of the knee. The mitigation of the impact of compressive forces is allowed by the anchoring of the meniscus to the tibial plateau, therefore meniscal extrusion does not occur [17]. If damage occurs the knee articular cartilage would be exposed to unaffordable loads, smaller tibiofemoral contact area, and peaks of contact pressure as if the patient had a meniscectomy.

One of the functions of the lateral meniscus posterior root is to stabilize the knee in anterior tibial translation (ATT) and internal rotation, which is crucial to understand the biomechanical mechanism in case of ACL deficiency. Its function as a second stabilizer in AAT underlies the need of LMPR repair during ACL reconstruction, to reduce the risk of graft overload with consequent failure and further instability [6].

Studies have shown the presence of the "New Terrible triad" in up to 8% of the patients. The Triad includes ACL tear with combined medial meniscus ramp lesion (MMRL) and lateral meniscus root tear (LMRT) [18]. From a biomechanical point of view the knee can be altered in different ways according to the combination of ACL tear and MMRL, or ACL tear and LMRT. The former increases the degree of ATT and external rotation, the latter increases the effects on translation and internal rotation of the knee. These findings underline the importance of MMRL and LMRT repair at the time of ACL reconstruction [18].

On the other hand, it has been observed that the medial meniscus plays a crucial role for the stability of chronically anterior cruciate ligament (ACL)-deficient knees [4]. The meniscus has a close relationship with the joint capsule, the posterior oblique ligament, and the semimembranosus tendon as it has been described by

Hunghston and Eilers [19]. They also explained the biomechanics of knee flexion: the posterior horn of the meniscus is translated posteriorly by the capsular arm of the semimembranosus tendon insertion. Furthermore, they studied the peripheral meniscal tear and proposed that it can be caused by the "compression" of the medial meniscus between the femur and the tibia during semimembranosus contraction. This specific tear can present in both knees with acute and chronic ACL tears [4].

Papageorgiou et al. [20] discussed that in a transected ACL there is an increase of forces of the 200% on the medial meniscus in response to anterior tibial loads, Similarly ACLR failure has been related to medial meniscus deficiency [4].

Stephen et al. [21] a cadaveric study to observe that sectioning the posteromedial menisco-capsular junction in ACL deficient knees considerably impacts on anterior tibial translation and external rotation laxities. Additionally, to restore stability it was not sufficient to perform anterior cruciate ligament repair (ACLR) in isolation, but rather it was necessary to combine ACLR and menisco-capsular repair [4].

3. Epidemiology

Meniscal root tears (MRTs), particularly those involving the posterior root of the medial meniscus, have gained increased recognition due to their biomechanical significance and strong association with rapid joint degeneration and early osteoarthritis. These lesions are notably more frequent in the medial meniscus than in the lateral, with medial meniscus posterior root tears (MMPRTs) accounting for a substantial proportion of symptomatic degenerative knee disorders in middle-aged individuals [1,22,23].

MMPRTs are most frequently observed in females over 50 years of age, with a clear predominance in patients with elevated body mass index (BMI) and varus knee alignment. Kamatsuki et al. found that the mean age of patients with acute MMPRTs was approximately 64 years, with 79.9% of patients being female, and 82.5% classified as overweight or obese. This demographic pattern supports the hypothesis that both mechanical overload and hormonal factors may contribute to the pathogenesis of degenerative root tears [23,24].

In contrast, lateral meniscus posterior root tears (LMPRTs) are less common and more often result from traumatic mechanisms, especially in the setting of anterior cruciate ligament (ACL) injuries. LMPRTs are typically seen in younger, more active individuals and often occur alongside other intra-articular lesions, including ramp lesions and meniscofemoral ligament injuries [6,18].

A notable correlation exists between MMPRTs and subchondral insufficiency fractures of the knee (SIFK). In a cohort of 253 patients with SIFK, 71.1% exhibited medial meniscus root or radial tears, indicating a high co-occurrence rate and reinforcing the role of the meniscal root in load transmission and subchondral protection [5].

Although MRTs are increasingly recognized in clinical practice, they remain underdiagnosed due to the subtlety of clinical symptoms and limitations in standard imaging modalities. Improved awareness and refined MRI criteria have led to increased detection rates, but many cases—especially degenerative MMPRTs—are only identified intraoperatively or retrospectively following progression of joint degeneration [2,25].

The injury mechanism in degenerative MMPRTs is often low-energy and related to daily activities. Kamatsuki et al. reported that 33.7% of patients experienced a painful popping sensation while descending stairs, 23.0% while standing up, and 20.3% while walking, with 89.9% of injury events occurring during routine activities [24].

Overall, the burden of meniscal root lesions is substantial, particularly given their prevalence among older adults and their strong association with knee osteoarthritis, functional impairment, and accelerated cartilage loss [1,17,26].

4. Diagnosis

The majority of MRT's are of degenerative aetiology (about 70% of meniscal posterior root tears), occurring in the absence of injury or as a result of minor traumas such as squatting. However, MPRT of traumatic aetiology can also be possible [22].

4.1. Risk Factors

Risk factors to be considered, that might have a role in the degenerative form of MPRT include female sex, older age, increased BMI and varus alignment [23].

4.2. Classification

The classification of posterior root tears according to La Prade et al. (2015) is based on arthroscopic morphology evaluation:

- Type 1 (7%): defined as partial and stable root tear
- Type 2 (68%): defined as a complete radial tear within 9 mm of the root attachment
    - Type 2a (38%): when the complete radial tear is within 0 to <3 mm
    - Type 2b (17%): when the complete radial tear is within 3 and <6 mm
    - Type 2c (12%): when the complete radial tear is within 6 and <9 mm
- Type 3 (6%): defined as a “bucket-handle tear” with complete root detachment
- Type 4 (10%): defined as complete oblique or longitudinal tear with complete root detachment
- Type 5: defined as a root bony avulsion [27].

4.3. Physical Exam

Clinical diagnosis of meniscal posterior root tears can be quite challenging as most patients do not present typical signs and symptoms pointing towards a meniscal tear.

Patients generally complain of posterior knee pain during full knee flexion along with a visibly restricted range of motion, joint-line tenderness and positivity to the McMurray test.

A popping noise might be heard when the examiner asks the patients to perform squatting-like activities, moreover, there is a low occurrence of meniscal mechanical symptoms such as locking, catching and giving away [2,11,14,17].

According to Akmese et al.: the implementation of the evaluation of the Akmese sign pre-operatively, could potentially be used as a specific pointer in the diagnosis of medial meniscal posterior root tears in physical examination.

The test is administered with the patient lying in supine position with the suspected pathological lower limb arranged in a figure-of-4 position, allowing for the medial collateral ligament and medial capsule to relax, as the knee is in slight varus; following this, the examiner palpates the median joint line while moving the knee into extension; additionally, while moving the knee into hyperflexion, the median joint line is palpated once again.

The test is positive when patients present with severe tenderness in hyperflexion or in angles close to extension during palpation of the median joint line [8].

4.4. Imaging

4.4.1. MRI

Magnetic Resonance Imaging (MRI) is the primary non-invasive modality used to diagnose meniscal root tears and associated intra-articular pathology. High-resolution MRI scans, particularly 3.0 Tesla systems with T2-weighted sequences in axial, sagittal, and coronal planes, offer optimal visualization of the meniscal attachments. This approach is highly effective for detecting posterior root tears of the medial meniscus; however, it is less sensitive for identifying tears in the lateral meniscal root due to anatomical complexities. The lateral root’s oblique orientation and its proximity to adjacent structures can obscure its visualization, making it more challenging to detect on standard MRI.

Although MRI is a valuable diagnostic tool, certain lesions may not be evident, especially when they are small or located in less accessible regions. In such cases, diagnostic arthroscopy remains the definitive method for confirming meniscal root injuries [11,14,25,28].

On MRI, attention should be directed toward anatomical zones prone to root pathology, including the intercondylar area between the tibial tubercles, the lateral tubercle, and the outer edge of the tibial eminence [28].

Specific MRI signs that support the diagnosis of a root tear include:

1. Radial tear sign: A perpendicular hyperintense line crossing the meniscus root on axial views, suggestive of a radial disruption at the root insertion.
2. Truncation sign: A sharp vertical defect or abrupt interruption of the meniscal contour, typically accompanied by extrusion of the medial meniscus exceeding 3 mm beyond the tibial margin.
3. Ghost sign: The apparent absence of the posterior meniscal root on sagittal slices, creating an impression of invisibility in the expected region

These imaging features, when present, provide strong evidence of a meniscal root tear. However, if clinical suspicion remains high despite inconclusive imaging, arthroscopic evaluation is recommended [10,17].

4.4.2. Ultrasound

Despite its potential, ultrasound has notable limitations. It is highly operator-dependent, and deep intra-articular structures such as posterior meniscal roots are difficult to assess due to acoustic shadowing from surrounding bones. Consequently, ultrasound may not reliably detect isolated or deep-root injuries lacking surface involvement.

While ultrasound is a useful adjunct, especially in cases where MRI is contraindicated or unavailable, it is not sufficient as a standalone tool for the diagnosis of meniscal root tears. MRI remains the imaging method of choice, and arthroscopy continues to serve as the gold standard when imaging and clinical findings are discordant [29].

5. Treatment

5.1. Indications

Over the years, therapeutic approaches to meniscal root injuries have evolved, encompassing conservative management, partial meniscectomy, and anatomical meniscal root repair. The latter is specifically aimed at restoring native knee biomechanics; however, it is not universally indicated. Careful patient selection is critical to optimize outcomes [30].

Individuals who demonstrate good functional capacity, minimal articular cartilage degeneration (Outerbridge grades I–II), and overall joint stability are considered suitable candidates for surgical intervention. In such patients, meniscal root repair is generally preferred over partial meniscectomy, particularly in acute avulsion-type injuries, due to its superior potential to preserve native joint mechanics and decelerate degenerative joint changes. Meniscectomy is more often indicated for chronic or degenerative root lesions in which the residual meniscal tissue is insufficiently viable for repair. However, in these cases, meniscectomy is associated with inferior clinical outcomes and accelerated osteoarthritic progression compared to meniscectomy for other meniscal tear patterns.

In patients presenting with acute root avulsions in conjunction with substantial varus malalignment, a staged or concurrent high tibial osteotomy (HTO) may be warranted to correct limb alignment, optimize load distribution, and enhance repair durability [1,30].

5.2 Meniscectomy versus Conservative Treatment in Degenerative Meniscal Lesions

Fairbank was the first to document radiographic changes such as joint space narrowing and osteophyte formation after a meniscectomy, Pengas et al. reported in a long-term study with a mean follow-up of 40 years that 81% of knees which had undergone meniscectomy developed osteoarthritis following the Kellgren and Lawrence grading, meanwhile only 18% in non-operated contralateral knees [26].

Even with partial meniscectomy, the risk of developing osteoarthritis is still present, as demonstrated by a 16-year follow-up study evaluating patients with isolated meniscal tears, which found that those who underwent partial meniscectomy had significantly higher rates of symptomatic and radiographic femorotibial osteoarthritis than matched control, no matter the size of the portion of the meniscus removed [2,26].

5.3. Surgical Technique

Surgical repair methods for meniscal root tears can be broadly divided into two main categories: trans-osseous (transtibial) suture repairs and suture anchor–based repairs. Both approaches are typically performed arthroscopically (or with arthroscopic assistance), thereby avoiding the need for extensive posterior dissection of the knee [31].

The concept of trans-osseous root repair was first introduced by West et al. for tears of the medial meniscus root [31]. Building on this, Raustol et al. described a fully arthroscopic technique that utilized an accessory high posteromedial portal to facilitate suture passage. In their method, two Beath pins were used to place a horizontal mattress suture through the meniscal root, and the suture was secured by tying it over an anterolateral bony bridge on the tibia [31].

Ahn et al**.** later refined the approach by adding a posterior trans-septal portal, which allowed instruments to be passed beneath the posterior cruciate ligament (PCL) and significantly improved visualization of the root attachment area in the posterolateral compartment [31]. In Ahn's technique, an ACL tibial guide was introduced through the posteromedial portal while a 2.9 mm cannulated drill was brought in from the anteromedial side to create a pathway for suture passage through the root. The authors subsequently expanded this into a double-row suture construct to potentially enhance fixation strength and healing. Another variation, described by Marzo et al**.**, avoided the use of any additional posterior portals. Marzo and colleagues employed a Scorpion suture-passing device to place the sutures through the root and drilled a 7 mm tibial tunnel through which the suture ends were retrieved and finally tied over a washer on the tibial cortex [31].

In addition to trans-osseous repairs, suture anchor fixation offers an alternative strategy. Engelsohn et al. were the first to report an anchor-based root repair, specifically for meniscal root avulsions in multi-ligament injured knees. Their technique involved placing a bioabsorbable "Corkscrew" suture anchor into the tibial plateau at the root attachment site via a high posteromedial portal and using a Viper device to pass the suture through the meniscus. Choi et al. later described a similar approach using a double-loaded metal anchor, with suture passage facilitated by a shuttle relay and hook device. One theoretical advantage of anchor techniques is that they eliminate the need to drill a tibial tunnel. This can be beneficial when root repairs are combined with other procedures (such as concurrent ligament reconstruction or high tibial osteotomy) and may reduce the risk of suture wear or failure, since there is no tunnel edge for the suture to abrade against [31].

5.4. Transtibial Pullout Repair

In the transtibial "pullout" repair technique, the surgeon begins by identifying the meniscal root's anatomic attachment site on the tibial plateau under arthroscopic visualization. The torn root insertion site is debrided (for example, with a curette or shaver) to create a bleeding bed and promote healing. Next, an ACL tibial drill guide is inserted through a small anteromedial incision on the proximal tibia to position a guide pin at the meniscal root footprint. Once correct pin placement is confirmed arthroscopically, a tibial tunnel approximately 5–6 mm in diameter is created by drilling over the guide pin with a reamer. Alternatively, a retrograde cutting reamer can be used from inside the joint to create a shallow socket (about 10 mm deep) at the root attachment instead of a full tunnel. The choice between a standard trans-tibial reamer and a retro-cutting (inside-out) reamer is typically based on the surgeon's preference [30].

After the bony tunnel or socket is prepared, a strong nonabsorbable suture (usually a No. 2) is passed through the meniscal root remnant using a suture-passing device of the surgeon's choice. The free ends of this suture are then retrieved and pulled out through the tibial tunnel. With the knee positioned at approximately 30° of flexion (to hold the meniscus in a reduced anatomic position), the suture is tensioned and secured on the tibial surface. Commonly, the suture ends are tied over a small cortical button or secured under a screw-and-washer construct on the anterior tibia. Maintaining the knee in slight flexion during fixation helps keep the meniscus properly reduced and optimizes the repair's integrity as the construct is tightened down [30].

5.5. Suture Anchor Repair

Suture anchor fixation is another technique for repairing a meniscal root avulsion, particularly of the medial meniscus. Instead of creating a tibial tunnel, this method uses one or more small anchors (either double-loaded metal anchors or bioresorbable anchors) to reattach the torn root to its native footprint on the tibial plateau. Proper anchor placement requires precise angulation of instrumentation, which is typically achieved by using an accessory high posteromedial portal or, in some cases, a high anterolateral quadricipital portal. A posterior trans-septal portal can also be added to improve visualization and access for anchor insertion if needed [32].

Once the anchor is implanted at the root attachment site, the attached sutures must be passed through the meniscal root tissue. This can be accomplished with a suture hook device (e.g., a SutureLasso) or a specialized meniscus repair tool such as the Arthrex Scorpion. Depending on tear location and surgeon preference, the suture passage is performed via either the anteromedial or posteromedial portal to ensure optimal access to the torn root. A key advantage of the suture anchor technique is that it obviates tibial tunnel drilling. This makes anchor fixation especially useful when the root repair is combined with other bony procedures (like an ACL reconstruction or high tibial osteotomy), as it avoids creating an additional tibial tunnel. Moreover, by not having a tunnel, the risk of suture abrasion at a tunnel exit during healing is eliminated, which potentially improves the durability of the repair [32].

5.6. Two-Tunnel Transtibial Pullout

A commonly used variant of the transtibial repair involves creating two separate trans-osseous tunnels for the meniscal root fixation. In this two-tunnel technique, two simple suture loops are passed through the torn root, and each is brought out through its own tibial tunnel; these sutures are then tied over a single cortical button on the anterior tibia to secure the root in place. The procedure is performed arthroscopically using the standard anterolateral and anteromedial portals (adjacent to the patellar tendon) as working channels. Additional accessory portals, such as a high posteromedial portal, can be established as needed to improve visualization or instrument access [1].

After the meniscal root tear is identified and probed, the native root footprint on the tibial plateau is debrided (for instance, with a curette) to promote healing. Using a dedicated root repair guide, the first tibial tunnel is created by inserting a guide pin through the posterior portion of the root attachment site and reaming over it with a cannulated drill. Then, a second tunnel is created in a similar manner, approximately 5 mm anterior to the first tunnel, so that both tunnels emerge at the meniscal root insertion site on the tibia. Once the tunnels are in the correct position, the guide pins are removed. Two nonabsorbable sutures are passed through the meniscal root (often in a simple stitch configuration), and each suture is retrieved through one of the tibial tunnels. Finally, the sutures are tensioned and tied over a small cortical button on the proximal tibia, securing the meniscal root back down to its anatomic attachment point [1].

5.7. Side-to-Side Meniscus Root Repair

In certain cases of radial meniscal root tears near the insertion site, a side-to-side suture repair (joining the tear edges together) can be performed, provided the detached fragment remains adjacent to the tibial attachment and the tissue quality is sufficient. Instead of reattaching the root to bone, this technique sutures the torn meniscal root directly to the remaining meniscal tissue. Ahn et al**.** described a side-to-side repair for complete radial tears of the posterior lateral meniscus root. In their approach, a polydioxanone (PDS) suture was first passed through the posterior horn of the lateral meniscus using a straight suture hook. Using the same hook, this suture was then passed through the torn root fragment. By tying a sliding knot with the two ends of the PDS suture, the tear was approximated, effectively creating a vertical side-to-side suture construct that stabilizes the root tear [32].

Wang et al**.** later reported a similar side-to-side technique for radial tears of the posterior medial meniscus root. In their method, a posterior trans-septal portal was established for improved visualization, and two posteromedial portals were used to facilitate suture passage through the tear. As an alternative to using PDS sutures and shuttle techniques, some authors have proposed all-inside meniscal repair devices as a less invasive way to achieve a comparable side-to-side repair for root tears [32].

5.8. Surgical Outcomes

In recent years, several clinical studies—primarily Level III and IV evidence—have assessed the outcomes of meniscal root repair. Despite being limited to retrospective studies and case series, the literature consistently reports improvements in clinical outcomes compared to baseline. Ahn et al. showed significantly better results with repair versus conservative treatment, and two comparative studies demonstrated superior outcomes with repair over partial meniscectomy. Notably, Chung et al. reported a 35% TKA conversion rate in the meniscectomy group versus 0% in the repair group [30,32].

Second-look arthroscopies have revealed variable healing rates. Cho and Song reported complete healing in 4 out of 13 patients, with others healing in a lax or scarred state, and 1 failure. Seo et al. observed similarly mixed outcomes. Feucht et al.'s systematic review found no cartilage degeneration in over 80% of patients, reduced meniscal extrusion in 56%, and complete healing in 62% of cases. Functional scores also improved, with Lysholm scores rising from 52.4 to 85.9 at an average follow-up of 30 months [30,32].

Reoperation rates remain low; Lee et al. reported a 5% rate, mostly due to retears. Long-term data are scarce, but one case followed for 20 years post-repair demonstrated sustained joint preservation and good function. Most studies utilized trans-osseous pull-out techniques. One comparative study showed better clinical outcomes and less joint space narrowing with repair versus meniscectomy [30,32].

Healing appears more consistent in lateral root repairs, particularly when combined with ACL reconstruction, as shown by Ahn et al., who reported complete healing in 8 of 9 patients. Medial root repairs, by contrast, show lower healing rates, and MRI results post-repair often indicate incomplete healing [30,32].

Findings on meniscal extrusion are mixed. While some studies report reduced extrusion post-repair, others show no change or even worsening, particularly in medial root tears. The progression of osteoarthritis appears limited in the short term, but the lack of long-term follow-up data suggests that conclusions should be drawn cautiously [30,32].

Overall, current evidence supports meniscal root repair as a joint-preserving procedure that improves clinical outcomes and may reduce the risk of future degenerative changes [30,32].

5.9. Rehabilitation Protocols

Rehabilitation following meniscal root repair must be meticulously designed to promote optimal tissue healing, functional recovery, and long-term joint stability. The protocol should be tailored to any concomitant procedures to preserve the biomechanical integrity of the meniscocapsular junction while allowing for a progressive return of function.

Early-phase rehabilitation focuses on limiting weight-bearing and employing controlled range-of-motion (ROM) exercises to reduce shear forces and mechanical stress on the repair site. Patients are typically instructed to remain non-weight-bearing for the first two weeks, then transition to partial weight-bearing with crutches as tolerated, and advance to full weight-bearing between weeks 4 and 6, based on the biomechanical robustness of the repair. During this period, passive and active-assisted ROM exercises should be initiated within a protective arc (0°–90° flexion) to prevent joint stiffness without overloading the healing meniscocapsular tissue. Early incorporation of progressive quadriceps activation is critical to counteract muscular atrophy and to enhance neuromuscular control, thereby minimizing the risk of compensatory movement patterns that may compromise repair integrity. Closed kinetic chain exercises are gradually introduced after six weeks, with a focus on proprioceptive training and controlled weight transfer to facilitate the restoration of normal joint biomechanics [21].

5.10. Rehabilitation Following Combined ACL Reconstruction and Meniscal Root Repair

When meniscal root repair is performed in conjunction with anterior cruciate ligament reconstruction (ACLR), the rehabilitation protocol generally aligns with standard ACL protocols but must be adjusted to safeguard the integrity of the meniscal repair. Given that meniscal root lesions contribute to persistent knee instability, early rehabilitation should promote joint mobility while minimizing posterior meniscal stress.

During the initial six weeks, flexion beyond 90° should be avoided to limit posterior tibial translation and prevent loading patterns that could impair healing. Ambulation should begin with non-weight-bearing or partial weight-bearing, progressing to full weight-bearing between weeks 6 and 8 based on clinical evaluation and imaging. Closed kinetic chain quadriceps strengthening and use of a stationary bicycle may be introduced between weeks 4 and 6, provided there is no evidence of compromise to the repair site.

Between weeks 8 and 12, rehabilitation should include progressive strengthening, proprioceptive training, and low-impact neuromuscular exercises to enhance dynamic stability and reduce compensatory motor deficits. Plyometric drills and return-to-sport (RTS) testing based on objective criteria should not be initiated earlier than 6 months postoperatively, and only if both the ACL graft and the meniscal root repair demonstrate satisfactory mechanical integrity.

6. Conclusions

Meniscal root tears (MRTs) represent a distinct and clinically significant subtype of meniscal injury, with substantial biomechanical consequences including meniscal extrusion, impaired load distribution, and rapid progression of cartilage degeneration akin to that seen after total meniscectomy [1,2,8]. are more prevalent and typically degenerative in nature, frequently affecting older, overweight female patients with varus knee alignment. In contrast, LMPRTs are more commonly traumatic and often occur in association with ACL injuries [4,22].

Accurate diagnosis remains challenging due to subtle clinical signs and variable MRI sensitivity, especially for lateral lesions; arthroscopy remains the diagnostic gold standard [6,7]. Treatment decisions must be individualized, but surgical repair—particularly transtibial pullout or suture anchor fixation—has shown superior outcomes over meniscectomy or conservative management, with better functional results and lower progression to osteoarthritis [11,12].

Despite encouraging mid-term results, the current body of evidence is limited by heterogeneity in surgical techniques and low-volume case series, which are further complicated by patient-specific factors such as body mass index, limb alignment, gender, and chronicity of injury. These variables make it difficult to draw definitive conclusions about the ideal surgical candidate. Healing rates remain inconsistent, particularly for medial repairs—and long-term data are lacking [11,12]. It is increasingly clear that indiscriminate repair of all meniscal root tears may lead to suboptimal outcomes and unnecessary procedures. Therefore, future research must focus on identifying the "optimal patient cohort" for meniscal root repair—those with high success rates as measured by patient-reported outcome measures (PROMs), low reoperation rates, and minimal conversion to total knee arthroplasty (TKA). Acknowledging and addressing these gaps will be essential to refine patient selection criteria and enhance surgical decision-making [1,2,8].

Author Contributions

U.G.L.: conceptualization, supervision, writing—review and editing; B.M.: methodology, data curation, writing—original draft preparation; M.N.: investigation, validation; M.M.: formal analysis, visualization; P.E.T.: resources, data curation; S.C.: literature search, writing—original draft preparation; A.d.S.: resources, formal

analysis, writing—review and editing; P.D.: supervision, critical revision of the manuscript for important intellectual content. All authors have read and agreed to the published version of the manuscript.

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