



Long-Term Results for Meniscus Repair

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Abstract

Purpose of review Meniscus tears are some of the most commonly managed orthopedic injuries that affect a wide variety of patient populations. Traditionally, meniscus tears were treated either conservatively or with partial meniscectomy. However, recent technological innovations have generated a rapid evolution in the modern evaluation and treatment of meniscus tears. The primary objective of this review is to provide a detailed overview of long-term results of meniscus repair after greater than five to ten years follow up, highlighting modern surgical techniques, clinical and radiologic outcomes, rates of failure and revision surgery, as well as emerging insights and future directions.

Recent findings Advancements in arthroscopic implants and techniques helped establish meniscus repair as the preferred approach for treating many meniscal tears due to its ability to preserve native knee kinematics and decrease the risk of osteoarthritic progression. In properly indicated patients, long-term clinical data supports performing meniscus repair over traditional treatments, such as partial meniscectomy, to preserve overall knee function and longevity. The impact of tear morphology on healing rates, potential for biologic augmentation, and optimal postoperative rehabilitation are substantial areas of active research.

Summary Undertaking a comprehensive, individualized approach evaluating careful patient selection, sound surgical technique, and ideal rehabilitation strategies is critical to guiding treatment decisions and achieving long-term successful outcomes.

Keywords Meniscus repair · Long-term outcomes · Meniscus tear treatment

This article belongs to the Topical Collection on Meniscus

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Introduction

The lateral and medial menisci are crescent-shaped fibrocartilaginous structures that attach anteriorly and posteriorly to the tibial plateau and collectively cover approximately 70% of the articular surface. Meniscus tears are considered one of the most common musculoskeletal injuries, with an incidence ranging from 0.6–0.7 tears per 1000 person-years [1]. Meniscus tears can occur acutely following a rotational force on a flexed knee, such as in cutting or pivoting sports, or spontaneously due to aging or degenerative processes [2]. Given the high prevalence of meniscus injuries, specific tear characteristics of the meniscus can vary widely depending on many factors, including patient anatomy, overall health, injury mechanism, and traumatic versus degenerative nature [2].

Meniscus tears are generally classified according to anatomic location, proximity to blood supply, and tear morphology (vertical/longitudinal, radial, oblique, horizontal cleavage, and complex/degenerative) [3]. In the past, meniscus tears were commonly resected due to traditionally being

considered a vestigial remnant [4]. However, in 1948, Fairbank suggested a chondroprotective role of the meniscus by demonstrating total meniscectomy predisposes the knee to early degenerative changes with radiographs after showing arthritic changes as early as 5 months post-operatively [5]. Multiple biomechanical and clinical investigations have since confirmed poor long-term outcomes and joint health in patients post-meniscectomy [2]. Over time, increased focus has been placed on meniscal preservation through a limited partial meniscectomy, meniscal repair, or biologic stimulation procedures due to the critical role shock absorption and secondary stabilization the meniscus plays. Surgical management of such injuries has rapidly evolved, and there has been increased rates of meniscal repair over partial meniscectomy in recent years [6]. Despite this, there is still no consensus regarding optimal treatment given the relative paucity of large, high-level clinical investigations reporting outcomes of meniscus repair after greater than five to ten years [7].

The primary objective of this review is to provide a detailed overview of long-term results of meniscus repair after greater than five to ten years follow up, highlighting modern surgical techniques, clinical and radiologic outcomes, rates of failure and revision surgery, as well as emerging insights and future directions.

Meniscus Repair – Modern Techniques and Arthroscopic Advances

Various surgical techniques have been described for meniscus repair, including open and arthroscopic approaches, inside-out and outside-in techniques, as well as modern

all-inside implants [7]. Indications for each repair type vary based on particular tear location, morphology, and tissue quality. While the inside-out technique has been described as the traditional gold standard for repair, advances in modern implants and instrumentation have caused a substantial increase in the amount of all-inside repairs performed (Fig. 1) [8]. Potential advantages of this technique include decreased operative time and lower odds of neurological injury without the need for an open exposure or skilled assistant [8]. However, new implant-related complications have also been introduced, including implant failure, prominence, and discomfort from local soft tissue irritation (Fig. 2) [9, 10]. Multiple systematic reviews and meta-analyses have demonstrated no differences in long term clinical outcomes, overall complications, or failure rates when comparing inside-out and all-inside techniques [7, 10–12]. However, it is important to note the significant heterogeneity present in available data regarding types of all-inside implants utilized, meniscus tear morphology, and tear location pooled for analysis within these reviews, largely compiled from lower-level evidence [8, 11]. As technology continues to evolve, perhaps larger, higher-level analyses with modern implants may impact comparisons of repair techniques (Fig. 3).

Recent advancements have also been made regarding suture passage and configuration techniques to promote stability and improve biomechanical strength and healing capacity. For radial tears, incorporating vertical mattress ripstop sutures into tie-grip repair constructs, where repair stitches are placed within the meniscus peripheral to ripstop mattress sutures in crossing fashion and tensioned to decrease risk of suture pull out during repair, has shown promise to increase biomechanical strength and may be

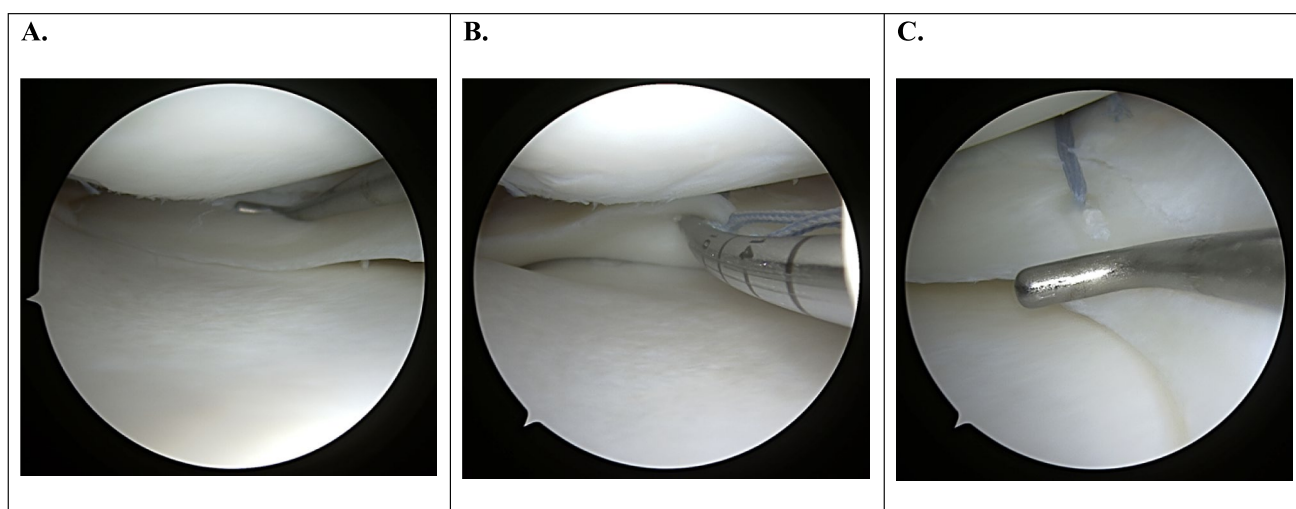


Fig. 1 All-Inside Medial Meniscus Repair. Arthroscopic view of a right knee medial meniscus from the anterolateral portal demonstrating **A** Vertical longitudinal tear of the medial meniscus determined

to be unstable upon diagnostic arthroscopy; **B** All-inside meniscus repair device being deployed to repair the tear; **C** Completed medial meniscus repair stable to arthroscopic probing

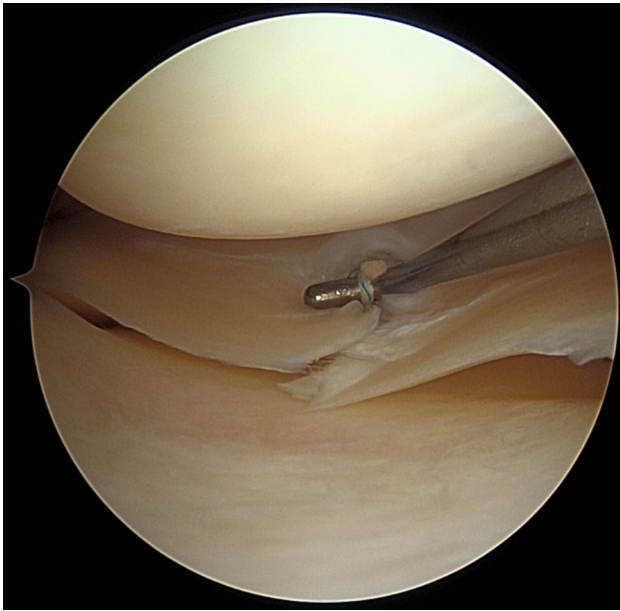


Fig. 2 All-Inside Implant Failure After Prior Medial Meniscus Repair. Arthroscopic view of a right knee medial meniscus from the anterolateral portal demonstrating all-inside implant failure with re-tear of the medial meniscus at the prior repair site

especially useful for poor-quality tissue environments (Fig. 4) [13]. The circumferential stitch is another technical development that uses either all-inside self-retrieving suture passage devices or inside-out techniques to repair challenging horizontal cleavage tears (Fig. 5) [14]. A recent study demonstrated that biomechanical performance of

trans-tibial pull out medial meniscus root repair is improved with knotless adjustable, suture-anchor based fixation compared with traditional trans-tibial cortical button-based techniques (Fig. 6) [15]. While these advancements show promise in early investigations, clinical superiority has yet to be determined. Multiple clinical analyses and systematic reviews have demonstrated improved patient outcomes with a variety of modern techniques, and direct comparisons have been limited by small sample sizes and short-term follow up [16–19]. Therefore, the long-term clinical impact for these emerging technologies remains undefined.

Long-Term Clinical Outcomes

A Functional Outcomes

Functional outcomes after meniscus repair often vary based on the type and location of tear, concomitant ACL reconstruction or other procedures, joint stability, and age of patient [20, 21]. Multiple clinical studies have demonstrated improved meniscus healing rates and reliable return to sport after ACL reconstruction in conjunction with meniscus repair, including improved outcomes compared to ACL reconstruction with meniscectomy [22–26]. In a recent series evaluating ten-year outcomes after second-generation all-inside meniscus repair in the setting of ACL reconstruction, Wright et al. demonstrated healing rates of up to 88% with maintained improvements in postoperative Knee Injury and Osteoarthritis Outcome Scores (KOOS, mean \pm SD) for pain (91 ± 14), symptoms (84 ± 17), activities of daily living (94 ± 14), sport/recreation (80 ± 25), and

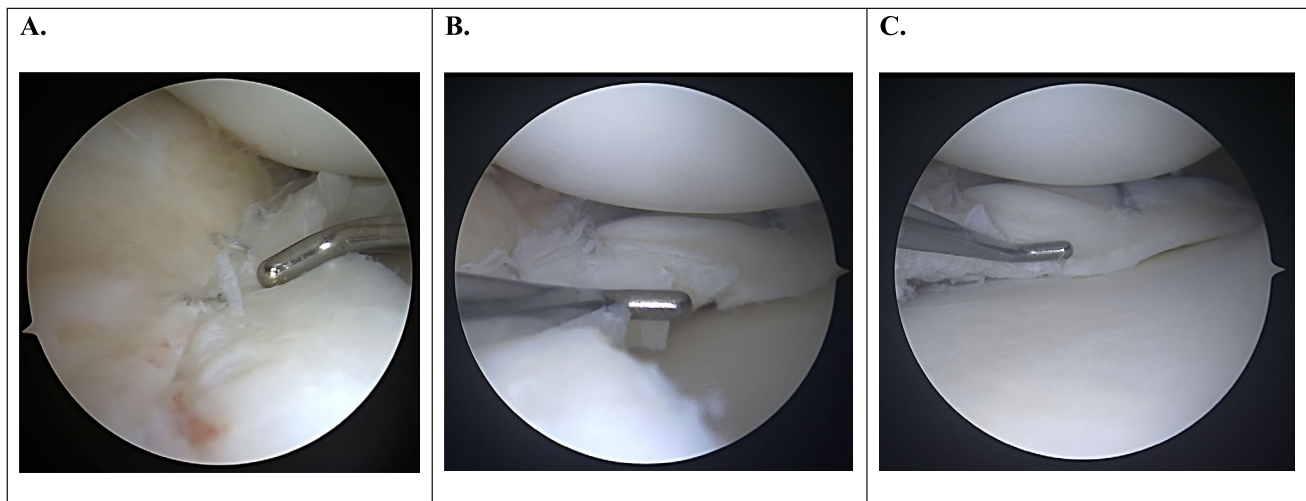


Fig. 3 Hybrid Inside Out and All-Inside Medial Meniscus Repair. Arthroscopic view of a left knee medial meniscus repair for a displaced bucket handle tear with an incomplete radial component at the junction of the posterior horn and body demonstrating **A** Inside-out repair sutures in the meniscus body and joint capsule after repair;

B Inside-out repair sutures in the mid-body portion and the repair stitch from an all-inside meniscus repair device closer to the posterior horn; **C** The all-inside repair stitch is better visualized near the medial meniscus posterior horn after completed repair

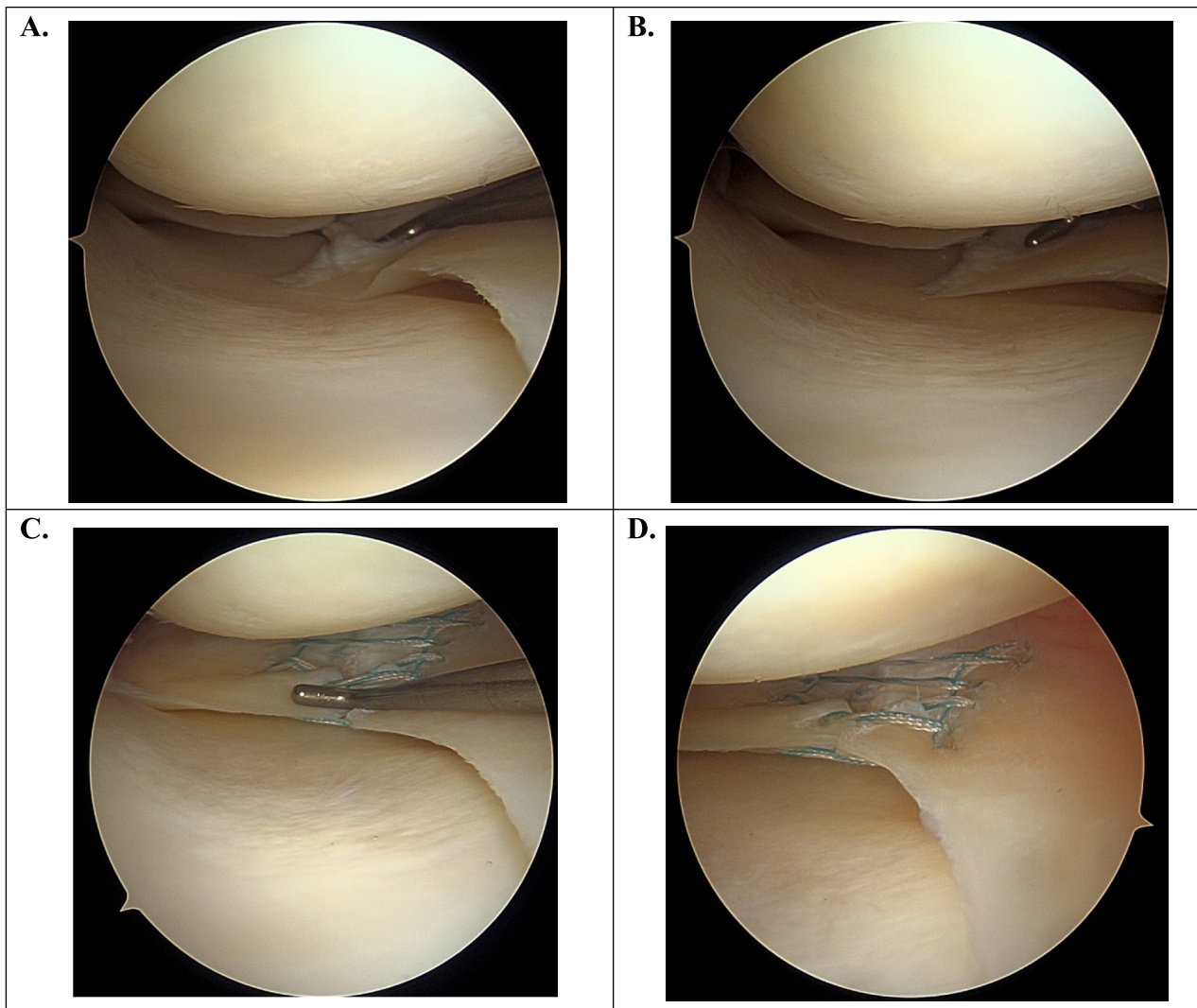


Fig. 4 Tie-Grip Rip Stop Inside Out Medial Meniscus Radial Tear Repair. Arthroscopic view of a right knee medial meniscus from the anterolateral portal demonstrating **A** and **B** Complete radial tear

extending to the joint capsule; **C** and **D** Finished inside-out repair with Tie-Grip Rip Stop suture configuration stable to arthroscopic probing

quality of life (76 ± 21), as well as International Knee Documentation Committee (IKDC) scores (78 ± 20) at mean 10.5 years. Similarly, Melton et al. described greater IKDC (84.2 vs 70.5 , $p = 0.008$) and Lysholm scores in 44 patients that underwent meniscus repair versus meniscectomy at the time of ACL reconstruction, including 89% survival for repair at 10 years follow up [22]. Large radial and bucket handle tears were commonly treated with meniscectomy due to the technically challenging nature of repair and concern for high failure rates (Fig. 7). However, more recent clinical studies with modern techniques have demonstrated satisfactory clinical outcomes along with a chondroprotective effect and lower rates of osteoarthritis at up to 10 years after repair of these challenging tears (Fig. 8) [27–30]. In their retrospective series of 66 patients with bucket handle meniscus tears,

successful repair was associated with significantly improved KOOS score (mean \pm SD, 89.6 ± 4.6 vs 77.8 ± 4.9 $p < 0.001$), IKDC score (mean \pm SD, 88.2 ± 5.1 vs 79.2 ± 5.2 $p < 0.001$), Lysholm score (mean \pm SD, 90.3 ± 5.3 vs 78.4 ± 7.8 $p < 0.001$), and lower rates of radiographic osteoarthritis (mean Kellgren-Lawrence score: 0.54) at median 114 months follow up [27]. In a ten year propensity-matched analysis of radial and bucket handle meniscus tear repairs, Krych et al. reported significant and durable postoperative improvement in VAS pain scores, Tegner activity levels, IKDC scores, and patient satisfaction with no differences between cohorts at mean 10.2 years [30].

Substantial variation in the literature exists regarding optimal postoperative rehabilitation after meniscus repair, with largely lower-level evidence predominating available

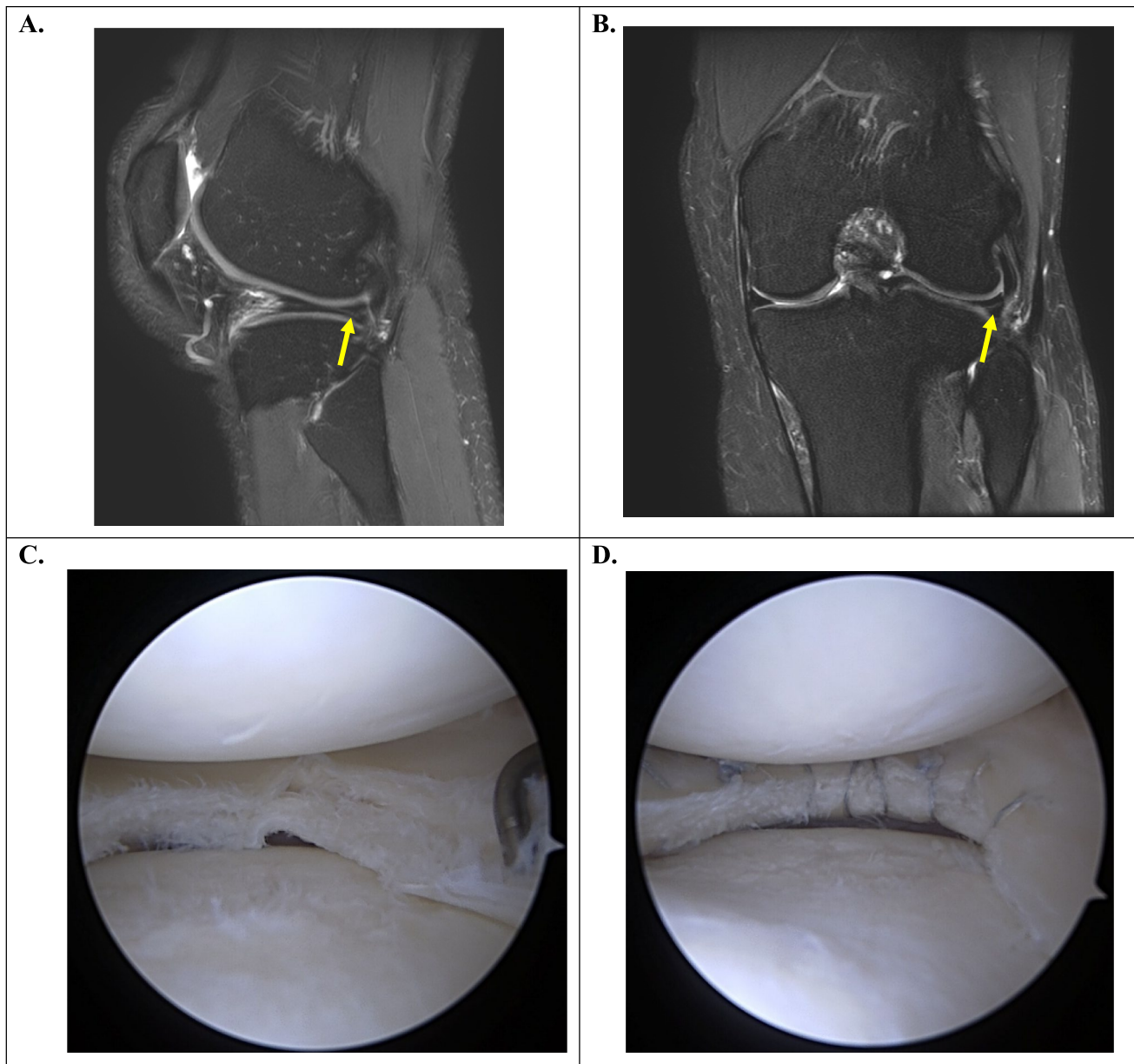


Fig. 5 Lateral Meniscus Horizontal Cleavage Tear Circumferential Meniscus Repair. **A** Sagittal and **B** Coronal STIR MRI sequences demonstrating a horizontal cleavage tear of the lateral meniscus in a left knee (yellow arrow); **C** Arthroscopic view of the lateral com-

partment from the anterolateral portal visualizing a horizontal cleavage tear of the lateral meniscus; **D** Completed circumferential suture repair of the lateral meniscus horizontal cleavage tear

data regarding postoperative management [31]. Rehabilitation protocols after meniscus repair are often divided into protective, restorative, and preparation to return to activity and sports phases [20]. Progression through the phases is typically dictated by criteria-based goals that can be influenced by tear characteristics and morphology, as well as patient-specific factors such as athletic demand [20, 32]. Some evidence suggests that accelerated protocols with immediate weight-bearing and early range of motion do

not negatively impact patient-reported outcomes or failure rates, particularly in the setting of vertical tear repairs [31–33]. However, other nuances of the rehabilitation process such as need for postoperative bracing and ideal management of certain pathology including ramp lesions are more controversial with a lack of clear consensus available [20, 31, 32].

B Radiological Outcomes

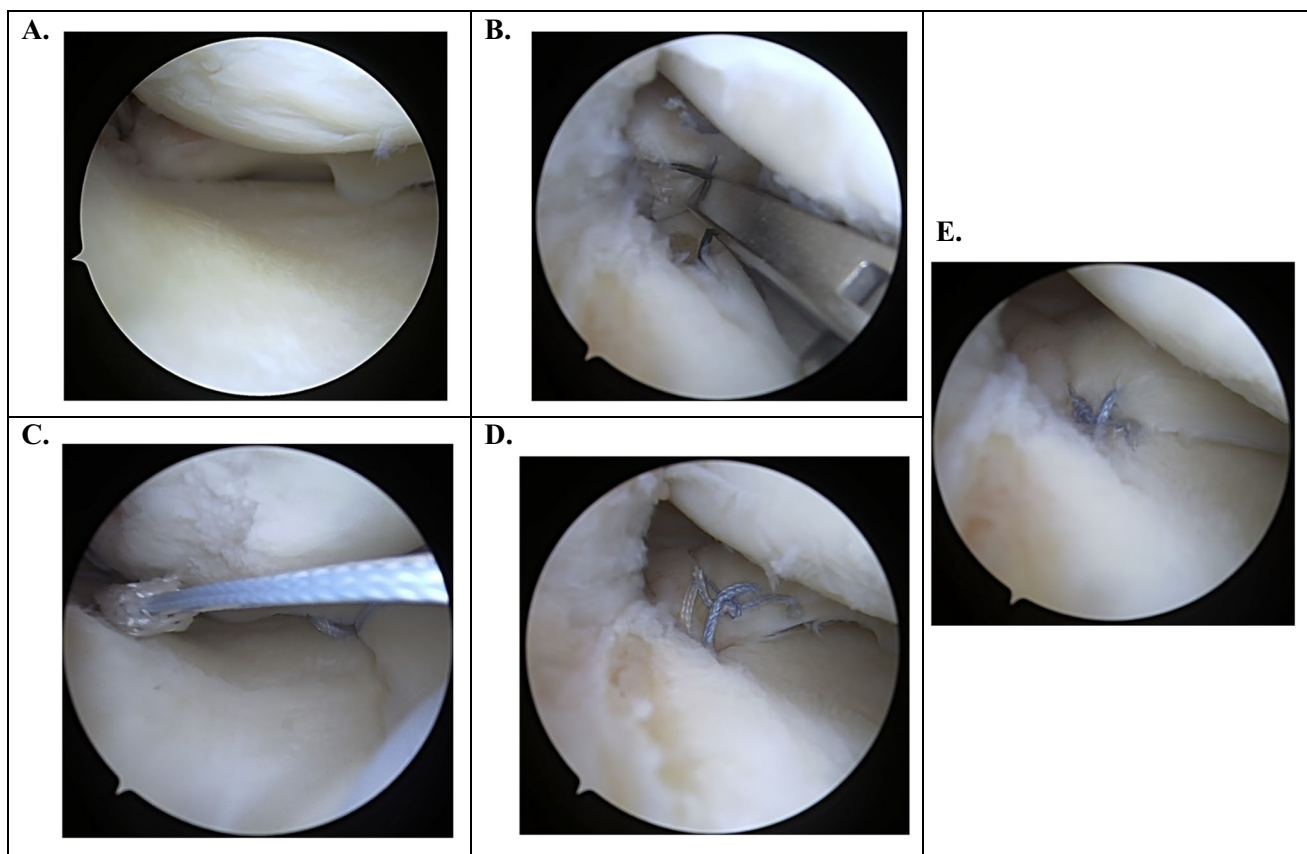


Fig. 6 Medial Meniscus Trans-Tibial Pullout Root Repair with Knotless Adjustable, Suture-Anchor Based Fixation. Arthroscopic view of a right knee medial meniscus demonstrating **A** Complete posterior root tear; **B** Arthroscopic grasper retrieving the nitinol suture lasso passed up a cannulated drill bit through a tibial tunnel at the root

attachment site; **C** Knotless adjustable suture anchor fixation device being deployed to the root attachment site; **D** Blue and white repair stitches brought down into the tibial tunnel for repair of the meniscus root; **E** Final tensioning of the root repair showing complete reduction

It can be challenging to determine what constitutes acceptable healing and the particular time point in the healing process after repair. MRI is the modality of choice to evaluate meniscus healing status, but postsurgical changes, sutures, and implants may obscure visualization and make assessment more difficult [34]. Emerging technologies such as T2 mapping may increase sensitivity and specificity in determining healing when compared to evaluation of traditional T1 and T2 MRI sequences [35]. No current guidelines exist regarding clinical monitoring of potential osteoarthritis development after repair besides patient-driven symptoms guiding further management. Similar to functional outcomes, radiographic outcomes following meniscal repair demonstrate a chondroprotective effect after successful repair, with mild osteoarthritic progression similar to the contralateral knee and at significantly lower rates compared to patients that undergo partial meniscectomy [36–40]. In a consecutive series of 50 arthroscopic meniscus repairs evaluated at minimum 10 years postoperatively, Johnson et al. reported 92% of patients had no degenerative findings

on postoperative AP radiographs, and 8% showed minimal osteoarthritic changes compared to 1% on the nonoperative knee [38]. There were also no significant differences found in joint space width when comparing the surgical compartment (5.97 mm) to the control compartment in the contralateral knee (6.29 mm) [38]. In a systematic review of 20 studies including 31,783 patients at approximately 6 years follow up, Migliorini et al. demonstrated that patients that underwent meniscus repair developed substantially lower rates of radiographic advanced osteoarthritis (KL Grade 3 or 4) (OR 0.51; 95% CI 0.39–0.69; $p < 0.05$) compared to those that underwent meniscectomy [37]. Bernard et al. evaluated 45 patients in a cohort study with medial meniscus root tears (15 treated nonoperatively, 15 with partial meniscectomy, and 15 with transtibial root repair) and found that the root repair group developed significantly less osteoarthritic KL-grade progression (nonoperative, 1.0; partial meniscectomy, 1.1; meniscal repair, 0.1; $p = 0.001$) [41]. These results were similar to a study by Chung et al. comparing results for medial meniscus root repair versus meniscectomy in 57

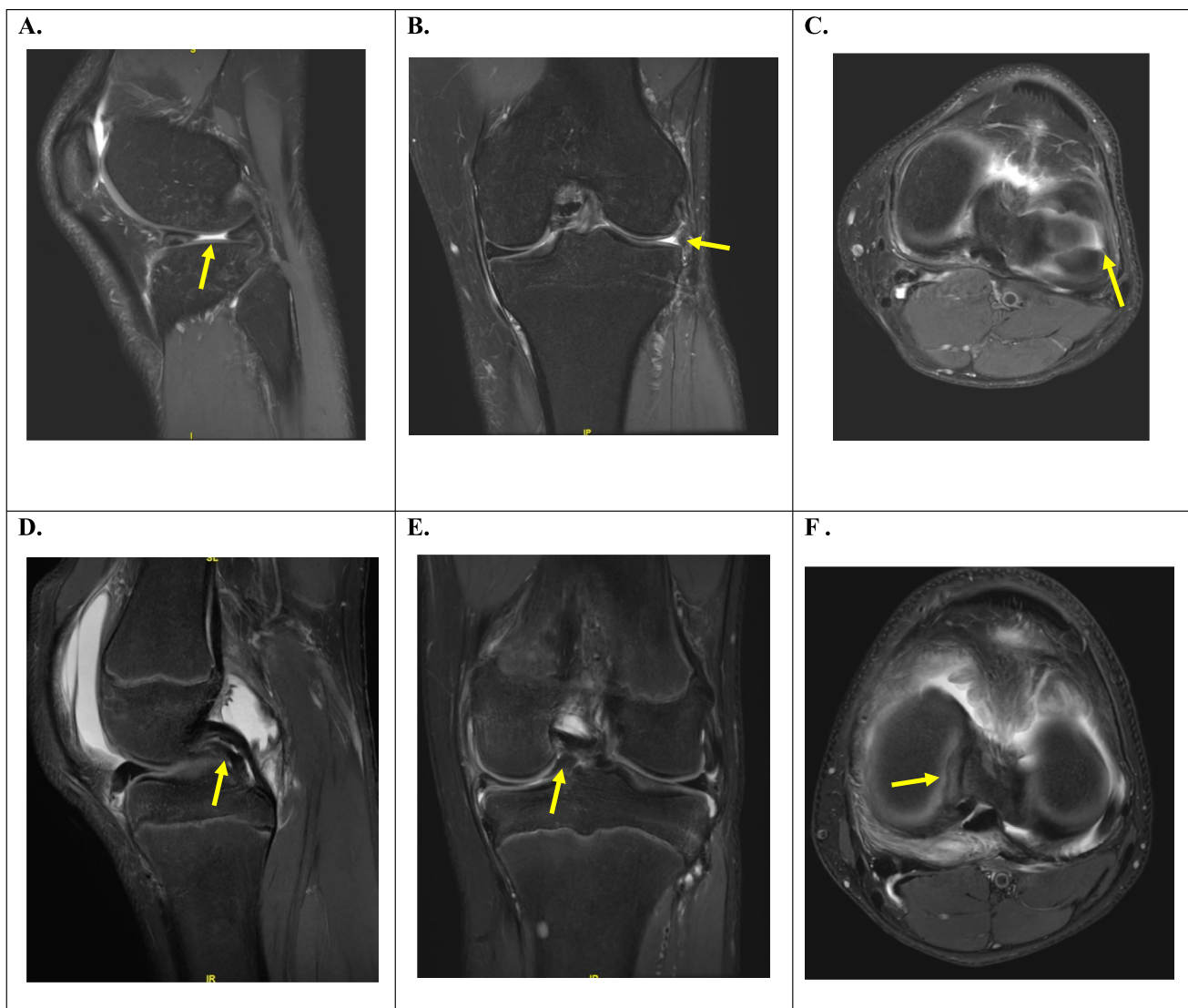


Fig. 7 MRI Findings of a Large Lateral Meniscus Radial Tear and a Displaced Medial Meniscus Bucket Handle Tear. STIR MRI sequences demonstrating a large lateral meniscus tear (yellow arrow) in the **A** Sagittal **B** Coronal and **C** Axial sequences. A large medial

meniscus bucket handle tear displaced into the intercondylar notch (yellow arrow) in the **C** Sagittal sequence with a double PCL sign, **D** Coronal, and **E** Axial sequence

patients that found substantially less KL-grade progression (14% KL grade ≥ 2 vs 80%) and severe joint space narrowing (5% ≥ 2 mm vs 45%) after repair versus meniscectomy at mean 67 months postoperatively [40].

III. Revision Rates and Failures

Reported long-term failure rates of meniscus repairs vary widely, as evidenced by a recent meta-analysis by Petersen et al. assessing results after meniscal repairs at minimum 7 postoperative years. Among the 12 investigations included in their analysis, failure rates were reported between 5–48% postoperatively, with studies evaluating children and adolescents reporting increased failures compared to those that

evaluated adults at long-term follow up [7]. Definition of failure also varied considerably, with 9 studies confirming repair failure upon revision arthroscopy, 2 studies citing clinical failure as either persistent symptoms or reoperation in combination with radiographs and MRI imaging, and one study not reporting definition of repair failure [7]. Notably, they found maintained good to very good clinical outcomes scores at greater than 7 years for both isolated meniscus repair and those combined with ACL reconstruction [7]. While it is recommended that meniscal repair be attempted in patients with a healthy knee and no absolute contraindications, assessment of the mechanical alignment, cartilage, and ligament integrity should be performed to

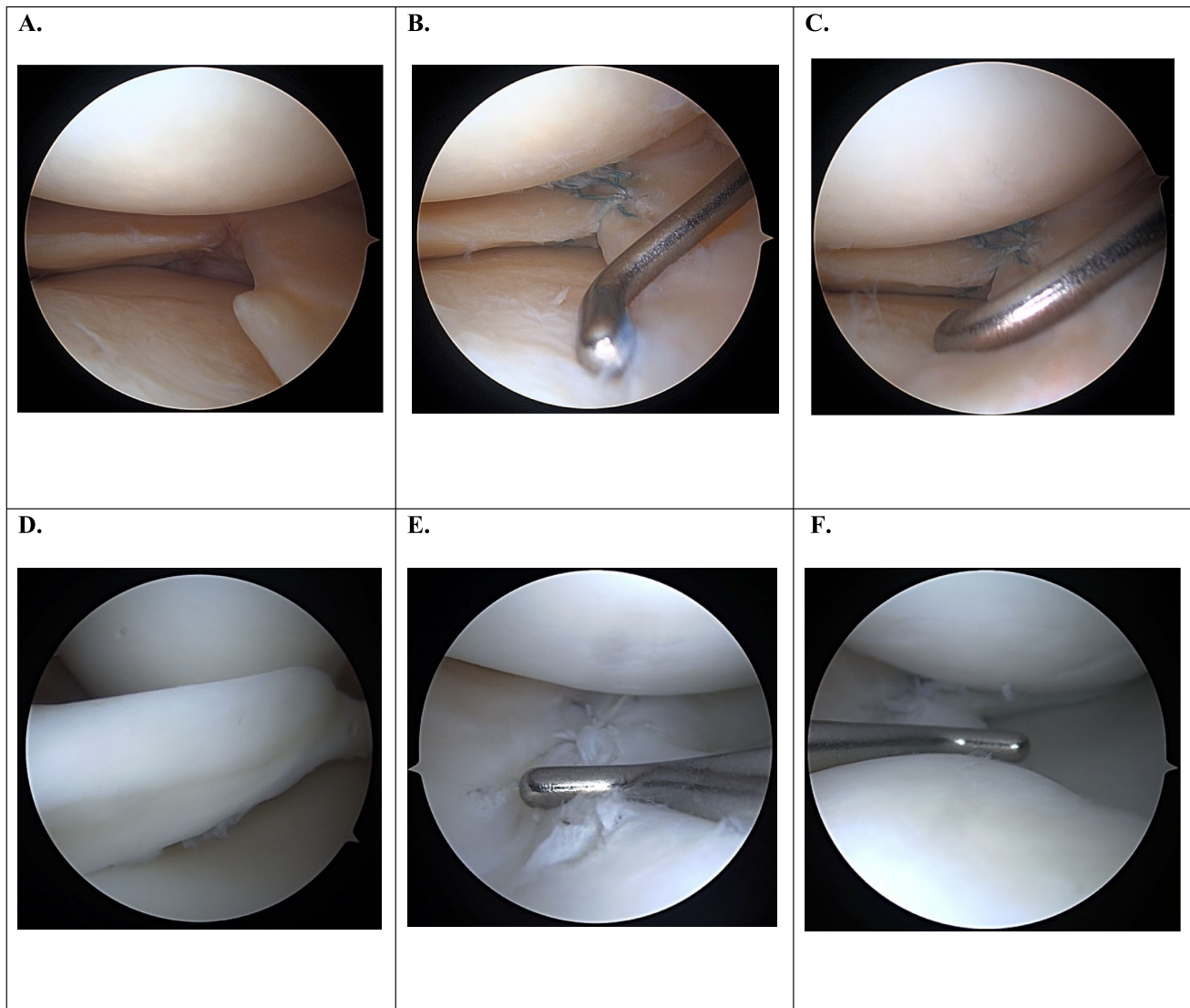


Fig. 8 Arthroscopic Repair of a Large Lateral Meniscus Radial Tear and a Displaced Medial Meniscus Bucket Handle Tear. Arthroscopic view of a left knee lateral meniscus viewing from the anterolateral portal demonstrating **A** Complete radial tear at the junction of the posterior horn and body; **B** and **C** Finished repair of the radial tear

via inside-out tie grip rip stop technique. Arthroscopic view of a left knee medial meniscus viewing from the anterolateral portal demonstrating **D** Displaced bucket handle fragment in the intercondylar notch; **E** and **F** Completed bucket handle tear repair via inside-out technique

protect the repair and ensure longevity of the knee [42]. Contraindications to meniscus repair include subchondral bone collapse, generalized or advanced arthritic changes, and malalignment greater than 5 degrees [42]. Additionally, obesity and milder forms of malalignment can be relative contraindications due to increased stresses placed on the repair [43]. It is important to note that meniscal repair has been associated with a higher rate of reoperation compared with partial meniscectomy, with one systematic review reporting reoperation rates of 16.5% for repair vs 1.4% after meniscectomy at minimum 10 years follow up [44]. A meta-analysis of 27 studies and 1,630 repairs reported an overall failure rate of 19.5% for modern repairs at minimum 5 years

[45]. Factors described to increase failure risk include high BMI, injury chronicity, tear length, and tear location within the relatively avascular white-white Cooper zone 3 [20, 46, 47]. While none of these elements represent absolute contraindications to repair, they should be discussed in detail preoperatively to form realistic patient expectations regarding surgical risks and expected outcomes. Some studies have suggested young age to be a risk factor for repair failure, but further analyses have demonstrated tear location and morphology (i.e. complex multiplanar tears) to impact failure risk more so than age in isolation [48, 49]. Despite higher rates of reoperation compared to meniscectomy, the vast majority of patients maintain high rates of return to

preinjury levels of activity and sustained clinical outcomes over time after meniscus repair [7, 50].

Controversial Topics and Emerging Insights

A The Debate on Meniscus Repair vs. Partial Meniscectomy

The decision between meniscus repair and partial meniscectomy remains a fundamental debate in orthopedic surgery. Historically, partial meniscectomy was the standard treatment for meniscal tears due to its simplicity and relatively short recovery period and return to activity [51]. However, multiple analyses at long-term follow-up have shown that partial meniscectomy is associated with increased risk of radiographic progression of osteoarthritis, as the meniscus plays a crucial role in force distribution and maintaining normal knee kinematics. In their systematic review, Petty et al. showed radiographic signs of osteoarthritis were significant at 8 to 16 years follow up after partial meniscectomy when comparing the contralateral unaffected knee [52]. In all 5 of the included studies in their review, higher incidences of radiographic osteoarthritis were noted post-meniscectomy compared to contralateral control knees as determined by either increased joint space narrowing, IKDC grading, or Fairbank changes [52]. Paradowski et al. performed a postoperative analysis of 221 patients that underwent meniscectomy 15–22 years prior at two separate postoperative time points 4–10 years apart. At the first assessment, 107 of 221 (48%) had developed radiographic tibiofemoral osteoarthritis in the affected knee, which progressed to 151 of 221 (68%) at overall 20–30 year follow up [36]. Among these patients, the incidence of contralateral knee osteoarthritis was 32% [36]. Paxton et al. found evidence of radiographic osteoarthritic degeneration in nearly 40% of patients that underwent partial meniscectomy at minimum 10 years postoperatively [44]. Among the 18 eligible studies that included imaging follow up at greater than 10 years, 78% of meniscus repairs (85 of 109) had no evidence of osteoarthritis on postoperative radiographs compared to 64% (66 of 104) of partial meniscectomies [44]. Additionally, patients that underwent meniscus repair experienced ≤ 1 grade Fairbank change in 97% of cases (106 of 109) compared to 88% for partial meniscectomy (91 of 104) [44].

Meniscus repair seeks to preserve as much tissue as possible with the goal of maintaining the load-sharing capacity of meniscus and reducing the likelihood of articular cartilage degeneration. Evidence suggests that patients who undergo meniscus repair have lower rates of osteoarthritis development, with some studies demonstrating improved maintenance of clinical knee function over time compared to partial meniscectomy [7, 53, 54]. In a series of 81 patients at mean 8.8 years follow up, Stein et al. reported no osteoarthritic

progression was seen in 81% of patients that underwent repair versus 40% after meniscectomy for traumatic isolated medial meniscus tears [54]. In their analysis, an initial mid-term assessment at average 3.4 years revealed no postoperative radiographic differences between repair and meniscectomy cohorts. However, repeat long-term assessment at 8.8 years revealed significantly worsened Fairbanks degenerative changes after meniscectomy compared to repair on postoperative radiographs [54]. Furthermore, this protective affect against osteoarthritis after repair was more pronounced in the younger patient subgroup ≤ 30 years of age [54]. Additionally, meniscectomy was significantly associated with loss of sporting activity at long-term follow up which was not seen after meniscus repair [54]. Return to pre-injury sports activity level was reported at 94.4% after meniscus repair in their series compared to 43.7% after meniscectomy [54]. In their cohort of 217 patients under age 25 years, Duethman et al. reported that IKDC score was greater after lateral meniscus repair than partial meniscectomy at mean 6.1 years follow up [55].

B Impact of Meniscus Repair on Osteoarthritis Development

The primary argument in favor of meniscus repair is its potential to delay or prevent osteoarthritic degeneration and need for total knee arthroplasty (TKA) [56]. The meniscus contributes to joint load distribution, and meniscal pathology can significantly alter knee biomechanics and overall function, leading to progressive cartilage wear [57]. Several clinical studies comparing repaired menisci to those treated with meniscectomy demonstrate a significant decrease in osteoarthritis progression, with patients that underwent meniscus repair showing better preservation of joint space and lower rates of conversion to TKA [58, 59]. In a review of a national clinical database comparing 8,125 patients that underwent meniscus repair and 240,209 patients that underwent partial meniscectomy, Bracey et al. demonstrated a 5 year TKA conversion incidence of 1.7% for repair versus 8.4% for meniscectomy [60]. Risk factors for conversion to TKA were male sex, increased age, obesity, and higher comorbidity index [60]. Similarly, a meta-analysis by Krivicich et al. showed that patients with medial meniscus root tears that underwent repair experienced significantly lower rates of conversion to TKA (9.8%) at 83 months compared to those that underwent meniscectomy (36%) [56]. Cost-analyses have shown that meniscus repair outperforms both nonoperative treatment and partial meniscectomy [58, 59]. In their study, Feeley et al. found that despite an increased failure rate of meniscus repair versus meniscectomy (relative risk of 4.37), repair demonstrated significant reductions in subsequent TKA (19.6% vs 27.9%) and overall discounted savings of \$2,384 [58]. They predicted that if 10% of partial meniscectomies

were performed as repairs, payers could save approximately \$43 million annually [58]. In an analysis of 295,772 patients utilizing a national insurance database, Brands et al. demonstrated that patients with meniscus tears treated with partial meniscectomy generated increased costs compared to nonoperative treatment (\$3842.57 vs \$411.05) and greater incidence of TKA conversion (11.4% at 676 days vs 9.5% at 402 days) [61]. However, surgical repair does not guarantee meniscus healing and prevention of osteoarthritic degeneration in the affected compartment. Several factors influence long-term outcomes, including surgical technique, patient age and medical comorbidities, and the presence of concurrent injuries such as ACL tears [7, 62–65]. Some studies suggest that even with successful surgical repair, subtle biomechanical and molecular changes persist, potentially accelerating cartilage wear and leading to eventual healing failure over time [66]. Moreover, rates of healing vary based on tear location, with peripheral tears (red-red zone) healing more predictably than avascular central tears (white-white zone) [67]. Therefore, while meniscus repair has demonstrated superior outcomes compared to meniscectomy in terms of preserving overall joint integrity and function over time, continued research is needed to fully assess the long-term impact of surgical repair on the development of osteoarthritis.

III. Influence of Age, Concomitant Knee Pathology, and Comorbidities

Patient-specific factors significantly influence the outcomes of meniscus repair. Older patients were traditionally thought to have a lower likelihood of success after meniscus repair due to known decreases in vascularity of the meniscus overtime, as well higher prevalence of degenerative changes with increasing age [68, 69]. However, multiple clinical analyses have demonstrated that age alone is not clinically associated with increased risk of failure after meniscus repair [48, 70–73]. In a cohort study evaluating meniscus repair in patients older than 40 years versus those younger than age 40 at minimum 10 years follow up, Steadman et al. reported no differences in failure rate, outcome scores, or subsequent revision knee arthroscopy or TKA [48]. Sedgwick et al. reported in a meta-analysis including 14 studies that meniscal repair failure rate in patients over age 40 was 12% and rate of revision surgery was 9.8%, both similar to repair failure and revision rates in patients under 40 [74]. Successful outcomes of meniscus repair have even been demonstrated in cohorts of patients over age 60, with superior clinical outcome scores than a comparative cohort that underwent partial meniscectomy at average 42 month follow up [75]. Therefore, patient age should not be considered a contraindication to meniscus repair.

A comprehensive, individualized approach evaluating multiple patient factors is optimal when considering

meniscus repair. Assessing for concomitant knee pathology such as mechanical malalignment, tear chronicity and location, and articular cartilage damage are critical, as all of these issues can significantly impact the success of repair [76, 77]. Associated medical comorbidities, such as obesity, diabetes mellitus, and smoking history can also negatively influence the outcome of meniscus repair [60, 65, 78]. In a clinical series of 78 patients that underwent repair of posterior horn longitudinal vertical meniscus tears, Tschopp et al. reported that varus malalignment $\geq 5^\circ$ was significantly associated with nonhealing [77]. Additionally, the combination of medial laterality and varus malalignment both significantly increased the risk of failure to heal and decreased clinical outcome scores [77]. A long-term study by Chung et al. followed 37 patients that underwent medial meniscus root repair for over 10 years and similarly found that preoperative mechanical varus alignment and persistent meniscal extrusion predicted clinical failure after root repair [79]. A retrospective analysis of 444 patients by Blackwell et al. demonstrated that meniscus repair failure risk was significantly increased among patients that smoked compared to non-smokers [65]. Increased Charlson Comorbidity Index and overall medical comorbidity burden have been associated with increased failures and adverse events after meniscus repair [60, 78].

Personal Observations and Clinical Insights

A Authors' Experience with Long-Term Outcomes

In our practice, we believe a modern evidence-based approach to the treatment of meniscus tears is centered around meniscus preservation in the properly indicated patient. Clinical evidence is clear that persistent meniscus dysfunction and decreased meniscus volume via partial meniscectomy has deleterious effects on knee kinematics and articular cartilage long-term [41, 54, 80, 81]. Certain tears such as medial meniscus posterior root tears (Fig. 9) fare particularly poorly with nonsurgical treatment or partial meniscectomy, with rapid arthritic deterioration and high rates of conversion to arthroplasty at 10 years [80, 82]. Several investigations have demonstrated maintenance of overall successful clinical outcomes with repair of various meniscus tear patterns among multiple populations at long term follow up, even in revision settings [49, 83–85]. Choosing the right candidates for repair is crucial for achieving a successful outcome. While younger patients with acute, peripheral tears may fare best with repair, modern evidence suggests this is not the only population that may experience the benefits of surgical repair compared to traditional treatments [63, 74, 75]. We prefer a comprehensive, individualized approach to each patient assessing the age, medical comorbidities, social

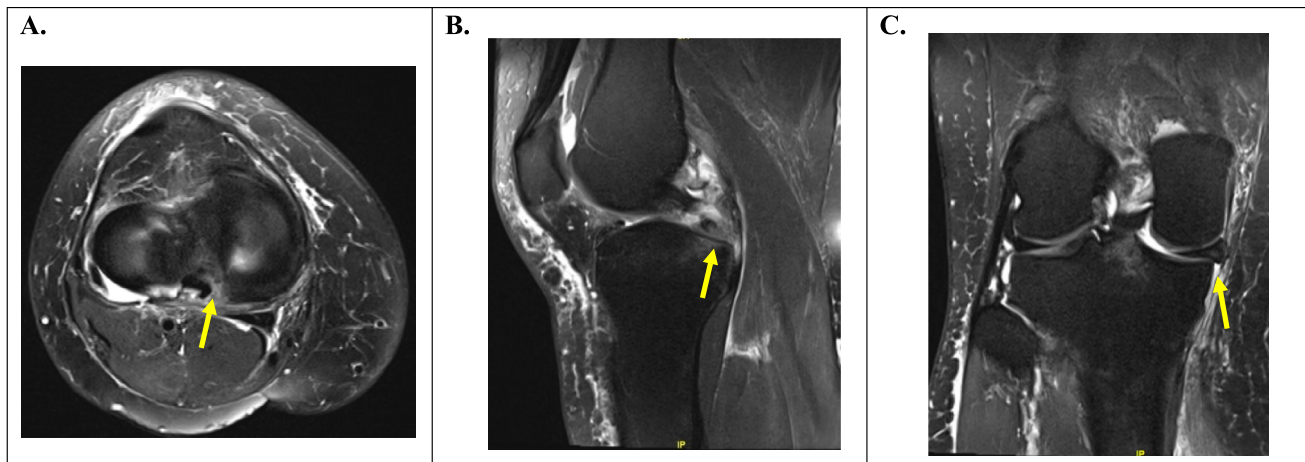


Fig. 9 Medial Meniscus Posterior Root Tear with Meniscus Extrusion. STIR MRI sequences demonstrating a medial meniscus posterior root tear (yellow arrow) in the A) Axial sequence demonstrating root detachment with abnormal signal at the attachment site; B)

Sagittal sequence with absence of meniscus tissue at the posterior root attachment site and associated subchondral edema; C) Coronal sequence demonstrating > 3 mm of meniscus extrusion

situation, mechanical alignment, concomitant intra-articular pathology, overall cartilage status, and tissue quality, in addition to meniscus tear location and morphology. An in-depth analysis of all these factors is requisite to provide accurate patient counseling and establish well-informed, realistic patient expectations regarding recovery time, meniscus healing potential, possible need for reoperation or revision surgery, and return to activities. In the setting of a well-informed patient with a relatively healthy knee willing to undergo dedicated rehabilitation, we advocate for meniscus repair whenever possible.

B Unresolved Questions and Future Directions

Despite advancements in meniscus repair, several unanswered questions remain. The lateral meniscus oblique radial tear (LMORT) is a particular type of lateral meniscus tear found concomitantly with ACL injury with a reported incidence of 12% (Fig. 10) [86]. Optimal treatment depends on specific tear classification, but biomechanical studies report beneficial effects on knee kinematics and stability after surgical repair [87, 88]. Early clinical trials have been conducted showing promising results after LMORT repair, but larger prospective trials are necessary to establish ideal treatment for each tear type and whether repair maintains successful outcomes at long-term follow up [89, 90]. Biologic augmentation to increase tear healing potential is another area with much potential for future innovation. While various promising techniques have been described including PRP, fibrin clots, and MSCs derived from bone marrow, synovial tissue, and adipose tissue, among others, none have demonstrated clear clinical superiority compared

to standard meniscus repair alone [91–93]. Further research is needed in this realm to produce cost-effective methods to augment meniscus healing with low comorbidity to the patient. Finally, even with modern advancements in imaging techniques, it has been shown that meniscus pathology can remain undetected as a surprising rate prior to diagnostic arthroscopy [94]. Emerging technologies such as machine learning and artificial intelligence have been shown to outperform traditional models for detecting pathology on imaging, as well as predicting risk of injury and failure after certain procedures [95–98]. Further resources dedicated to these technologies may help surgeons more accurately diagnose injuries, provide comprehensive preoperative counseling, and potentially choose optimal treatment in years to come.

Conclusion

Meniscus repair has emerged as the preferred approach for treating many meniscal tears due to its ability to preserve native knee kinematics and decrease risk of osteoarthritic progression. Long-term clinical data supports meniscus repair over traditional treatments such as partial meniscectomy in properly indicated patients. Variability in healing rates among tear morphologies, patient-specific factors, and emerging repair technologies are major areas of active research. Undertaking a comprehensive, individualized approach considering patient selection, surgical technique, and optimal rehabilitation for each case is critical to guiding treatment decisions and achieving long-term success.

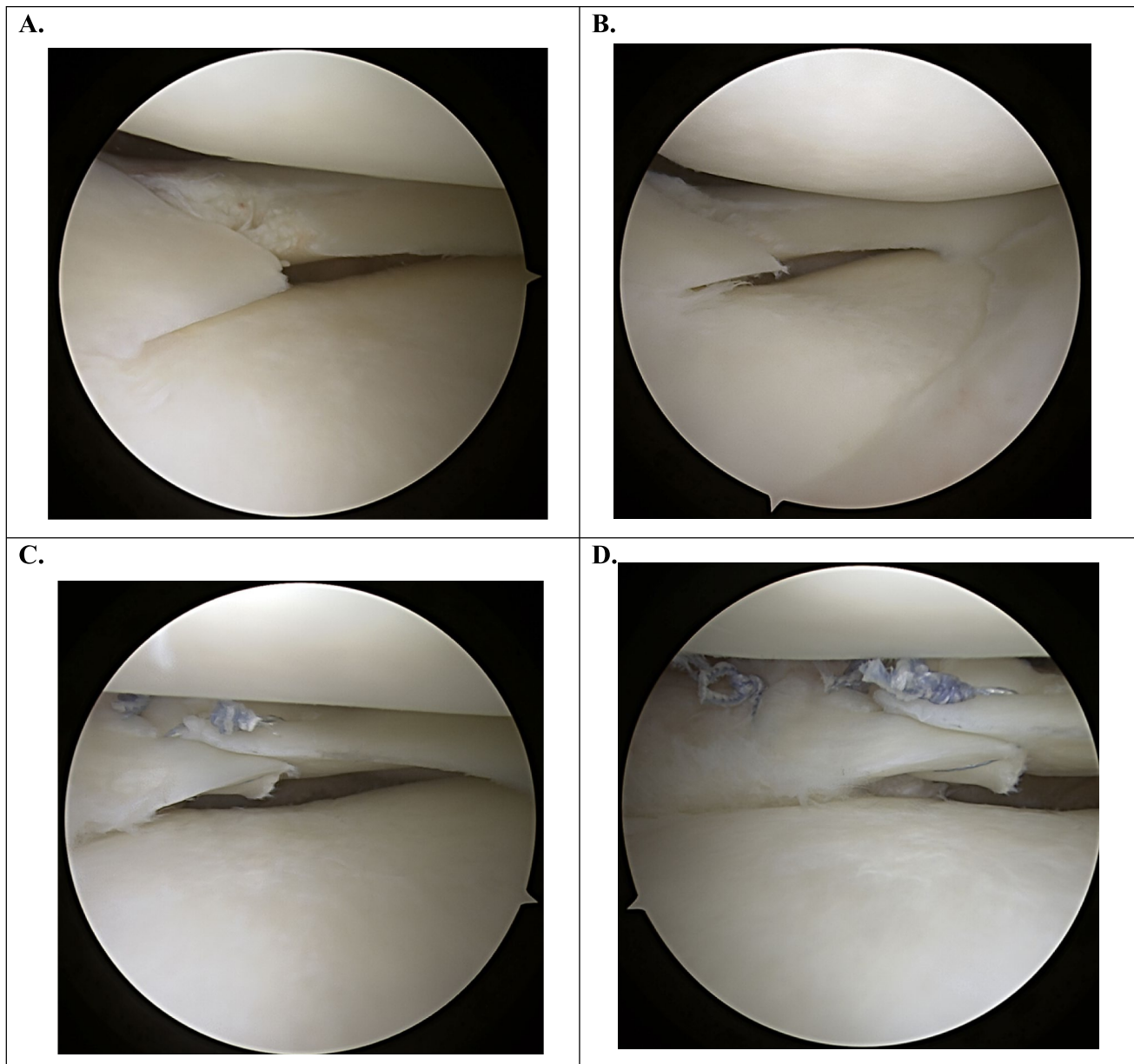


Fig. 10 Lateral Meniscus Oblique Radial Tear (LMORT) Repair. Arthroscopic view of a left knee lateral meniscus during anterior cruciate ligament reconstruction demonstrating A) and B) Full-Thickness

LMORT Type 4 tear of the lateral meniscus; C) and D) Completed LMORT repair using all-inside techniques with a self-retrieving suture passage device and arthroscopic knot-tying

Key References

This reference was important because it documents that meniscus root repair leads to less arthritic progression compared to partial meniscectomy.

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- This reference was important as it demonstrated overall good to excellent long-term clinical outcomes after isolated meniscal repair.
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- This reference was important because it demonstrated post-operative PROMs (IKDC) was greater after repair compared to meniscectomy.
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 - This study was important as it showed a high rate of progression to TKA following partial medial meniscectomy.
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 - This reference was important as it documented long-term outcomes after meniscal repair with concomitant anterior cruciate ligament reconstruction.
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 - This study was important as it documented long-term outcomes following radial and bucket-handle meniscal tear repairs.
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 - This study was important as it shows new meniscal tear patterns as well as a biomechanical analysis.
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Declarations

Conflict of interest Brandon Cabarcas, Emily Peairs, Sanathan Iyer, and Jason Ina declare that they have no conflict of interest. Mario Hevesi: DJO – Enovis: Paid consultant; Elsevier: Publishing royalties, financial or material support; Journal of Cartilage and Joint Preservation: Editorial of governing board; Moximed: Paid consultant; Vericel: Paid consultant. Adam J. Tagliero: American Orthopaedic Society for Sports Medicine: Board or committee member. Aaron J. Krych: American Journal of Sports Medicine: Editorial or governing board; Arthrex, Inc: IP royalties, Paid consultant; Arthroscopy Association of North America: Board or committee member; International Cartilage Repair Society: Board or committee member; Springer: Editorial or governing board.

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