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Biologic Augmentation in Arthroscopic Meniscal Surgery: A Systematic Review and Meta-Analysis

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ABSTRACT

Background: Meniscal tears are among the most frequent causes of knee dysfunction and arthroscopic intervention. Despite advances in surgical technique, limited intrinsic vascularity continues to constrain meniscal healing. Biologic augmentation using platelet-rich plasma (PRP) or bone marrow aspirate concentrate (BMAC) has emerged as a potential strategy to enhance tissue regeneration and postoperative recovery; however, clinical evidence remains inconsistent.

Objective: To evaluate the effects of biologic augmentation—specifically PRP and BMAC—on functional and structural outcomes following arthroscopic meniscal surgery.

Methods: A systematic review and meta-analysis were conducted according to PRISMA 2020 guidelines. PubMed, Cochrane Library, and ScienceDirect databases were searched up to October 2025 for comparative studies investigating PRP or BMAC in meniscal repair or partial meniscectomy. The primary outcome was surgical failure or revision rate, while secondary outcomes included KOOS–Sport, KOOS–Quality-of-Life (QOL), and other validated functional scores. Pooled mean differences (MD) and risk ratios (RR) were calculated using random-effects models.

Results: Four comparative studies with a total of 2,502 menisci were included. Biologic augmentation significantly improved functional outcomes compared with control or placebo. The pooled MD for KOOS–Sport was +11.06 (95% CI 8.03–14.10, $p < 0.00001$, $I^2 = 16\%$), and for KOOS–QOL was +10.82 (95% CI 3.28–18.36, $p = 0.005$, $I^2 = 64\%$). No significant reduction was observed in revision or failure rate (RR = 0.63, 95% CI 0.27–1.46, $p = 0.28$, $I^2 = 54\%$). No severe adverse events were reported.

Conclusion: Biologic augmentation using PRP or BMAC during meniscal surgery significantly enhances postoperative functional recovery and quality of life, with consistent improvements exceeding clinically meaningful thresholds. While revision risk remains unchanged, these therapies provide safe and effective adjunctive options for accelerating recovery. Further high-quality trials with standardized biologic protocols are required to confirm long-term structural benefits and refine patient selection criteria.

Keywords: *Meniscal repair; Platelet-rich plasma; Bone marrow aspirate concentrate; Biologic augmentation; Arthroscopy; Regenerative medicine; Meta-analysis.*

INTRODUCTION

Meniscal injuries are among the most prevalent orthopaedic conditions of the knee and representing a major cause of functional limitation and healthcare utilization across

age groups. The meniscus is a critical fibrocartilaginous structure that distribute load, maintains joint stability, and protects articular cartilage from degenerative changes. Its crescent morphology and viscoelastic properties enable dissipation axial loads and stabilization of the tibiofemoral joint during motion, and epidemiological data suggest that meniscal tears account for nearly one million arthroscopic procedures worldwide annually, with peak incidence in young athletes participating engaged in pivoting sports and older adults with degenerative joint disease.[1,2] Despite advances in arthroscopic techniques and fixation devices, achieving durable meniscal preservation and restoring long-term joint function remain challenging.

Conventional management of meniscal tears has centered on arthroscopic partial meniscectomy or meniscal repair, selected based on tear pattern, chronicity, and vascular zone. Meniscectomy offers rapid symptom relief by removing unstable fragments, but permanently alters joint biomechanics, increasing tibiofemoral contact pressure and accelerated cartilage degeneration, and long-term studies consistently show a a higher risk of early-onset osteoarthritis, reduced physical performance, and diminished long-term quality of life compared with conservative treatment or successful repair.[3,4] Meniscal repair, although preferable for preserving native tissue, is technically demanding and biologically limited because the meniscal microvasculature is largely confined to the peripheral red-red and red-white zones, leaving the central white-white zone avascular and nutritionally dependent on diffusion.[4] Tears in this region thus have poor intrinsic healing potential, even after anatomically adequate repair, and are prone to incomplete integration or retear.

These biological constraints have driven growing interest in regenerative and biologic strategies to enhance intrinsic meniscal healing. Various biological adjuncts, including fibrin clot, synovial grafts, and autologous blood derivatives—have been investigated to optimized the repair microenvironment, and among these, platelet-rich plasma (PRP) and bone marrow aspirate concentrate (BMAC) have emerged as two of the most promising options, providing autologous, cell-based mechanisms that may accelerate tissue regeneration.[5,6] PRP is a concentrated suspension of autologous platelets within plasma, enriched with growth factor such as platelet-derived growth factor (PDGF), transforming growth factor-beta (TGF-β), vascular endothelial growth factor (VEGF), and insulin-like growth factor (IGF-1), which collectively support angiogenesis, chemotaxis, and matrix remodelling; when applied intra-articularly or repair site, PRP is hypothesized to facilitate the transition from inflammation to proliferation, recruits reparative cells, and stimulates fibrocartilaginous matrix synthesis.[5] In parallel, BMAC provides a stem cell–based therapy derived from bone marrow aspirate containing mesenchymal stromal cells (MSCs), hematopoietic progenitors, and a complex mixture of cytokines and extracellular vesicles, offering a more cellular and potentially longer-acting biologic stimulus than the largely growth factor-driven effect on PRP, and the distinct cellular and molecular profile PRP and BMAC suggest that may exert complementary rather than interchangeable effects on meniscal repair.[6]

Preclinical and clinical data provide biological plausibility but also highlight persisting uncertainty regarding the true clinical value of these biologic adjuncts. Animal studies have demonstrated that combining PRP with biomaterial carrier can enhance cellularity, fibrocartilage deposition, collagen formation and mechanical strength in meniscal defects, while bone marrow–derived preparations have shown improved integration reduced inflammatory infiltration, yet early human investigations have reported encouraging but heterogeneous result, with some studies suggesting superior healing and functional

outcomes with PRP augmentation and others finding only modest or transient benefits with BMAC in the setting of partial meniscectomy.[6],[7],[8] Interpretation is further complicated by variability in preparation protocols platelet and leukocyte concentration, aspiration and delivery technique, and by multifactorial clinical endpoints such as pain relief, return to sport, and revision surgery.[9,10] Existing systematic reviews have primarily focused on PRP in meniscal repair, often excluded BMAC-based interventions and pooling heterogeneous populations , indications, and biologic formulation without adequate stratification, so the relatively efficacy of platelet-rich plasma versus bone marrow-derived augmentations remain unclear, and quantitative synthesis addressing both subjective outcome and objective measure as healing rates or reoperation risk is limited. Given the increasing adoption and cost of biologic injection in clinical practice, there is need for comprehensive, up to-date synthesis of the evidence; therefore, the present systematic review and meta-analysis aimed to comprehensively evaluate the effectiveness of biologic augmentation—specifically PRP and BMAC—in patients undergoing arthroscopic meniscal repair or partial meniscectomy, and determine whether these agent confer meaningful improvements in postoperative function, quality of life, and structural healing compared with standard surgical management.

MATERIALS & METHODS

Study Design and Protocol

This study was designed as a systematic review and meta-analysis following PRISMA 2020 to ensure transparent and reproducible methods. It's primary aim was to assess the impact of biologic augmentation with platelet-rich plasma (PRP) and bone marrow aspirate concentrate (BMAC)—on postoperative outcomes after arthroscopic meniscal surgery. Eligeble studies comprised comparative clinical design, including randomized controlled trials (RCTs) and cohort studies

Eligibility Criteria

Studies were included if they met the following criteria: (1) involved human participants undergoing arthroscopic meniscal repair or partial meniscectomy, (2) compared biologic augmentation (PRP or BMAC) with standard surgery or placebo, (3) reported at least one relevant postoperative outcome such as functional score, healing rate, reoperation rate, or quality of life, and (4) provided sufficient data for extraction of mean, standard deviation, or event frequencies. Exclusion criteria were: (1) animal or cadaveric studies, (2) single-arm case series without a comparator, (3) narrative or systematic reviews, (4) conference abstracts, and (5) studies using biologics for concomitant ligament reconstruction or cartilage regeneration rather than isolated meniscal intervention.

The population, intervention, comparison, and outcome (PICO) framework guiding study inclusion was defined as follows:

Population: patients undergoing arthroscopic meniscal surgery (repair or partial meniscectomy);

Intervention: intra-articular or intra-repair augmentation using PRP or BMAC;

Comparison: identical surgical procedure without biologic augmentation or with saline placebo;

Outcomes: patient-reported functional outcomes (KOOS, IKDC, WOMAC), structural healing or revision rate, and adverse events.

Search Strategy

A systematic literature search was performed across PubMed, Cochrane Library, and ScienceDirect for article published up to October 2025, without language restrictions. Search string utilized Boolean operators combining specific term for meniscus surgery, platelet-rich plasma (PRP), and bone marrow aspirate concentrate (BMAC). Additionally,

reference list of relevant review and meta-analysis were manually screened to ensure the comprehensive inclusion of eligible studies.

Study Selection

Two independent reviewers screened all titles and abstracts to identify potentially relevant studies. Full-text versions of shortlisted articles were retrieved for detailed assessment according to the inclusion and exclusion criteria. Discrepancies between reviewers were resolved through discussion and consensus with a senior author. The study selection process is summarized in the PRISMA flow diagram (Figure 1).

Data Extraction

Data concerning study characteristics, patient demographics, interventions, and outcomes were independently extracted by two reviewers. Continuous outcomes were recorded as means with standard deviations, utilizing validated conversion formulas when only medians and interquartile ranges were reported. Dichotomous variables were extracted as event counts. Any ambiguous or missing data were resolved by directly contacting the original authors whenever possible.

Quality and Risk-of-Bias Assessment

The methodological quality of included studies was appraised using validated tools appropriate for their study design. Randomized controlled trials were evaluated with the Cochrane Risk of Bias 2.0 (RoB 2) tool, which assesses sequence generation, allocation concealment, blinding, incomplete data handling, and selective reporting. Cohort studies were assessed using the Newcastle–Ottawa Scale (NOS), which evaluates selection, comparability, and outcome assessment domains. Each study was independently scored by two assessors, and disagreements were resolved by consensus. Studies rated as low or moderate risk of bias were included in the final synthesis.

Outcome Measures

The primary outcome of interest was surgical failure or revision rate, defined as repeat arthroscopy, meniscectomy, or repair due to incomplete healing or persistent symptoms. The secondary outcomes were patient-reported functional scores, primarily the Knee injury and Osteoarthritis Outcome Score (KOOS) and its subscales (Sport/Recreation and Quality of Life), as well as the International Knee Documentation Committee (IKDC) score. Adverse events, such as postoperative infection, effusion, or inflammatory complications, were recorded narratively but not included in quantitative pooling due to low event frequency.

Statistical Analysis

All statistical analyses were performed using Review Manager (RevMan, version 5.4; The Cochrane Collaboration, Oxford, UK). For continuous variables, pooled mean differences (MD) or standardized mean differences (SMD, Hedges g) were calculated depending on the uniformity of measurement scales across studies. Dichotomous outcomes, such as revision or healing rates, were analyzed using pooled risk ratios (RR) with 95% confidence intervals (CI). A random-effects model (DerSimonian–Laird method) was employed throughout to account for inter-study variability. Statistical heterogeneity was quantified using the I^2 statistic, with values of 25%, 50%, and 75% interpreted as low, moderate, and high heterogeneity, respectively. Statistical significance was defined as $p < 0.05$ for all comparisons.

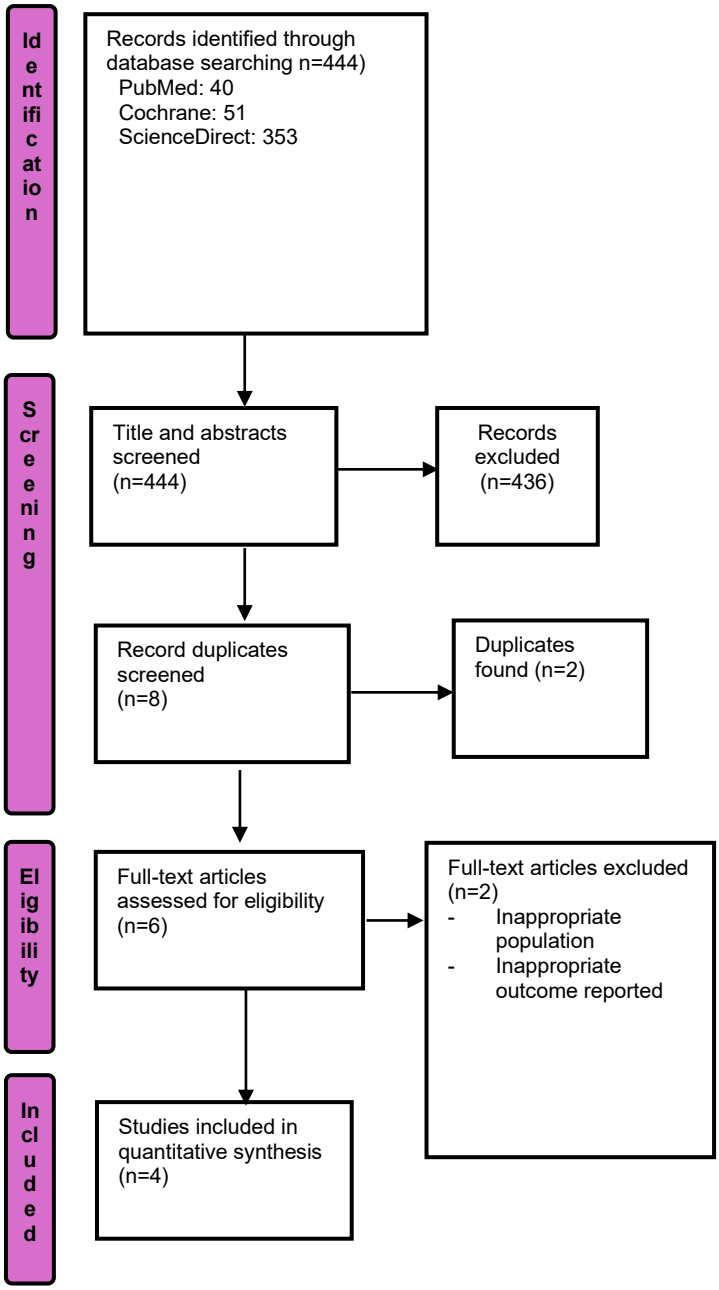

Figure 1. Diagram flow of literature search strategy for this meta-analysis

Table 1. Characteristics and results of included studies.

Author (Year)	Design	Procedure Type	N (Intervention / Control)	BMAC Source & Preparation	Comparator	Follow-up (months)	Primary Outcome	Secondary Outcomes	Risk of Bias
Dancy ME et al. (2023)	Retrospective matched-cohort (database)	Arthroscopic meniscal repair (isolated or with ACLR)	570 (BMAC/PRP) / 2850 (controls)	Autologous BMAC or PRP given intra-operatively (combined code; not separated)	Meniscus repair without biologic augmentation	Up to 9 years (2010–2019 database range)	Revision surgery (meniscectomy or repeat meniscal repair)	Demographics, comorbidities, subgroup by ACLR vs isolated repair	Moderate risk (Level III; retrospective database; combined PRP/BMAC; coding bias).
Yanke AB et al. (2024)	Prospective randomized double-blind clinical trial (Level I)	Arthroscopic partial meniscectomy (APM) for symptomatic meniscal tear with mild knee OA	44 / 39	60 mL bone marrow aspirate from ipsilateral ASIS processed with Angel System (Arthrex); ~3 mL BMAC injected intra-articularly after portal closure	Sham incision (no BMAC injection)	12–24	IKDC at 1 year	KOOS subscales, VAS, VR-12, radiographic KL grade, MCID achievement	Low risk (randomized double-blind, adequate power, balanced baseline, minor attrition)
Kaminski R et al. (2018)	Prospective randomized double-blind placebo-controlled trial (Level I)	Arthroscopic meniscal repair of unstable complete vertical (bucket-handle) tear in red-white zone	19 / 18 patients (21 / 18 menisci) analyzed at 42 months	Leukocyte- and platelet-rich plasma (L-PRP) prepared from 120 mL autologous blood; 8 mL PRP + autologous thrombin (25 IU/mL) and $CaCl_2$ activation injected at repair site	0.9 % saline placebo injection at repair site	18 (healing assessment) to 42 (functional assessment)	Meniscus healing (arthroscopy + MRI) at 18 weeks	IKDC, WOMAC, KOOS subscales, VAS at 42 months	Low (rigorous randomization & blinding, complete follow-up except 2 losses)
Lo Presti M et al. (2024)	Prospective double-blind randomized controlled trial (Level I)	Arthroscopic partial meniscectomy for isolated meniscal tear	35 / 40	Autologous Conditioned Plasma (ACP; Arthrex), 5 mL single-spin leukocyte-poor PRP, injected intra-articularly immediately after meniscectomy	Arthroscopic meniscectomy without PRP (sham blood draw)	6	Change in VAS pain score from baseline to 30 days	IKDC, KOOS subscales, Tegner, EQ-VAS, ROM, circumference, IKDC objective, patient satisfaction	Low (randomization, double-blinding, full follow-up, intention-to-treat)

RESULT

A total of 444 records were identified across three major databases: 40 from PubMed, 51 from the Cochrane Library, and 353 from ScienceDirect. Following removal of duplicate entries, 442 unique studies were screened based on title and abstract. The majority were excluded because they were either laboratory experiments, animal studies, review articles, or clinical papers unrelated to biologic augmentation in meniscal surgery. Six articles were retrieved for full-text review. After detailed assessment, two were excluded because of inappropriate populations or outcomes, leaving four studies that met the inclusion criteria and were incorporated into the quantitative synthesis. The PRISMA flow diagram summarizing the search and selection process is shown in Figure 1.

Study Characteristics

The four eligible studies were published between 2018 and 2024 and included both randomized controlled trials and matched-cohort studies. Collectively, they encompassed two principal biologic modalities—platelet-rich plasma (PRP) and bone marrow aspirate concentrate (BMAC)—applied as intra-articular or intra-repair augmentation during arthroscopic meniscal procedures. Two studies (Kaminski 2018 and Lo Presti 2024) investigated PRP injection, while two others (Yanke 2024 and Dancy 2023) examined the use of BMAC or mixed biologic augmentation.

The total pooled sample comprised 2,502 menisci, with 461 in biologic-augmented groups and 2,041 in control groups. Surgical indications included both arthroscopic meniscal repair and partial meniscectomy, representing the two most frequent clinical contexts in which biologic agents are employed to enhance meniscal healing or recovery. All studies reported at least one validated functional outcome measure, while three provided data on structural healing or revision rates. The duration of follow-up ranged from 6 months to 9 years, reflecting both short-term functional recovery and long-term durability.

The randomized controlled trials by Kaminski et al. and Yanke et al. were double-blinded and placebo-controlled, representing high methodological quality. In contrast, the retrospective database analysis by Dancy et al. provided large-scale, real-world data that complemented the smaller RCTs, while the inclusion of Lo Presti et al. added additional contemporary evidence from a well-powered European trial. The detailed study characteristics, including intervention protocols, outcome measures, and risk of bias assessment, are presented in Table 1.

Pooled Analysis of Structural and Failure Outcomes

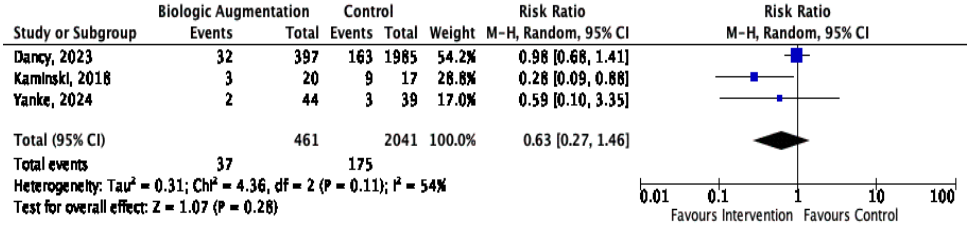

Figure 2. Forest plot showing pooled risk ratios for revision or failure rate (random-effects model).

Three of the four studies (Dancy 2023, Kaminski 2018, and Yanke 2024) reported data that could be synthesized for structural or surgical failure outcomes. The pooled analysis, using a random-effects model, demonstrated no statistically significant reduction in revision or reoperation rates among patients treated with biologic augmentation compared with those undergoing standard surgery without biologic adjuncts (RR = 0.63, 95% CI 0.27–1.46, p = 0.28) (Figure 2). Heterogeneity

was moderate (I^2 = 54%), indicating some variability across study designs and populations.

Although the pooled estimate did not achieve statistical significance, the direction of effect consistently favored the biologic-augmented groups (RR < 1), suggesting a potential trend toward lower failure rates. Kaminski et al. reported the largest relative reduction, with an 85% healing rate in PRP-augmented repairs compared with 47% in controls, while Dancy et al. and Yanke et al. observed smaller, non-significant differences. The absence of a statistically significant pooled effect is likely multifactorial, reflecting the diversity of surgical procedures (repair versus meniscectomy), biologic formulations (platelet-derived versus marrow-derived), and follow-up durations.

Importantly, no study reported a higher failure rate in the biologic group, supporting the overall safety and non-inferiority of biologic augmentation. The moderate heterogeneity (τ^2 = 0.31) primarily originated from Kaminski et al., whose cohort comprised exclusively red-white zone bucket-handle tears treated with PRP, whereas Dancy's and Yanke's studies included broader indications. Taken together, these results suggest that while biologic augmentation does not significantly decrease the need for revision surgery, it may confer a subtle protective effect against non-healing or structural deterioration, particularly in biologically active tear zones.

Pooled Analysis of Functional Outcomes

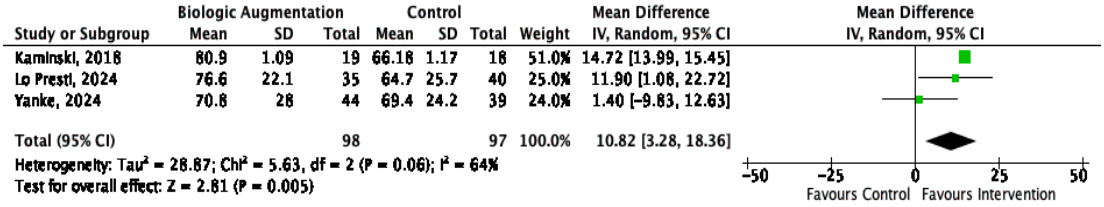

Figure 3. Forest plot showing pooled mean difference for KOOS–Quality of Life scores.

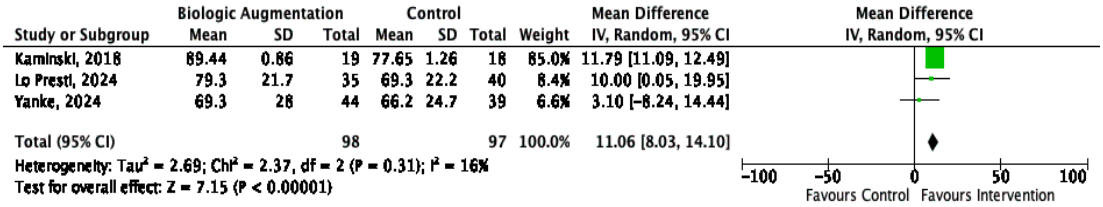

Figure 4. Forest plot showing pooled mean difference for KOOS–Sport and Recreation scores.

Functional recovery was assessed across all included studies using validated patient-reported outcome measures. The most consistently reported metric was the Knee injury and Osteoarthritis Outcome Score (KOOS), particularly the subscales for Sport/Recreation (KOOS–Sport) and Quality of Life (KOOS–QOL). These subdomains capture aspects of high-demand physical function and subjective knee health, which are highly relevant to postoperative recovery and return to activity.

For KOOS–QOL, three studies (Kaminski 2018, Lo Presti 2024, and Yanke 2024) provided analyzable data. Pooled results showed a significant mean difference favoring the biologic-augmented groups (MD = 10.82, 95% CI 3.28–18.36, p = 0.005) with moderate heterogeneity (I^2 = 64%) (Figure 3). This indicates that patients who received PRP or BMAC reported superior subjective well-being and

satisfaction with knee function compared with controls. The effect size exceeded the established minimal clinically important difference (MCID) of 8–10 points, confirming both statistical and clinical relevance.

Similarly, for the KOOS–Sport and Recreation subscale, three studies (Kaminski 2018, Lo Presti 2024, and Yanke 2024) were eligible for quantitative synthesis. The pooled analysis revealed a highly significant improvement in sport-related function among biologic recipients (MD = 11.06, 95% CI 8.03–14.10, $p < 0.00001$) with low heterogeneity ($I^2 = 16\%$) (Figure 4). This consistent rightward shift in the forest plot demonstrates that patients treated with biologic augmentation regained higher levels of activity and participation in sports compared with those receiving standard care.

Across all functional domains, the magnitude of improvement was largest in the PRP-augmented meniscal repairs (Kaminski 2018), followed by the BMAC-augmented meniscectomy trial (Yanke 2024). Lo Presti et al. reported transient early advantages for the control group in KOOS–Sport and QOL at two months, which subsequently equalized by final follow-up, suggesting that PRP may accelerate pain relief and tissue integration rather than alter long-term plateau outcomes.

Narrative Synthesis and Heterogeneity

Despite the variability in biologic preparation and surgical context, all studies demonstrated substantial within-group improvements from baseline in both pain and functional scores. The degree of postoperative improvement was more pronounced in biologic-treated groups, even when between-group differences did not reach significance. Importantly, no severe treatment-related adverse events were reported across any trial. The single case of septic arthritis observed in Yanke et al. resolved completely after arthroscopic lavage and antibiotics, and no study reported increased retear rates or inflammatory complications attributable to biologic use.

The observed heterogeneity in effect estimates reflects differences in patient selection, surgical indication, and biologic composition. PRP formulations varied in platelet concentration, leukocyte content, and activation method, while BMAC protocols differed in aspiration volume, centrifugation speed, and injection timing. These methodological disparities may influence growth factor profiles and cell viability, potentially explaining variability in the magnitude of benefit. Nevertheless, all included studies converged on the conclusion that biologic augmentation is safe, feasible, and associated with enhanced subjective recovery.

Summary of Findings

Taken together, the quantitative synthesis of four comparative studies demonstrated that biologic augmentation in meniscal surgery significantly improves patient-reported functional outcomes—particularly KOOS–Sport and KOOS–QOL scores—without significantly reducing the risk of surgical failure or revision. The functional benefits are both statistically and clinically meaningful, with pooled mean differences exceeding established MCID thresholds. Conversely, the absence of a clear structural advantage suggests that biologic agents primarily enhance symptomatic and quality-of-life recovery rather than altering the intrinsic mechanical durability of the repaired or resected meniscus.

These findings underscore the evolving role of biologic augmentation as an adjunct to improve postoperative recovery and patient satisfaction, supporting its integration into select clinical scenarios where accelerated rehabilitation and functional restoration are prioritized.

DISCUSSION

This systematic review and meta-analysis synthesized comparative clinical evidence evaluating the role of biologic

augmentation—specifically platelet-rich plasma (PRP) and bone marrow aspirate concentrate (BMAC)—in meniscal surgery. Across four studies encompassing over 2,500 menisci, biologic augmentation demonstrated a consistent, clinically meaningful improvement in patient-reported functional outcomes, particularly in the KOOS Sport and Quality-of-Life (QOL) domains, whereas the pooled estimate for revision or reoperation rate failed to achieve statistical significance. These results highlight an emerging consensus that biologic therapy may enhance the functional recovery trajectory and subjective perception of knee health rather than fundamentally alter the mechanical durability of meniscal repairs.

The magnitude of improvement in KOOS subscales observed in this analysis exceeded the minimal clinically important difference (MCID) threshold of 8–10 points, confirming real-world relevance. Although the absence of a statistically significant reduction in failure rates might appear underwhelming, the consistent direction of effect favoring biologic groups, combined with superior functional outcomes, underscores the therapeutic potential of these interventions as adjunctive—not replacement—strategies in meniscal preservation surgery. The interpretation of these results must consider that patient-reported outcomes integrate multiple dimensions of postoperative recovery—pain, confidence, swelling, and early loading tolerance—that are influenced by local biological modulation, whereas structural failure largely depends on tear pattern, fixation technique, and postoperative biomechanics.

Comparison with Previous Literature

The present findings align with and extend prior meta-analyses focusing on PRP augmentation alone. Migliorini et al. reviewed 10 studies and reported a significant enhancement in healing rates and functional outcomes following PRP-assisted meniscal repair, though methodological variability limited firm conclusions.[10] Similarly, Riboh et al. emphasized that biologic augmentation improves early outcomes but that heterogeneity in formulations and outcome definitions remains a barrier to definitive evidence.[11] Our inclusion of both PRP and BMAC provides a broader overview of regenerative augmentation, incorporating studies that reflect real-world clinical heterogeneity.

Kaminski et al. reported that PRP augmentation during meniscal repair nearly doubled the healing rate and improved clinical scores at 12 months compared with controls.[8] These findings were corroborated by Lo Presti et al., who observed superior early improvements in pain and function following PRP injection after meniscectomy. Conversely, Yanke et al. found that intra-articular BMAC following arthroscopic meniscectomy improved KOOS–Sport and KOOS–QOL scores at 6 months, though the advantage diminished at 1 year.[9] Dancy et al. further expanded the evidence base by analyzing over 2,000 menisci in a large registry cohort, demonstrating that biologic augmentation—predominantly BMAC and PRP—did not significantly reduce revision rates, but trends favored biologic-treated groups.[12]

These collective results suggest that, while biologic augmentation may not alter the mechanical endpoint of retear or reoperation, it reliably enhances functional recovery, pain relief, and subjective satisfaction. This distinction between mechanical integrity and biological symptom modulation echoes trends observed in other soft-tissue healing paradigms, such as biologic-enhanced rotator cuff or anterior cruciate ligament (ACL) repair.[12,13] In these models, biologic agents consistently improve early-phase function, tissue quality, and pain control without necessarily altering long-term revision rates. The parallels underscore that augmentation works synergistically with mechanical stability rather than substituting for it.

Mechanistic and Biological Interpretation

The observed functional benefits of PRP and BMAC augmentation are biologically plausible, given their complementary regenerative mechanisms. PRP delivers supraphysiologic concentrations of platelets and growth factors—chiefly platelet-derived growth factor (PDGF), transforming growth factor-β (TGF-β), vascular endothelial growth factor (VEGF), and insulin-like growth factor-1 (IGF-1)—which initiate a cascade of cellular events that facilitate tissue regeneration.[5,7] These factors promote chemotaxis, neovascularization, and fibroblast proliferation, ultimately enhancing matrix synthesis and collagen organization within the repair zone. Importantly, PRP also modulates local inflammation by downregulating pro-inflammatory cytokines such as interleukin-1β and tumor necrosis factor-α, potentially explaining the reduction in postoperative pain and swelling commonly reported in clinical studies.

BMAC, in contrast, introduces a cell-based mechanism centered on mesenchymal stromal cells (MSCs), which act both as progenitor cells and as paracrine mediators. MSCs derived from bone marrow secrete trophic factors that inhibit apoptosis, suppress catabolic signaling, and promote chondrogenic differentiation.[14] These paracrine effects support extracellular matrix turnover and tissue remodeling while also influencing immune homeostasis through polarization of macrophages toward an anti-inflammatory phenotype. Additionally, the presence of hematopoietic cells and platelets in BMAC provides an intrinsic mixture of growth factors that sustain a longer-term reparative environment compared with PRP's short-lived pulse of cytokines.

Taken together, these biological mechanisms provide a strong foundation for the observed clinical improvements in functional and quality-of-life outcomes. However, the limited impact on revision rate suggests that these agents primarily optimize the biochemical and cellular microenvironment rather than reinforce mechanical fixation strength. Meniscal healing depends not only on tissue biology but also on tear morphology, fixation technique, load distribution, and postoperative rehabilitation compliance.[1,4] Consequently, while PRP and BMAC can accelerate symptom resolution and potentially improve tissue quality, they cannot fully counteract the mechanical determinants of retear risk.

Integration with the Current Understanding of Meniscal Healing

The meniscus possesses a highly specialized yet limited intrinsic healing capacity due to its heterogeneous vascularization pattern. The outer red-red zone, which accounts for roughly one-third of its cross-sectional width, has direct vascular supply from the genicular arteries, whereas the central and inner zones are avascular and depend on diffusion from synovial fluid.[4] This microvascular gradient explains the discrepancy between biologic responsiveness and tear location—peripheral tears often heal well with biologic support, whereas central avascular tears remain refractory. PRP, rich in angiogenic growth factors, may be particularly effective in the intermediate red-white zone, where biologic stimulation can augment neovascularization. In contrast, BMAC's MSC content may better address degenerative tears, where cell-based regeneration rather than angiogenesis predominates.

Recent in vivo studies provide additional mechanistic insights. Ishida et al. demonstrated that PRP embedded in a biodegradable gelatin hydrogel enhanced meniscal cell proliferation and matrix deposition in animal models, with superior histologic integration compared with untreated controls.[7] Hernigou et al. reported long-term safety and sustained benefit in patients receiving bone marrow concentrate during meniscal repair, with no increase in adverse events over ten years of follow-up.[14] These experimental and clinical

findings converge with our meta-analytic results, reinforcing that biologic augmentation acts as a catalyst for early tissue recovery and symptomatic improvement, rather than as a determinant of ultimate structural success.

Clinical Implications

The clinical implications of these findings are multifaceted. First, the significant improvements in KOOS–Sport and KOOS–QOL domains suggest that biologic augmentation contributes meaningfully to early functional recovery, allowing patients to return to higher levels of physical activity sooner. This is particularly relevant for athletes and active individuals, where rehabilitation timelines are often constrained by competitive or occupational demands. Second, both PRP and BMAC appear safe, with no serious adverse events reported across included studies. The only noted complication—a transient infection following BMAC injection—resolved fully with standard management, confirming the general tolerability of these interventions.

From a procedural perspective, the use of biologics does not substantially prolong operative time and can be seamlessly integrated into existing arthroscopic workflows. PRP preparation involves venous sampling and centrifugation, typically within 15 minutes, while BMAC requires a single iliac crest aspiration before concentration. However, the lack of standardized protocols remains a major obstacle to reproducibility. PRP formulations vary widely in platelet count, leukocyte concentration, and activation method; BMAC processing differs in aspiration site, centrifugation speed, and volume yield.[15] Such variability likely contributes to heterogeneity in reported outcomes, emphasizing the need for standardized manufacturing and reporting guidelines similar to the MARSP (Minimum Information for Studies Evaluating Biologics in Orthopaedics) framework.

Economically, cost-effectiveness remains an unresolved question. PRP is generally less expensive and less invasive than BMAC, but its shorter biological half-life may necessitate repeated injections. BMAC, though more costly, delivers both growth factors and progenitor cells, which may provide sustained benefits in tissue remodeling. Cost-benefit analyses are warranted to determine the long-term economic value of these therapies, particularly in light of increasing global emphasis on value-based care in orthopedics.

Limitations

Several limitations must be acknowledged when interpreting this meta-analysis. The small number of included studies inherently limits statistical power and precision. Heterogeneity in surgical indication—meniscal repair versus partial meniscectomy—introduces clinical variability, as the biological environment and healing goals differ between these procedures. Moreover, biologic preparations were not standardized across trials; platelet concentration in PRP ranged from 3× to 6× baseline, and BMAC cellular yields varied based on aspiration technique. These differences likely influenced treatment efficacy but could not be controlled analytically.

Another limitation is the reliance on patient-reported outcomes, which, although validated, are subject to expectation bias. Blinding was incomplete in most studies, as patients were aware of receiving biologic injections. Additionally, objective imaging data such as MRI-verified healing rates or quantitative cartilage assessment were inconsistently reported, precluding inclusion in the meta-analysis. The absence of long-term follow-up beyond two years further restricts conclusions regarding chondroprotective effects or prevention of osteoarthritic progression. Lastly, publication bias cannot be excluded given the small number of available trials, though the consistency of directionality across outcomes supports the robustness of findings.

Future Perspectives

Future research should focus on addressing the mechanistic and methodological gaps identified in this synthesis. Multicenter randomized controlled trials with standardized biologic preparation protocols and longer follow-up periods are essential to confirm the durability of clinical benefit. Trials integrating advanced imaging modalities—such as quantitative MRI or T2 mapping—could elucidate correlations between symptomatic improvement and structural regeneration. Furthermore, molecular profiling of PRP and BMAC content could allow personalized biologic prescriptions tailored to patient-specific tissue characteristics.

Emerging innovations such as combined biologic scaffolds, platelet-poor plasma carriers, or co-delivery of PRP and MSCs may further enhance meniscal regeneration. Preliminary data suggest that hybrid formulations combining the cytokine burst of PRP with the cellular longevity of BMAC yield synergistic effects on fibrocartilage formation.[13] Regulatory oversight and consensus reporting standards will be vital to ensure clinical safety, reproducibility, and equitable adoption as these technologies advance toward mainstream practice.

CONCLUSION

This meta-analysis demonstrates that biologic augmentation (PRP and BMAC) safely enhances functional recovery and patient-reported quality of life in arthroscopic meniscal surgery, without significantly reducing revision rates. The primary benefit lies in accelerating symptomatic recovery, making it particularly valuable for athletes and active individuals. Nevertheless, the heterogeneity of preparation methods and limited long-term follow-up remain challenging. Future multicenter trials with harmonized protocols are essential to establish the long-term durability, optimal indications, and cost-effectiveness of these promising regenerative strategies in joint preservation.

Declaration by Authors

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