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Return to sport after meniscectomy, meniscal repair, and meniscal allograft transplantation for meniscal lesions in athletes: A systematic review and meta-analysis

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Abstract

Purpose: The aim of this systematic review and meta-analysis was to quantify and compare the evidence on the results obtained with the surgical treatments for meniscal lesions in athletes.

Methods: A literature search was conducted on PubMed, Cochrane and Web of Science in August 2025 according to the PRISMA guidelines. Inclusion criteria were clinical studies (randomised controlled trials [RCTs], non-randomised comparative studies and case series), ≥6 patients, in the English language, on the surgical treatment of meniscal lesions in athletes. A meta-analysis was conducted on the rate of patients returning to sport, the time to return to sport, and the rate of patients returning to the pre-injury level of sport. Patient-reported outcome measures, adverse events, failures and reoperation rates, as well as risk of bias and quality of evidence, were also documented. The risk of bias was assessed using the Cochrane RoB 2.0 tool, the Cochrane ROBINS-I tool, and the JBI Critical appraisal checklist. The quality of evidence was assessed using a modified Coleman score and the GRADE tool.

Result: The mean time to return to sport was 2.1 months for meniscectomy, 5.8 months for meniscal repair, and 8.9 months for meniscal allograft transplantation (MAT). Statistically significant differences were observed between meniscectomy and repair and between meniscectomy and MAT (both $p < 0.001$). Meniscectomy showed a return to sport rate of 98.2%, meniscal repair of 96.9%, and MAT of 94.2%, while return to the same pre-injury level of sport was reported as 84.4% for meniscectomy, 81.3% for meniscal repair, and 77.4% for MAT, with no statistically significant differences between groups. The mean modified Coleman Methodology Score for the included studies was 66.6 ± 7.0.

Conclusion: Meniscectomy, meniscal repair, and MAT are all able to provide high rates of return to sport in athletes. In the investigated treatment cohorts, meniscectomy presented the shortest pooled time to return to

Abbreviations: BMI, body mass index; Cis, confidence intervals; IKDC, International Knee Documentation Committee; KOOS, Knee injury and Osteoarthritis Outcome Score; MAT, meniscal allograft transplantation; MCMS, Modified Coleman Methodology Score; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis; PROMs, Patient-Reported Outcome Measures; RCTs, randomised controlled trials; VAS, Visual Analog Scale; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

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sport, followed by meniscal repair and MAT. Importantly, all treatments offered good rates of return to the same level of athletic performance. The treatment choice should be guided by an individualised, multidisciplinary approach aimed at providing a patient-tailored treatment strategy to optimise both athletic recovery and joint preservation.

Level of Evidence: Level I.

KEYWORDS
athlete, meniscus, meniscectomy, meniscal allograft transplantation, repair

INTRODUCTION

Meniscal lesions are among the most common knee injuries in athletes, accounting for approximately 10%–20% of all sports-related knee injuries [26, 38]. These lesions occur across a wide spectrum of sports, with higher incidences reported in pivoting and contact disciplines and significant implications for both short-term performance and long-term joint health [43]. Conservative management may be appropriate for selected cases, particularly for small and stable tears, but many athletes require surgical intervention to minimise symptoms, restore function, and facilitate a timely return to sport [65]. Additionally, the urgency to resume pre-injury activity levels, especially in elite and professional athletes, often leads towards a surgical approach [14].

Different surgical strategies are currently available in clinical practice for the management of meniscal lesions [55]. Meniscectomy has been used for decades and represents the most frequently used approach for meniscal lesions in athletes thanks to its rapid symptom relief and short rehabilitation period [19]. However, compelling evidence increasingly highlighted the long-term consequences of meniscal tissue loss, including accelerated joint degeneration and early-onset knee osteoarthritis [31, 36]. This growing awareness shifted the clinical focus towards meniscal preservation strategies [64]. Meniscal repair techniques, supported by advancements in suture devices and technical improvements, expanded the indications for repair even in challenging tear patterns [42]. When preservation is not feasible, meniscal allograft transplantation (MAT) offers a reconstructive option aimed at restoring meniscal function and delaying degenerative joint changes [15, 66]. Each surgical option carries distinct potential and limitations, and the optimal treatment strategy in athletes, balancing the need for rapid return to sport with long-term joint health, remains a matter of ongoing debate. In this light, a systematic review and meta-analysis addressing the outcomes of the most used surgical options for meniscal lesions in athletes would be of clinical relevance, helping to elucidate the strengths and weaknesses of each approach, offering valuable insights to guide the surgical indications, and ultimately contributing to a more personalised and effective treatment strategy for the injured athlete.

The aim of this systematic review and meta-analysis was to quantify the outcomes of meniscectomy, meniscal repair, and MAT for the treatment of meniscal lesions in athletes in terms of rate, time, and level of return to sport, as well as clinical outcomes.

MATERIALS AND METHODS

Literature search

A systematic review of the literature was performed on the surgical treatments for meniscal lesions in athletes. The literature search was conducted on the PubMed, Cochrane, and Web of Science databases on 26 August 2025 using the following search string for titles and abstracts, without any time or language restriction at this stage of the search process: (sport* OR athlet*) AND menisc* (Supporting Information: Table 1s). The trial was registered on PROSPERO and the guidelines for Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used (Figure 1) [44].

Studies selection and data extraction

The screening and analysis processes were conducted separately by two independent observers (A.P. and G.A.F.) and any discrepancies between them were resolved by discussion and consensus with a third author (A.B.). First, the articles were screened by title and abstract. The inclusion criteria were clinical studies (randomised controlled trials [RCTs], non-randomised comparative studies and case series) of any level of evidence involving a minimum of six patients, written in English language, with no time limitations, on the surgical treatment of meniscal lesions in athletes. The exclusion criteria were studies published in languages other than English, literature reviews, preclinical in vivo studies, case reports, case series with less than six patients, congress abstracts, studies not reporting

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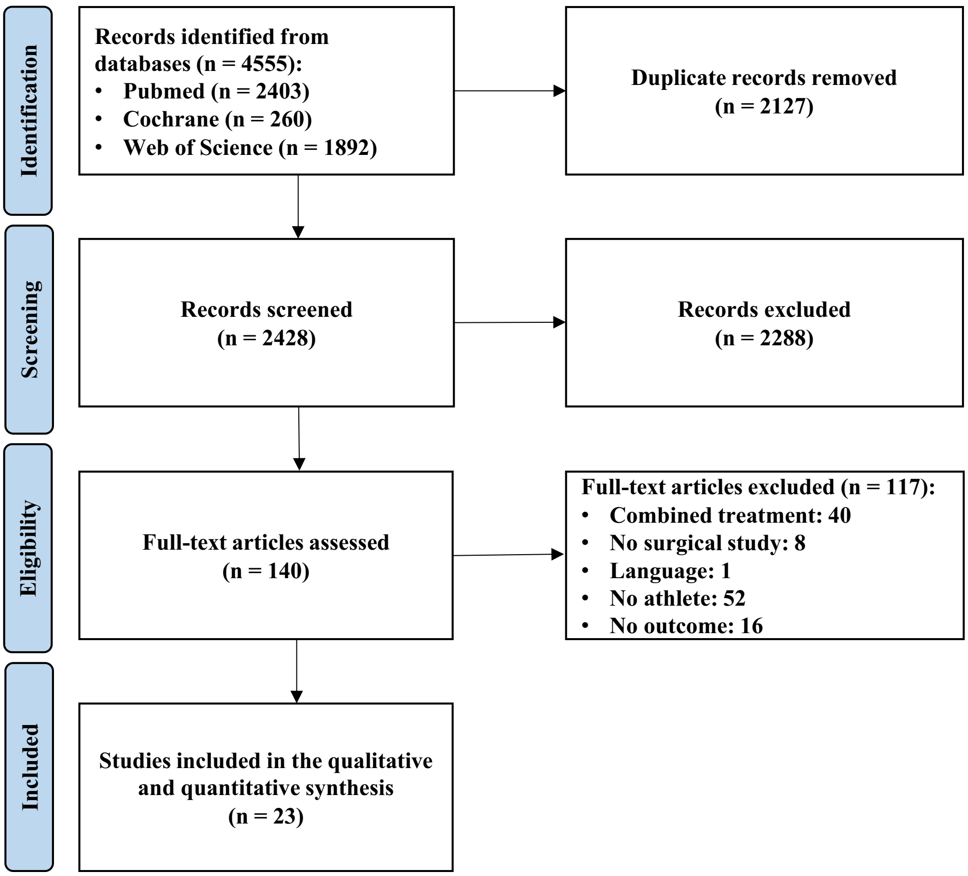

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram.

clinical outcomes, studies reporting only on combined treatments with other conditions (e.g., anterior cruciate ligament reconstruction), and clinical studies not including athletes (Supporting Information: Table 2s). The initial screening was performed manually based on the title and abstract. Subsequently, the full texts of the selected articles were screened, with further exclusions according to the previously described criteria. Relevant data were extracted from the included studies' full texts, figures, and tables. The extracted data included authors' names, publication year, journal, study country, study design, patients' sex, age and body mass index (BMI), sample size, type of surgical treatment, meniscal lesion type, meniscus side (medial or lateral), sport practiced, sport level, % of patients returning to sport, time to return to sport, % of patients returning to the same level of sport, patient-reported outcome measures (PROMs), adverse events, failures, and reoperation rates. These data were then summarised and analysed to address the study objectives. A meta-analysis was conducted on the rate of patients returning to sport, time to return to sport, and rate of patients returning to the same level of sport. Studies reporting only return to competition rate or time to return to competition were not included in the aforementioned meta-analyses, as those cannot be assimilated to return to sport and carry the potential confounding factor of injury timing (during season vs off-season). Two sub-analyses were performed for medial and lateral meniscus, respectively. Each outcome was included in the meta-analysis only if it was reported by at least three studies.

Risk of bias and quality of evidence

The risk of bias and quality of each article was assessed independently by two authors (A.P. and G.A.F) and any discrepancies between them were resolved by discussion and consensus with a third author (A.B.). The risk of bias for RCTs was assessed using the Cochrane Collaboration's Revised Risk of Bias Tool for RCTs (RoB 2.0), which evaluates five domains and categorises the overall risk as low, some concerns, or high [59]. For comparative studies, the Cochrane ROBINS-I (Risk Of Bias In Non-randomised Studies - of Interventions) tool was used [58]. This tool includes seven domains that can be classified as 'low', 'moderate', 'serious' or 'critical' risk of bias. If a study is ranked low in all domains, it is considered low risk of bias; if it is ranked moderate, serious or critical in at least one domain, it is considered moderate, serious or

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critical risk of bias, respectively. For case series, the risk of bias was evaluated using the Joanna Briggs Institute (JBI) Critical appraisal checklist for case series, which includes 10 criteria covering study design, data reporting and outcome assessment [45]. Each study was then classified as having low, moderate or high risk of bias based on the number of criteria met. The Modified Coleman Methodology Score (MCMS) was applied to assess quality of the individual publications [35]. The MCMS was classified as excellent for scores of 85 and above, good for 70–84, fair for 55–69 and poor for below 55 [27]. For each outcome included in the meta-analysis, the quality of evidence was evaluated according to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) guidelines [56]. In the GRADE system, the baseline rating is 'high'. Five criteria are used to potentially downgrade the quality rating by one or two levels, reflecting 'serious' or 'very serious concerns', respectively. These criteria include risk of bias in individual studies, inconsistency of results across studies, indirectness of evidence, imprecision, and publication bias. Finally, the overall quality of evidence is graded as 'high', 'moderate', 'low', or 'very low'.

Statistical analysis

The statistical analysis and Forest plots were carried out by an independent professional statistician. The analysis was performed using random effects for the continuous variables [21]. For the dichotomous variables, the logit transformation was used to provide the pooled rates across the studies [6]. A statistical test for heterogeneity was first conducted with the Cochran Q statistic and I^2 metric. When no heterogeneity was found with $I^2 < 25\%$, a fixed-effect model based on the Mantel–Haenszel method was used to estimate the expected values and 95% confidence intervals (CIs). In case of I^2 values ≥ 25%, a random-effect model was applied, and the I^2 metric was evaluated for the random-effect to check the correction of heterogeneity. The comparisons among the groups were based on the analysis of variance [13]. A p-value of 0.05 was considered significant. The statistical analysis was carried out with Microsoft Excel 2010 and MetaXL add-in.

RESULTS

Characteristics of included studies and patients

A total of 4555 articles were retrieved. After removing duplicates and screening titles, abstracts, and full texts, 23 studies, published between 1994 and 2025, were included in the meta-analysis according to the eligibility criteria (Figure 1). Of these, eight studies (34.8%) focused on meniscectomy, 10 (43.5%) on meniscal repair, 4 (17.4%) on MAT, and one focused on both meniscectomy and meniscal repair (4.3%). These studies collectively enrolled 1171 patients, with a mean age of 26.3 ± 7.6 years. Twelve studies included both medial and lateral meniscal lesions, two studies only medial meniscal lesions, six studies only lateral meniscal lesions, and three studies did not report if medial or lateral meniscal lesions were included. The meniscectomy group included 734 patients (62.7% of the total; mean age 26.9 ± 8.1 years), the meniscal repair group included 339 patients (28.9%; mean age 22.8 ± 4.4 years), and the MAT group included 98 patients (8.4%; mean age 26.4 ± 2.6 years). The characteristics of the included studies and patients are detailed in Table 1. The overall meta-analysis results are reported in Figure 2, while detailed results are described in the following paragraphs.

Meta-analysis

Time to return to sport

Data on time to return to sport were available from 11 studies with four study groups reporting on meniscectomy, seven on meniscal repair, and three on MAT. The pooled mean time to return to sport was 2.1 months (95% CI: 1.5–2.7) for meniscectomy, 5.8 months (95% CI: 5.3–6.3) for meniscal repair and 8.9 months (95% CI: 6.2–11.6) for MAT. Statistically significant differences were observed between meniscectomy and MAT ($p < 0.001$, MD = 6.8 months) and between meniscectomy and repair ($p < 0.001$, MD = 3.7 months), while a statistical tendency emerged from the comparison between repair and MAT ($p = 0.090$, MD = 3.1 months) (Figure 3).

The sub-analysis on medial meniscal lesions revealed a pooled mean time to return to sport of 2.0 months (95% CI: 0.9–3.1) for meniscectomy and 4.8 months (95% CI: 4.2–5.4) for meniscal repair ($p < 0.001$, MD = 2.8 months). The sub-analysis on lateral meniscal lesions revealed a pooled mean time to return to sport of 2.4 months (95% CI: 1.7–3.0) for meniscectomy and 6.5 months (95% CI: 5.9–7.1) for meniscal repair ($p < 0.001$, MD = 4.2 months). Data were not sufficient for the MAT sub-analysis.

Return to sport rate

Meniscectomy showed a pooled return to sport rate of 98.2% (95% CI: 93.5–100.0), meniscal repair of 96.9% (95% CI: 92.6–99.5) and MAT of 94.2% (95% CI: 83.8–100.0). No statistically significant differences

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TABLE 1 Characteristics of the included studies and patients as well as Modified Coleman Methodology Score results.

	Author	Study type	*N* Patients	Women	Men	Age	BMI	Medial	Lateral	Lesion characteristics	Sport played	Sport level	Time to return to sport (months)	Return to sport rate	Rate of return to the pre-injury level	MCMS
Meniscectomy	Ackermann et al. [1]	Comparative	49	1	48	23.8 ± 5.0	NR	0%	100%	17 Longitudinal 4 Horizontal 13 Radial 15 Complex	Soccer	Professional	4.0	100.0%	89.0%	80
	Bolia et al. [10]	Case series	36	0	36	20.0 ± 2.4	NR	18.4%	81.6%	NR	American football	Elite	2.4 ± 1.3	100.0%	100.0%	70
	Bonneux et al. [12]	Case series	29	9	20	25.0	25.0 ± 3.7	0%	100%	12 Flap 6 Radial 5 Bucket Handle 3 Degenerative (Discoid) 2 Horizontal 2 Parrot Beak 1 Vertical	NR	Competitive	NR	100.0%	100.0%	50
	Chowdhury et al. [17]	RCT	80	5	75	NR	NR	100%	0%	48 Bucket handle 3 Anterior flap 8 Mid third flap 21 Posterior flap	42 Football 15 Cricket 7 Wrestling 6 Ha-du-du 10 Other	Non-professional	NR	NR	NR	47
	Erickson et al. [23]	Case series	168	0	168	25.0 ± 5.0	NR	51.0%	49.0%	101 Acute 43 Overuse	Baseball	Professional	1.4	80.0%	76.0%	70
	Kim et al. [34]	Case series	56	11	45	26.7	NR	28.6%	71.4%	NR	15 Soccer 10 Basketball 7 Baseball 5 Volleyball 4 Rugby	12 Elite 23 Competitive 21 Recreational	2.2 ± 1.4	100.0%	NR	70
	Nawabi et al. [47]	Case series	90	0	90	23.0 ± 3.8	NR	53.3%	46.7%	29 Vertical 4 Horizontal 15 Radial 42 Complex	Soccer	Professional	1.4 ± 3.1	100.0%	NR	70
	Osti et al. [48]	Case series	41	14	27	26.0	NR	0%	100%	8 Longitudinal 13 Radial 1 Horizontal 19 Complex	19 Football 12 Basketball 6 Volleyball 2 Tennis 2 Running	Competitive and recreational	1.8 ± 4.3	98.0%	63.0%	60
	Sayegh et al. [57]	Case series	185	90	95	46.3 ± 11.9	28.8 ± 6.2	78.9%	21.1%	NR	Running	Non-professional	NR	100.0%	41.0%	70
Meniscal repair	Ackermann et al. [1]	Comparative	40	1	39	22.5 ± 5.4	NR	0%	100%	27 Longitudinal 12 Radial 1 Complex	Soccer	Professional	6.0	97.5%	70.0%	80

(Continues)

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TABLE 1 (Continued)

	Author	Study type	*N* Patients	Women	Men	Age	BMI	Medial	Lateral	Lesion characteristics	Sport played	Sport level	Time to return to sport (months)	Return to sport rate	Rate of return to the pre-injury level	MCMS
	Alvarez-Diaz P et al. [4]	Case series	14	0	14	28.0	NR	NR	NR	Complete longitudinal in the posterior horn	Soccer	Competitive	4.3	92.0%	21.4%	70
	Atsumi et al. [5]	Case series	9	2	7	27.8	NR	NR	NR	Horizontal in the middle and posterior segments	NR	Non-professional	5.7 ± 2.6	100.0%	77.8%	65
	Benhenneda et al. [8]	Case series	30	5	25	20.1 ± 5.0	23.8 ± 2.6	0%	100%	Radial	NR	Non-professional	NR	86.7%	86.7%	70
	Heath et al. [30]	Case series	33	0	33	26.3 ± 4.4	23.5 ± 1.5	100%	0%	NR	Soccer	Professional	5.3 ± 2.7	100.0%	100.0%	70
	Hirtler et al. [32]	Case series	37	12	25	24.2 ± 12.2	NR	87.2%	12.8%	24 Acute 13 Chronic	6 American football 5 Football 5 Running 5 Ski 3 Hockey 2 Tennis 2 Cheerleading 2 Badminton 2 Climbing 1 Rugby 1 Snowboarding 4 Other	Professional	6.3 ± 4.0	100.0%	100.0%	65
	Nakayama et al. [46]	Case series	46	12	34	22.9 ± 9.6	NR	39.1%	60.9%	17 Longitudinal 5 Radial 8 Complex 16 Bucket handle	NR	Non-professional	6.3 ± 3.9	80.4%	NR	70
	Torre et al. [60]	Case series	14	2	12	21.0	NR	0%	100%	Radial	NR	Professional	NR	100.0%	86.0%	60
	Uchida et al. [61]	Case series	46	8	38	19.1 ± 2.9	26.2 ± 4.6	0%	100%	Radial	NR	Non-professional	7.6 ± 7.0	100.0%	73.9%	70
	Vanderhave et al. [62]	Case series	18	NR	NR	13.11	NR	33.3%	66.7%	NR	NR	Non-professional	5.6 ± 1.4	100.0%	100.0%	65
	Vrgoč et al. [63]	Case series	52	14	38	25.5	NR	NR	NR	Radial, longitudinal, bucket handle, or radial	NR	Professional and recreational	6.5	100.0%	84.6%	70
MAT	Alentorn-Geli et al. [2]	Case series	15	NR	NR	28.1	NR	43.8%	56.2%	Post-meniscectomy	Soccer	Competitive	7.6	85.7%	85.7%	70

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TABLE 1 (Continued)

Author	Study type	*N* Patients	Women	Men	Age	BMI	Medial	Lateral	Lesion characteristics	Sport played	Sport level	Time to return to sport (months)	Return to sport rate	Rate of return to the pre-injury level	MCMS
Bonanzinga et al. [11]	Case series	13	0	13	23.4 ± 4.0	NR	46.2%	53.8%	Post-meniscectomy	10 Football 1 Basketball 1 Fencing 1 Wrestling	Professional	11.8 ± 3.8	100.0%	69.0%	65
Chen et al. [16]	RCT	60	0	60	28.9 ± 3.9	22.8 ± 1.6	33.3%	66.7%	Post-meniscectomy	17 Soccer 7 Badminton 2 Tennis 6 Basketball 5 Martial arts 10 Baseball 2 Handball 1 Volleyball 4 Taekwondo 1 Wrestling 2 Judo 3 Other	Amateur	NR	NR	NR	70
Marcacci et al. [40]	Case series	10	0	10	25.1	23.2	40.0%	60.0%	Post-meniscectomy	Soccer	Professional	7.4 ± 2.7	91.7%	80.0%	65

Abbreviations: BMI, body mass index; MAT, meniscal allograft transplantation; MCMS, Modified Coleman Methodology Score; NR, not reported.

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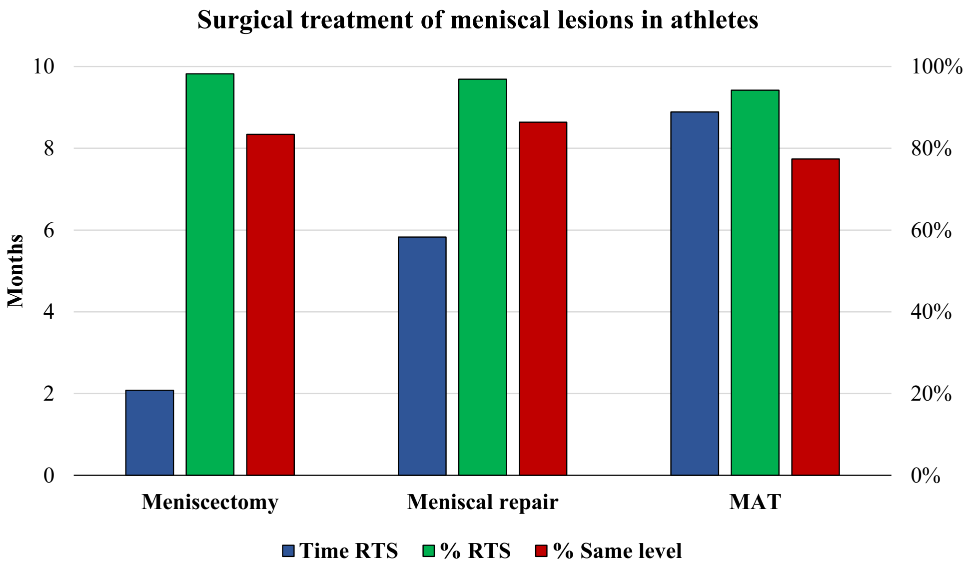

FIGURE 2 Overview of time to return to sport, return to sport rate, and return to the pre-injury level of sport rate for meniscectomy, meniscal repair, and meniscal allograft transplantation (MAT). RTS, return to sport.

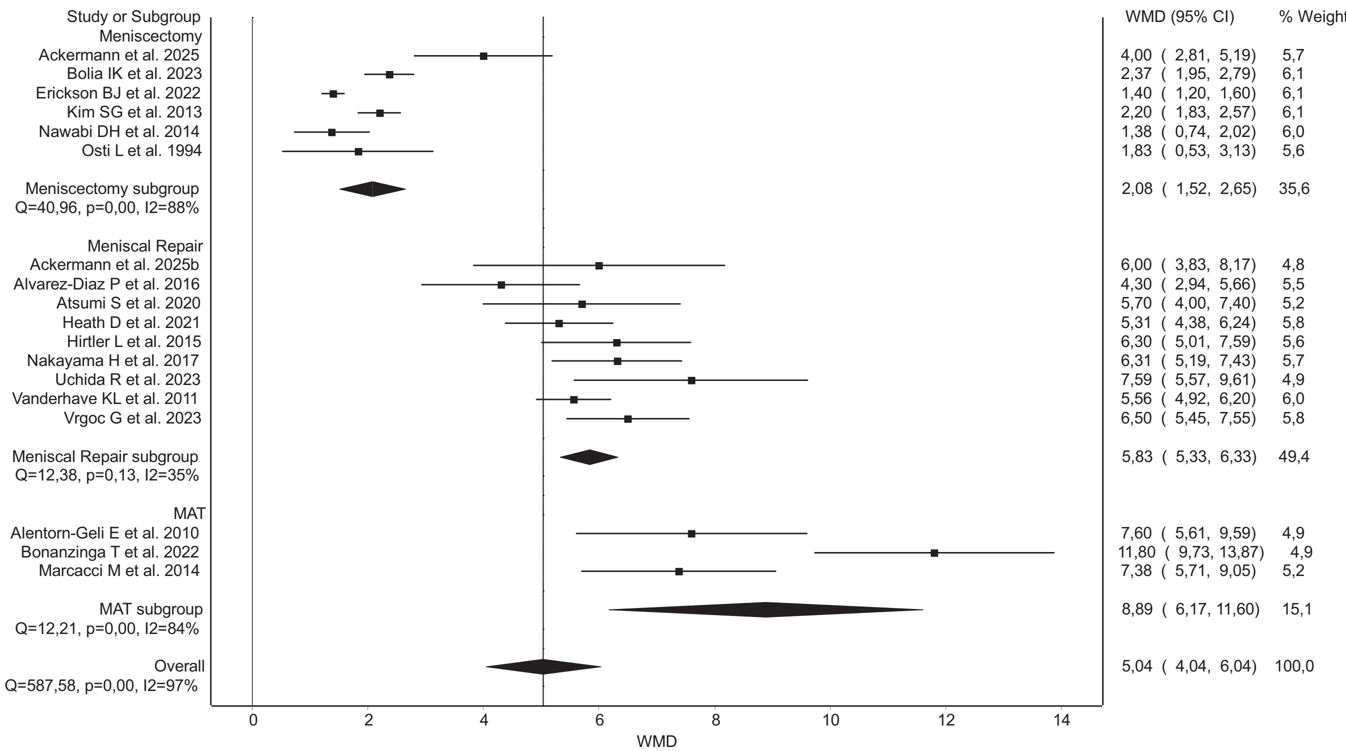

FIGURE 3 The forest plot displays the weighted mean difference (WMD) with 95% confidence intervals (95% CI) for each study included in the time to return to sport analysis in the three treatment categories: Meniscectomy, meniscal repair, and meniscal allograft transplantation (MAT).

were observed in each individual comparison between groups (Figure 4).

In the sub-analysis on medial meniscal lesions, meniscectomy showed a pooled return to sport rate of 97.0% (95% CI: 87.9–100.0) and meniscal repair of 95.6% (95% CI: 85.3–100.0). In the sub-analysis on lateral meniscal lesions, meniscectomy showed a pooled return to sport rate of 97.7% (95% CI: 93.1–100.0) and meniscal repair of 95.2% (95% CI: 88.3–99.4). No statistically significant differences were observed in the individual comparison between groups. Data were not sufficient for the MAT sub-analysis.

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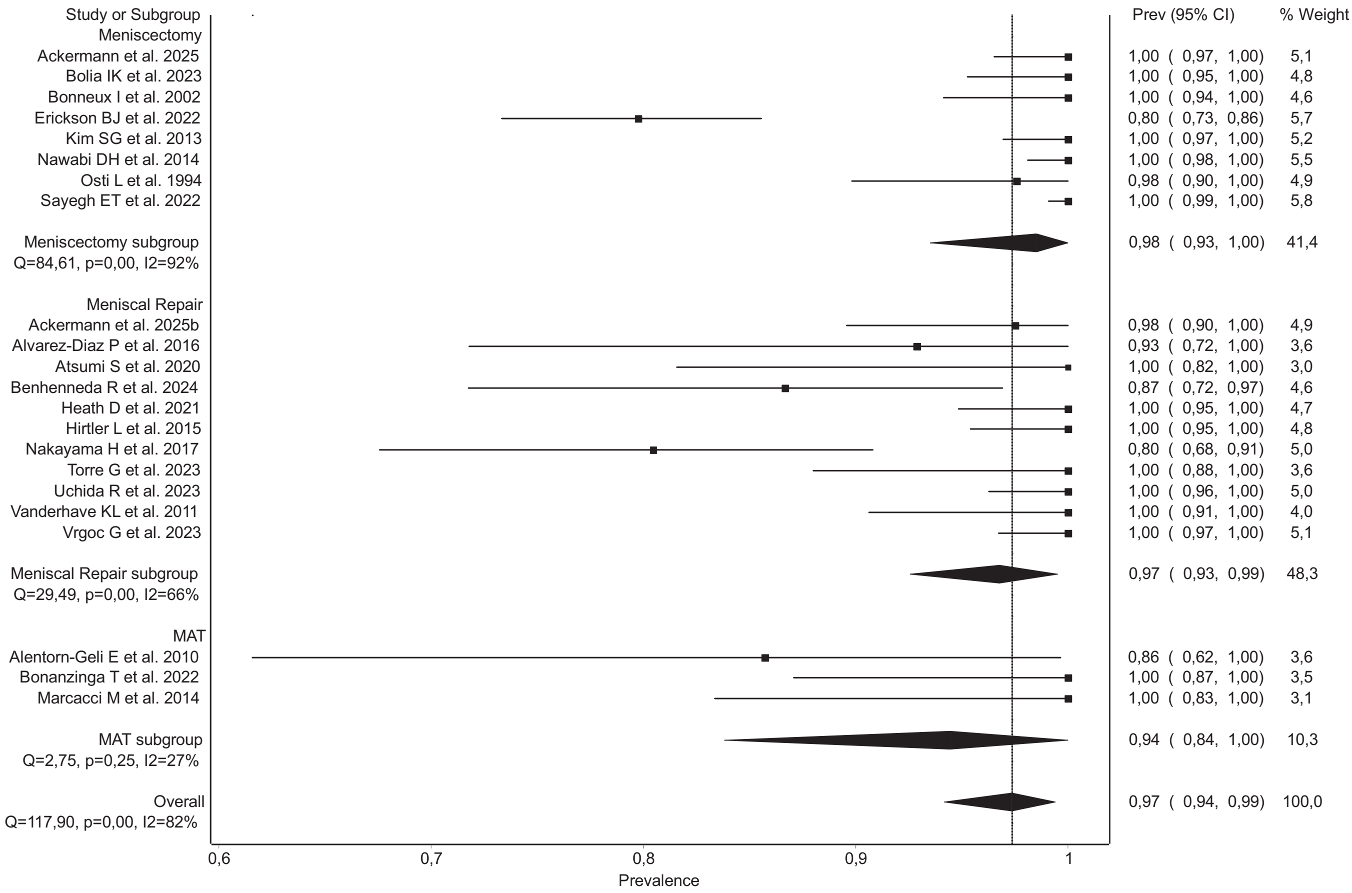

FIGURE 4 The forest plot displays the prevalence (Prev) with 95% confidence intervals (95% CI) for each study included in the return to sport rate analysis in the three treatment categories: Meniscectomy, meniscal repair, and meniscal allograft transplantation (MAT).

Return to pre-injury level

The return to the same pre-injury level of sport was reported as 84.4% (95% CI: 60.7–99.0) for meniscectomy, 81.3% (95% CI: 62.3–95.1) for meniscal repair, and 77.4% (95% CI: 62.5–89.5) for MAT. No statistically significant differences were observed in each individual comparison between groups (Figure 5).

In the sub-analysis on medial meniscal lesions, the return to the same pre-injury level of sport was reported as 99.1% (95% CI: 96.2–100.0) for meniscal repair. In the sub-analysis on lateral meniscal lesions, the return to the same pre-injury level of sport was reported as 84.6% (95% CI: 52.8–100.0) for meniscectomy and 82.6% (95% CI: 72.0–91.1) for meniscal repair. No statistically significant differences were observed in the individual comparison between groups. Data were not sufficient for the medial meniscectomy and for the MAT sub-analyses.

Patient-reported outcome measures (PROMs)

The most commonly reported PROMs in the included studies were the Visual Analog Scale (VAS) for pain, the International Knee Documentation Committee (IKDC) score, the Lysholm score, the Knee injury and Osteoarthritis Outcome Score (KOOS), the Tegner activity scale, and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). These PROMs were reported with heterogeneity across studies and timepoints, which impaired the possibility to perform a meta-analysis, similarly to adverse events, failures, and reoperation rates. The pooled trajectories of VAS pain, IKDC, Lysholm, KOOS, and Tegner for each individual treatment are reported in Figure 6.

Risk of bias and quality of evidence

The risk of bias assessment using the RoB 2.0 tool revealed that one RCT included in the analysis presented some concerns, while the other had a high risk of bias. The domains related to the presence of risk of bias concerned the randomisation process and missing outcome data. A summary of the risk of bias assessment for the RCTs is presented in the supplementary materials (Supporting Information: Figure 1s). The evaluation using the

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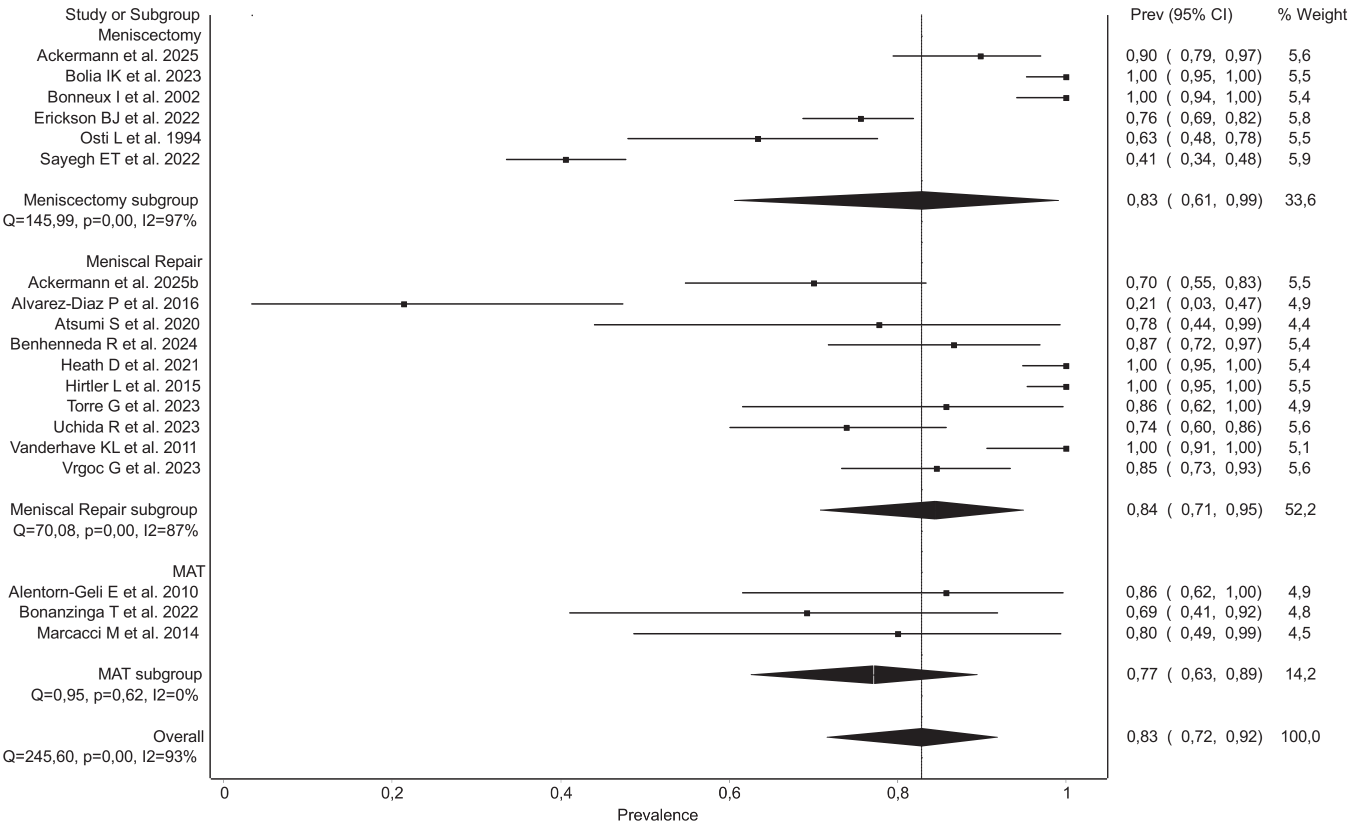

FIGURE 5 The forest plot displays the prevalence (Prev) with 95% confidence intervals (95% CI) for each study included in the return to pre-injury level analysis in the three treatment categories: Meniscectomy, meniscal repair, and meniscal allograft transplantation (MAT).

ROBINS-I tool showed that the only comparative study included had a moderate risk of bias, mainly due to the 'Confounding' and 'Deviations from intended interventions' domains. A summary of the risk of bias assessment for the comparative study is presented in the supplementary materials (Supporting Information: Figure 2s). For the case series, the JBI Critical Appraisal Checklist was applied. Among the 20 included studies, two were classified as having a low risk of bias, 13 had a moderate risk, and five were judged to have a high risk of bias. The most frequently unmet criteria involved incomplete follow-up reporting and unclear inclusion methods. A detailed overview of the case series risk of bias assessment is provided in the supplementary materials (Supporting Information: Figure 3s). The mean MCMS score for the included studies was 66.6 ± 7.0 with no studies graded as excellent (85–100), 14 studies as good (70–84), 7 as fair (50–69), and 2 as poor (<55) (Table 1). The GRADE evaluation showed that the level of evidence of the results was moderate in three outcomes, low in five, and very low in one. A detailed overview of the quality of evidence assessment of the meta-analysed outcomes is provided in the supplementary materials (Supporting Information: Table 3s).

DISCUSSION

The main finding of this meta-analysis is that meniscectomy, meniscal repair, and MAT were all able to provide high rates of return to sport in athletes. Meniscectomy presented the shortest time to return to sport, followed by meniscal repair and MAT. Importantly, although the literature overall showed high heterogeneity, all treatments showed good rates of return to the same level of athletic performance.

Menisci play a fundamental role in maintaining knee joint homoeostasis, contributing to load transmission, shock absorption, stability, and proprioception [25]. In the athletic population, the integrity of the meniscus is even more critical, given the elevated functional demands and the high-risk environment for joint injuries [20]. Meniscal lesions are a frequent occurrence among athletes and still represent a clinical challenge [39]. Despite the expanding armamentarium of surgical options, selecting the optimal treatment pathway remains complex, particularly in this population where the goals of rapid return to sport and long-term joint preservation must be carefully balanced. In this sense, the choice of the most appropriate surgical option to manage meniscal lesions in this category of patients with elevated functional demand remains of paramount importance to optimise the overall outcomes while

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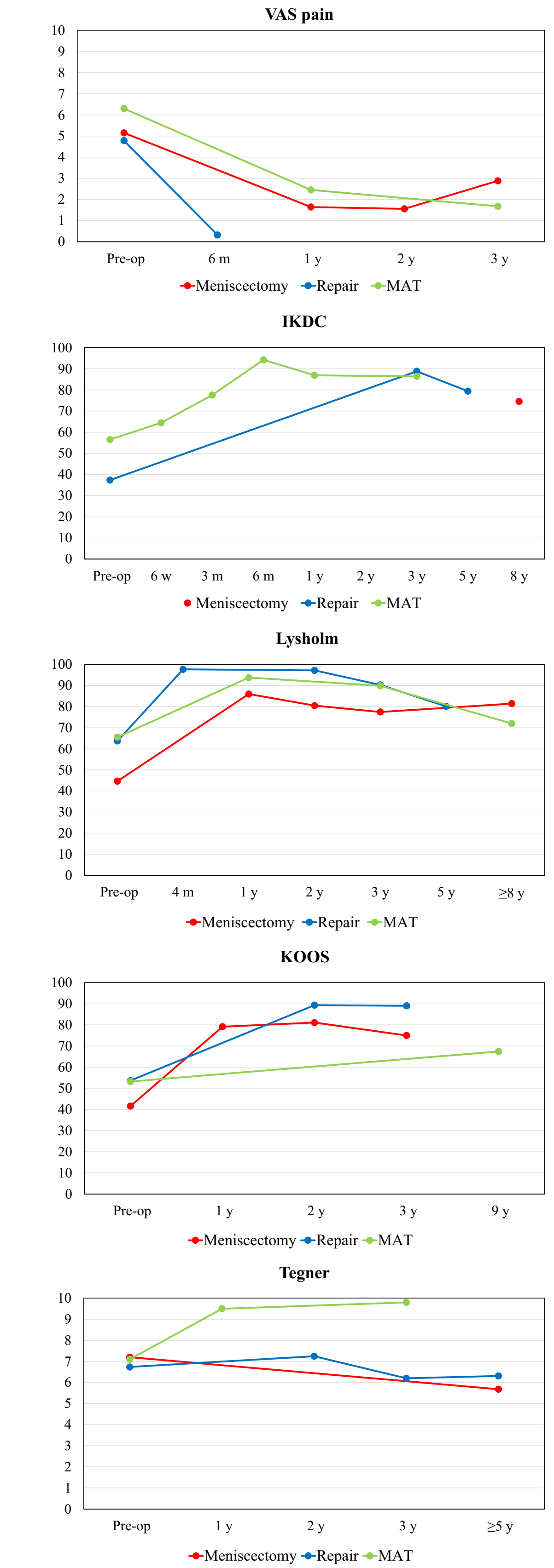

FIGURE 6 Longitudinal changes in patient-reported outcome measures for meniscectomy (red), meniscal repair (blue), and meniscal allograft transplantation (MAT) (green). Panels display mean scores (calculated as sample-size-weighted means of score values reported at each timepoint by the available studies, and not as formal meta-analytic estimates, for mere descriptive purposes) over time for Visual Analog Scale (VAS) pain, International Knee Documentation Committee (IKDC) score, Lysholm score, Knee injury and Osteoarthritis Outcome Score (KOOS), and Tegner activity scale.

hastening performance recovery and return to competition.

Meniscectomy has been used for decades and represents a common treatment to provide rapid symptom relief with a short rehabilitation period [14]. In this study, meniscectomy presented the shortest time to return to sport, with an average of about two months, while offering similar rates of return to sport and return to the same pre-injury level of sport compared to meniscal repair and MAT. These findings confirm previous literature reports suggesting the role of meniscectomy in scenarios where fast recovery and prompt return to competitive activity represent the main priority [41]. However, the attractive advantages of rapid return to sport must be weighed against the long-term consequences of removing meniscal tissue. Several biomechanical and clinical studies established that even partial meniscectomy may significantly alter load distribution, increase tibiofemoral contact pressures, and accelerate joint degenerative changes [3, 7]. In fact, the mechanical function of the meniscus, particularly in terms of load distribution and shock absorption, is fundamental to preserving joint integrity under repetitive high-impact stress. The removal of this important structure with meniscectomy is proven to predispose the knee to cartilage degeneration and early-onset osteoarthritis [54]. This is particularly concerning in the athletic population, where the knee is subject to heavy mechanical demands over extended periods. The clinical implication is that, while meniscectomy may offer the fastest return to sport, representing a reasonable option in selected acute scenarios, it should generally be approached with caution and reserved for irreparable lesions and cases where it is not technically feasible to preserve the meniscus, which should always be prioritised when possible.

Meniscal repair has increasingly emerged as a preferred strategy when preservation is feasible, benefitting from substantial advances in arthroscopic techniques and fixation devices [22, 49]. The progressive shift in clinical practice from tissue resection to preservation is supported by the high success rates of meniscal repair in the athletic population. The results of the present meta-analysis showed that meniscal repair achieved a return to sport rate of 97%, with a return to pre-injury performance level in 81% of cases. The mean time to return to sport was less than six months, which was significantly longer than that of meniscectomy. As such,

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the longer rehabilitation and progressive return to sport inherent to meniscal repair techniques require counselling and adherence to protocols, and the decision to opt for meniscal repair should also consider the sport-specific biomechanical demands, the athlete's willingness to commit to a more gradual rehabilitation programme, and the overall risk stratification for recurrence of the trauma that led to the tear, knowing that a meniscus repair is never as strong as the original tissue. Nevertheless, the excellent rates of return to sport and return to the pre-injury level of sport highlight meniscal repair as a compelling option also in athletes, capable of balancing the need for function restoration with the preservation of joint integrity. Technological advances have expanded the range of tears amenable to repair, including complex, radial, and root tears that were once deemed irreparable [37]. Moreover, biologic augmentation strategies, such as platelet-rich plasma (PRP), are increasingly used to favour healing, especially in tears located in the avascular zones [68]. Preclinical and clinical evidence is showing the benefits of orthobiologic products in modulating joint environment and enhancing tissue healing potential, supporting their integration in meniscal preservation strategies [68]. Future studies should investigate the additional value of such techniques in elite athletes, where the role of meniscal repair is particularly crucial and joint longevity should be a paramount goal.

MAT has emerged as a viable reconstructive strategy when meniscal loss is irreparable in symptomatic patients, with an evolving role even among active athletes [29]. The results of the present study confirm the positive literature findings on the general population also in the challenging joints of athletes, suggesting that MAT is able to provide a 94% return to sport rate, with 77% of athletes achieving their pre-injury level. The time to return to sport was longer compared to meniscectomy and meniscal repair, approaching nine months. This reflects the complexity of the procedure in a compromised joint suffering from a previous meniscectomy and an altered articular environment, and the need for cautious rehabilitation. The promising functional results of MAT in athletes confirmed previous studies demonstrating good survivorship and acceptable complication rates, even in patients with elevated physical demands [28]. Among the studies included in the present meta-analysis, graft-related reoperations were reported in only 13% of cases, and knee replacement was required in just over 1% of cases, figures comparable to or even lower than those observed in the general population. Accordingly, MAT can represent a viable option for symptomatic post-meniscectomy athletes who are otherwise limited in their activity and lack alternatives for meniscal function restoration. However, the lack of long-term high-quality data in elite athletes and the variability in surgical techniques, graft sources, and fixation methods represent important limitations in fully establishing MAT as a routine option for athletic patients [33]. Despite the encouraging results demonstrated by the present study, the risk of failure and need for reoperation remain major concerns following MAT, especially in patients returning to high-impact sports. In fact, activity level is a critical determinant of graft longevity, and unrestricted participation in pivoting sports may accelerate graft wear or failure [33]. Nonetheless, the relatively low rates of severe complications observed suggest that MAT can restore acceptable joint function and sport participation in properly selected athletes. These data challenge the traditional view of MAT as an exclusive last-resort procedure and support further exploring its indication also in high-demand individuals requiring meniscal function restoration.

The results of the sub-analyses on medial and lateral meniscal lesions showed similar results to the main analysis for all three surgical treatments. However, the number of studies available for sub-analysis was limited, which hindered the possibility to clearly prove possible differences in terms of return to sport outcomes between medial and lateral meniscal lesions in athletes. For instance, previous literature suggested that lateral meniscectomy is potentially career shortening while medial meniscectomy is generally better tolerated in athletes [19]. As such, future studies should aim at further elucidating the potential differences between medial and lateral meniscus surgeries to inform both sport physicians and athletes on return to sport outcomes, overall impact on the sport career, and subsequent implications in knee health after retirement.

Besides the most used surgical options investigated in this meta-analysis, emerging strategies involving tissue engineering and regenerative medicine are expanding the therapeutic landscape for meniscal lesions. Scaffolds, either biological, such as collagen-based matrices, or synthetic, such as polyurethane-based constructs, as meniscal substitutes may represent possible alternatives for specific indications [53]. These devices aim to replicate the biomechanical and structural roles of native meniscal tissue, providing support for host cell infiltration and tissue regeneration, with encouraging outcomes in terms of pain relief and functional improvement [18]. In the context of athletes, the potential of scaffold-based therapies lies in restoring joint mechanics while preserving biological potential, thus offering a hybrid approach between repair and replacement [67]. This approach could represent a solution particularly in younger patients where joint preservation remains the primary goal. However, the clinical availability, as well as the absence of robust, sport-specific data and long-term follow-up limit the ability to draw firm conclusions.

Biological augmentation with growth factors or mesenchymal stromal cells is another field of growing interest in meniscal surgery. Orthobiologic therapies aim to stimulate intrinsic healing mechanisms, modulate inflammation, and enhance extracellular matrix

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production, creating a more favourable environment for tissue repair and regeneration [9, 24]. In athletes undergoing meniscus surgery, such approaches may improve outcomes by accelerating the healing response and improving tissue integration. Previous studies highlighted the synergistic potential of combining meniscus surgery with biologically active agents, such as PRP or mesenchymal stromal cells [50, 68]. Preliminary evidence suggests these adjuncts may reduce failure rates and improve functional recovery, although the available evidence remains limited and with scattered results. As research evolves, these strategies have the potential to become integral components of a biologically personalised treatment plan for athletes with meniscal pathology, optimising the overall management of this high-demand patient category together with optimal selection of surgical option and post-operative rehabilitation strategy [51, 52].

From a clinical perspective, this comprehensive analysis confirms the good results achievable by matching the surgical strategy to the athlete's profile. Meniscectomy remains indicated in selected cases where rapid return to sport is prioritised and tissue preservation is not feasible. Meniscal repair represents the treatment of choice whenever possible, combining favourable clinical outcomes with the long-term benefits of native tissue preservation. MAT offers a reliable reconstructive alternative for athletes with previous meniscectomy and persistent symptoms, providing satisfactory outcomes and low complication rates if correctly indicated in motivated patients willing to follow a long rehabilitation process. Ultimately, the choice should be guided by an individualised, multidisciplinary approach aimed at providing a patient-tailored treatment strategy and optimising joint preservation and athletic recovery.

This meta-analysis presents some limitations that require consideration. First, the overall quality of evidence of the included articles was limited, with the presence of risk of bias and several studies with a retrospective design. Second, the selected studies lacked standardisation in data collection and reporting of outcome measures and associated follow-up timeframes, reducing the amount of data available for the meta-analyses and hindering the possibility to meta-analyse patient-reported outcome measures. This, together with the considerable heterogeneity in type and level of sport played, lesion characteristics, outcome definitions, rehabilitation protocols, and surgical techniques, limited the possibility to perform more granular subgroup analyses. Studies reporting only return to competition rate or time to return to competition were not meta-analysed due to the limited data availability and potential confounding factor of injury timing (during season vs off-season). Despite rigorous statistical and analytical methodology, residual confounding remains likely, precluding definitive treatment superiority claims and warranting caution towards comparative evaluations. Finally, the included studies primarily focused on short- to medium-term outcomes, and therefore, the long-term results of meniscectomy, meniscal repair, and MAT on joint health could not be assessed in athletes, neither the impact of each procedure on the joint. Despite these limitations, the present study provided a comprehensive literature analysis on the most used surgical options for meniscal lesions in athletes, offering important information for the choice of the most suitable treatment for this demanding category of patients in clinical practice. The surgical management of meniscal injuries in athletes must rely on a personalised strategy, balancing the need for early functional recovery with the imperative of joint preservation. Meniscectomy, repair, and MAT can all lead to excellent return to sport rates, but with distinct indications and outcome profiles. A deeper understanding of patient characteristics, sport-specific demands, and evolving surgical and regenerative technologies will be essential to refine treatment algorithms and improve care in the challenging and high-stakes athletic population.

CONCLUSION

Meniscectomy, meniscal repair, and MAT are all able to provide high rates of return to sport in athletes. In the investigated treatment cohorts, meniscectomy presented the shortest pooled time to return to sport, followed by meniscal repair and MAT. Importantly, all treatments offered good rates of return to the same level of athletic performance. The treatment choice should be guided by an individualised, multidisciplinary approach aimed at providing a patient-tailored treatment strategy to optimise both athletic recovery and joint preservation.

AUTHOR CONTRIBUTIONS

Alessandro Bensa: Conceptualisation; data curation; formal analysis; investigation; methodology; supervision; validation; visualisation; writing—original draft. **Andrea Piano**: Data curation; formal analysis; investigation; methodology; visualisation; writing—original draft. **Giacomo Arthur Fumagalli**: Data curation; formal analysis; investigation. **Aaron John Krych**: Validation; writing—review and editing. **Peter Verdonk**: Validation, writing—review and editing. **Giuseppe Filardo**: conceptualisation; investigation; methodology; project administration; resources; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

None declared. PROSPERO ID: CRD420251008615.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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