










Anterior Cruciate Ligament Reconstruction With Hamstring Autografts and Suture Tape Augmentation Results in Lower Failure Rates While Maintaining Functional Outcomes and Complication Rates Similar to Nonaugmented Techniques

A Systematic Review and Meta-analysis

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Background: Anterior cruciate ligament reconstruction with suture augmentation (ACLR-SA) has been explored for its potential to provide additional graft protection.

Purpose: To compare failure rates, complications, patient-reported outcomes, and return to sport between ACLR-SA and non-augmented ACLR.

Study Design: Systematic review and meta-analysis; Level of evidence, 2.

Methods: Randomized controlled trials and quasi-experimental studies were included if they provided data on population (patients with anterior cruciate ligament tear), intervention (ACLR-SA regardless of SA material and graft type), comparator (non-augmented ACLR), and outcomes (failure, arthrofibrosis and cyclops, subsequent meniscal surgery, hardware removal, Lysholm and International Knee Documentation Committee scores, and/or return to sport).

Results: Eleven articles (1179 patients) were included. ACLR performed with hamstring autograft augmented with FiberTape reduced failure rates as compared with non-augmented ACLR (3.1% vs 8.5%; odds ratio [OR], 2.86; 95% CI, 1.03-7.90; $P = .043$; $I^2 = 0\%$). In addition, the 2 techniques showed no differences in arthrofibrosis/cyclops (OR, 0.94; 95% CI, 0.26-3.33; $P = .919$; $I^2 = 0\%$), subsequent meniscal surgery (OR, 1.05; 95% CI, 0.32-3.44; $P = .942$; $I^2 = 0\%$), International Knee Documentation Committee score (mean difference, -1.20 ; 95% CI, -3.06 to 0.06 ; $P = .206$; $I^2 = 0\%$), and Lysholm score (mean difference, -0.96 ; 95% CI, -4.53 to 2.61 ; $P = .597$; $I^2 = 65\%$). When the FiberWire was utilized for hamstring autograft suture augmentation, no significant differences in failure rates were observed between groups. The pooled synthesis for all graft and augmentation combinations showed that ACLR-SA was associated with an increased return to preinjury activity level (72.5% vs 54.0%; OR, 0.44; 95% CI, 0.21-0.91; $P = .027$; $I^2 = 0\%$).

Conclusion: Available evidence supports the use of suture tape augmentation in ACLRs performed with hamstring autografts, as it reduces failure rates while maintaining equivalent complication rates and patient-reported outcomes as compared with non-augmented ACLR.

Keywords: ACL; ACL reconstruction; failure rates; suture augmentation

Anterior cruciate ligament (ACL) tears rank among the most common orthopaedic injuries, with an incidence of approximately 1 in every 1330 individuals in the United States.⁹ ACL reconstruction (ACLR) is the standard of care for patients seeking to return to sports, generally yielding favorable outcomes.^{12,24,37,42} However, failure rates remain a concern, ranging from 3% to 25%,^{2,6,27,62} depending on patient characteristics, surgical techniques, and rehabilitation protocols. To reduce failure rates, surgeons have incorporated additional procedures alongside ACLR, such as lateral extra-articular procedures, varus and slope correction osteotomies, meniscal ramp lesion repair, and biological and intra-articular augmentations.^{5,21,28,33,52,53}

Intra-articular augmentations have been employed to enhance tensile strength and protect grafts from irreversible elongation.^{3,40,49} Early devices, such as the Kennedy ligament augmentation device and ligament advanced reinforcement system, failed to show advantages and were associated with higher rates of failure, synovitis, effusion, and infection.^{8,30,32,57} Suture augmentation (SA), which uses smaller biocompatible materials to minimize disturbances to the intra-articular environment, has recently gained attention in the literature. These techniques employ polyethylene sutures or tapes to brace the graft internally.^{3,49} The material is tensioned and fixed independently and more loosely than the graft during ACL surgery, offering additional protection against excessive strain, particularly during the ligamentization process.^{49,50}

Preliminary evidence from biomechanical studies, animal models, and case series have demonstrated promising results regarding SA mechanical properties and safety.^{7,17,35,43} Subsequently, clinical studies were conducted to compare outcomes between ACLR with SA (ACLR-SA) and nonaugmented ACLR.[#] A previous systematic review²² compared the outcomes of 5 such studies^{11,19,31,46,58} but did not perform a meta-analysis owing to the variability of outcome measures. While the review indicated comparable graft failure rates and clinical outcomes between the groups, it concluded that the evidence was insufficient for definitive conclusions.

Since that review, other clinical studies have been published, including data that may strengthen the power of pooled outcomes.^{18,39,55,56} Therefore, we aimed to update the previous systematic review comparing ACLR-SA with nonaugmented ACLR by doubling the population size

and conducting a meta-analysis. We hypothesized that ACLR-SA would have lower failure rates and similar complication rates when compared with nonaugmented ACLR.

METHODS

This systematic review with meta-analysis was prospectively registered in PROSPERO (CRD42024580938) and conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines and the *Cochrane Handbook for Systematic Reviews of Interventions*.^{13,45}

Eligibility Criteria

The inclusion criteria were (1) randomized controlled trials (RCTs) and quasi-experimental studies and (2) full-text peer-reviewed articles published in English that included the following (based on the PICO method):

Population: skeletally mature patients from all competitive sport levels with ACL rupture

Intervention: ACLR-SA performed with any SA material and any graft type

Comparator: nonaugmented ACLR with any graft type as the control

Outcomes: complications such as failure, arthrofibrosis, subsequent meniscal surgery, hardware removal, and infection; patient-reported outcomes (PROs) such as Lysholm and International Knee Documentation Committee (IKDC) scores; and return to sport (RTS)

The exclusion criteria were (1) studies without a control group, (2) biomechanical studies conducted in vitro, (3) studies including patients with partial ACL ruptures or revision surgery, and (4) interventions with other techniques in addition to the augmentation (eg, bone marrow aspirate). Only data from the largest sample size were included for articles with overlapping populations.

Information Sources and Search Strategy

We systematically searched PubMed, Embase, and Cochrane Library from inception to September 2024 with the following search strategy: (ACLR OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction”) AND

[#]References 11, 18, 19, 31, 39, 40, 46, 48, 55, 56, 58.

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(“suture tape” OR augmented OR augmentation OR reinforced OR reinforcement OR “internal brace”).

Study Selection and Data Collection

Registers identified in the systematic search were imported into Zotero for manual duplicate removal. The deduplicated data set was uploaded into Rayyan for screening. Two reviewers (R.B.C. and A.R.S.O.F.) independently screened titles and abstracts to identify studies meeting the inclusion criteria. Full texts were then assessed for eligibility and outcome inspection. A third reviewer (D.P.L.) resolved discrepancies.

Two reviewers (R.B.C. and E.M.) independently collected data based on predefined criteria: general study information (design and follow-up), number of patients and their characteristics, surgical techniques for intervention and control, number of events for complications and RTS, and mean and standard deviation for PROs. For other measures of dispersion, standard deviation was estimated following Cochrane handbook guidelines.¹³

Bias Analysis

The Cochrane Risk-of-Bias 2 tool was used to evaluate bias in the RCT across 5 domains: randomization, deviations from intended interventions, missing outcome data, outcome measurement, and selection of reported results. Overall bias was categorized as low risk, some concerns, or high risk. For nonrandomized studies, the ROBINS-I tool assessed bias as low, moderate, serious, or critical through 7 domains: confounding, intervention classification, participant selection, deviations from intended interventions, missing data, outcome measurement, and selection of reported results. Two authors (R.B.C. and V.F.C.) performed the assessments.

Outcome Measures and Statistical Analysis

All statistical analyses were performed with R programming language (Version 4.4.2). Meta-analyses were performed when the outcome was reported in >3 studies. Dichotomous outcomes were analyzed per the random effects Mantel-Haenszel method, presenting odds ratios (ORs) and 95% confidence intervals (95% CIs). Continuous outcomes were assessed with the random effects inverse-variance method, presenting mean differences (MDs) with 95% CIs. Heterogeneity was evaluated by I^2 , Cochran Q test, and τ^2 (restricted maximum likelihood estimator). Heterogeneity was categorized as follows: might not be important ($I^2 = 0\%$ -40%), moderate heterogeneity ($I^2 = 30\%$ -60%), substantial heterogeneity ($I^2 = 50\%$ -90%), or considerable heterogeneity ($I^2 = 75\%$ -100%).²⁰

Subgroup analyses were conducted to explore sources of heterogeneity ($I^2 > 30\%$) and to verify nuances within specific patient subsets. Subgroups were based on ACLR graft type—hamstring tendon (HT), quadriceps tendon (QT), or bone-patellar tendon-bone (BTB)—and augmentation

material such as FiberTape (Arthrex), FiberWire (Arthrex), and Infinity-Lock (Xiros). Sensitivity analyses were performed when heterogeneity ($I^2 > 30\%$) persisted after subgrouping. Leave-1-out sensitivity analysis was applied to evaluate the stability of pooled effects by excluding 1 study at a time from a subgroup model. A Baujat plot was used to visually assess each study's contribution to overall heterogeneity. Meta-regression was used to estimate the influence of other baseline patient characteristics (age and sex) on treatment effect.

Reporting Bias and Certainty Assessment

Potential reporting bias was assessed visually with funnel plots and numerically with the Egger test in cases of visual asymmetry. The overall quality of evidence was evaluated according to the GRADE (Grading of Recommendations, Assessment, Development, and Evaluations) guidelines. Each outcome was rated as having either “serious limitation” or “no serious limitation” across the following domains: risk of bias, imprecision, inconsistency, indirectness, and publication bias. The overall certainty of evidence for each outcome was then categorized as very low, low, moderate, or high.

RESULTS

Study Selection

The systematic search identified 2066 articles. After duplicate removal and the exclusion of ineligible studies, 30 full-text articles were screened per the inclusion and exclusion criteria. Of these, 19 studies were excluded and 5 were included in the previous review. Six additional studies met all inclusion criteria, resulting in a total of 11 articles[#] in this systematic review and meta-analysis (Figure 1).²⁶

Study Characteristics

A total of 1179 patients were included in this meta-analysis, with 552 (47%) undergoing ACLR-SA. Most studies (8 of 11) used FiberTape for augmentation, accounting for 339 patients (61%). Two studies employed No. 5 FiberWire for the augmentation among 143 ACLRs (26%), while 1 study utilized the Infinity-Lock for 70 augmentations (13%). The most common graft choice was the HT, as used in 879 patients (75%), whereas BTB and QT grafts accounted for 183 (15%) and 117 (10%) patients, respectively. Only 1 study utilized grafts other than autografts, incorporating semitendinosus allografts and mixed autografts/allografts.¹¹ A detailed description of the technical characteristics of each study is provided in Table 1. Sample sizes across the studies ranged from 20 to 111 patients. Five studies had a mean patient age between 21 and 30 years, 3 studies had a mean age <21 years, while the mean age was >30 years in 3 studies. Overall, 422 females (36%) were included (Table 2).

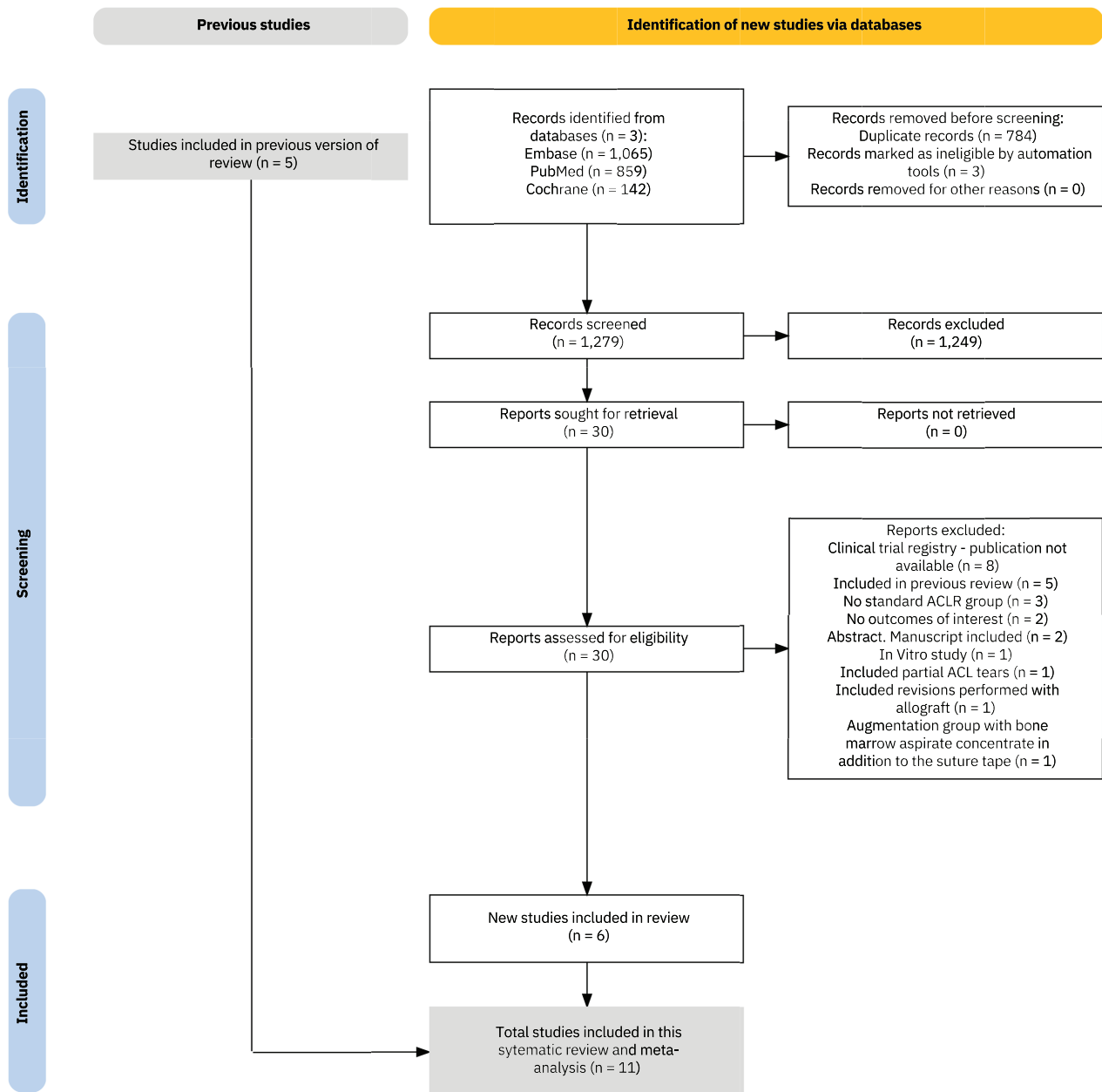


Figure 1. Study selection process according to the PRISMA guidelines. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction.

Failure was reported in all studies: “ACL reinjury requiring revision,”¹¹ “graft failure/ACL revision,”^{18,19,46,48,55} “graft rupture or recurrent instability symptoms,”³¹ “ACL rerupture,”^{56,58} and “persistent clinical instability resulting from ruptured, lax, or otherwise incompetent graft confirmed on MRI.”⁴⁰ Daniel et al¹⁹ reported failure rates for each graft type. The BTB graft data overlapped with a subsequent study by the same authors.¹⁸ In this case, data from the most recent and larger study were included.

Arthrofibrosis/cyclops was reported in 6 studies,^{11,18,46,48,56,58} hardware removal in 3 studies,^{11,18,31} and subsequent meniscal surgery in 5 articles with 1 excluded owing to overlap.^{18,31,46,58} RTS was presented in 4 studies: in 2 studies,^{18,46} patients considered returning to any sports, and in the other 2 studies,^{11,31} they returned to preinjury activity levels. That difference was treated as subgroups in the forest plot. Six studies evaluated PROs using Lysholm^{31,39,46,48,55,56} and IKDC.^{11,39,46,48,55,56}

TABLE 1
Specific Technical Characteristics of ACLR With and Without Suture Augmentation in Each Study^a

Study	Graft Type	Augmentation Device	ACLR Technique	Fixation Method	Tunnel Technique
Bodendorfer (2019) ¹¹	Quadrupled ST	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory (ACL TightRope + ABS) Tibial: Suspensory (ABS) SA: SwiveLock	Femoral: Retrograde drilling (FlipCutter) Tibial: Retrograde drilling (FlipCutter)
Daniel (2023/2024) ^{18,19}	All soft tissue QT, BTB, or quadrupled ST	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory adjustable loop device (TightRope) Tibial: Suspensory adjustable loop device (TightRope) (QT and HT); absorbable interference screw (BTB) SA: SwiveLock	Femoral: Antegrade drilling through AM Tibial: retrograde drilling tibial socket (QT and HT) or full tibial tunnel (BTB grafts)
Kitchen (2022) ³¹	Quadrupled HT (double ST and double gracilis)	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory (ACL TightRope) Tibial: interference screw SA: the 2 limbs of the tape are tied on the outer cortex of the interference screw on the tibia	Femoral: Retrograde drilling (FlipCutter) Tibial: Standard tunnel creation
Meng (2024) ³⁹	4- or 5-strand HT (ST and gracilis)	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory Endobutton Fixation System Tibial: bioresorbable interference screw SA: SwiveLock anchor (In the nonaugmentation group, the suture tails of the sutured grafts were secured with a staple made of Kuntzcher wire as secondary fixation.)	Femoral: Antegrade drilling through AM portal Tibial: Standard tunnel creation
Mohan (2023) ⁴⁰	6-strand HT (ST and gracilis)	Infinity-Lock neoligament (Xiros)	Anatomic single bundle	Femoral: Hybrid technique—suspensory fixation with a 20-mm Endobutton Fixation System, with aperture fixation using a bioabsorbable shim wedge (Megashim) Tibial: Interference screw (Biosure) SA: Sutured to the graft using 2-0 Vicryl and fixated within the tibial tunnel with an interference screw.	Femoral: Antegrade drilling through AM portal Tibial: Standard tunnel creation
Parkes (2021) ⁴⁶	Quadrupled ST or combined quadrupled ST and gracilis	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory (ACL TightRope) Tibial: Suspensory (ACL TightRope + ABS) SA: SwiveLock anchor	Femoral: Antegrade drilling through AM portal Tibial: Retrograde drilling tibial socket (FlipCutter)
Ramadan (2022) ⁴⁸	Quadrupled ST	FiberTape (Arthrex)	Anatomic single bundle	Femoral: Suspensory (ACL TightRope) Tibial: Suspensory (ABS) SA: ABS (tightened independently of the graft)	Femoral: Antegrade drilling through AM portal Tibial: Retrograde drilling tibial socket (FlipCutter)
Tavakoli Darestani (2023) ⁵⁵	Quadrupled ST	No. 5 FiberWire (Arthrex)	Anatomic single bundle	Femoral: Suspensory Retrobutton Tibial: Biocomposite interference screw SA: 3.5-mm stainless-steel fully threaded cortical screw and washer	Not specified

(continued)

TABLE 1
(continued)

Study	Graft Type	Augmentation Device	ACLR Technique	Fixation Method	Tunnel Technique
Tensho (2024) ⁵⁶	HT (ST tendon divided into AM and PL bundles). Gracilis tendon is added if ST length or thickness is insufficient.	No. 5 FiberWire (Arthrex)	Double bundle	Femoral: Suspensory (ACL TightRope RT) Tibial: DSP system SA: Tied to the DSP on a blunt hook, securing the suture slightly looser than each graft.	Femoral: Outside-in technique for creating AM and PL bundle tunnels Tibial: Full-length tunnels for AM and PL bundles.
von Essen (2022) ⁵⁸	All soft tissue QT or quadrupled ST	FiberTape (Arthrex)	Anatomic single bundle	Femoral: ACL Tight-Rope RT Tibial: Tight-Rope ABS with a 14- or 20-mm button SA: tied over the tibial Tight-Rope ABS button in full extension.	Femoral: Antegrade drilling through AM portal Tibial: Standard tunnel creation

^aABS: Attachable Button System (Arthrex); Biosure Regenesorb (Smith & Nephew); DSP: Double Spike Plate (Meira Co); Endobutton (Smith & Nephew Endoscopy); Endobutton Fixation System (Smith & Nephew); Infinity-Lock Button System (Xiros); Megashim (Biovision GmbH); No. 5 FiberWire (Arthrex); Retrobotton (Arthrex). ACLR, anterior cruciate ligament reconstruction; AM, anteromedial; BTB, bone–patellar tendon–bone; HT, hamstring; PL, posterolateral; QT, quadriceps tendon; SA, suture augmentation; ST, semitendinosus.

TABLE 2
Characteristics of the Studies in the Meta-analysis^a

Study	Design	SA Material	ACLR/ACLR-SA, No.		ACLR/ACLR-SA, Mean			Outcomes
			Graft Choice	Female	Age, y	BMI	Follow-up, mo	
Bodendorfer (2019) ¹¹	Retrospective	FiberTape (Arthrex)	HT: 19/21 HTallo: 2/2 HTcom: 9/7	17/17	30/29	26.7/25.8	30/29	Failure, arthrofibrosis, HR, MR, RTS, Lysholm, IKDC
Daniel (2023) ¹⁹	Retrospective	FiberTape (Arthrex)	HT: 28/26 QT: 26/51 BTB: 46/23	51/51	20/19	26.1/25.5	49/33	Failure, HR, MR
Daniel (2024) ¹⁸	Retrospective	FiberTape (Arthrex)	BTB: 62/52	35/20	18/19	27.0/26.6	62/60	Failure, HR, MR, RTS
Kitchen (2022) ³¹	Retrospective	FiberTape (Arthrex)	HT: 40/40	22/21	15/16	NR	29/28	Failure, HR, MR, infection, RTS, Lysholm
Meng (2024) ³⁹	Retrospective	FiberTape (Arthrex)	HT: 20/20	5/5	36/34	25.2/25.4	24/24	Failure, Lysholm, IKDC
Mohan (2023) ⁴⁰	Retrospective	Infinity-Lock (Xiros)	HT: 111/70	23/18	30/34	28.5/27.7	20/18	Failure
Parkes (2021) ⁴⁶	Retrospective	FiberTape (Arthrex)	HT: 72/36	22/11	25/25	25.0/25.9	31/26	Failure, MR, arthrofibrosis, cyclops, infection, RTS, Lysholm, IKDC
Ramadan (2022) ⁴⁸	RCT	FiberTape (Arthrex)	HT: 20/21	0/0	27/30	NR	18/18	Failure, arthrofibrosis, Lysholm, IKDC
Tavakoli Darestani (2023) ⁵⁵	Retrospective	No. 5 FiberWire (Arthrex)	HT: 79/90	7/2	32/30	27.5/26.3	24/24	Failure, infection, Lysholm, IKDC
Tensho (2024) ⁵⁶	Retrospective	No. 5 FiberWire (Arthrex)	HT: 53/53	30/31	28/29	NR	25/26	Failure, cyclops, Lysholm, IKDC
von Essen (2022) ⁵⁸	Retrospective	FiberTape (Arthrex)	HT: 20/20 QT: 20/20	9/9 8/8	29/29 29/30	NR	24/24 24/24	Failure, cyclops, MR

^aACLR, anterior cruciate ligament reconstruction; BTB, bone–patellar tendon–bone; HR, hardware removal; HT, hamstring tendon; HTallo, hamstring allograft tendon; HTcom, hamstring combined (autograft and allograft); IKDC, International Knee Documentation Committee; MR, meniscal repair; NR, not reported; QT, quadriceps tendon; RCT, randomized controlled trial; RTS, return to sport; SA, suture augmentation.

Synovitis^{46,48,56,58} and infections^{31,46,55} were summarized narratively, as meta-analysis was not feasible.

Risk of Bias

The RCT had a low risk of bias in 4 domains analyzed, with some concerns with bias noticed in the domain of outcome measurement. Regarding nonrandomized studies, 4 articles^{46,55,56,58} had a low risk of bias (40%), and in 6 articles,^{11,18,19,31,39,40} some concerns were identified (60%). Bias attributed to confounding was the main source of bias (Figure 2).

Pooled Analysis Results

Complications. Considering all graft and augmentation types, ACLR-SA was associated with a significantly lower rate of graft failure as compared with standard ACLR (2.5% vs 5.7%; OR, 2.01; 95% CI, 1.02-3.94; $P = .043$; $I^2 = 0\%$; high-certainty evidence) (Figure 3). Rates of the following were not significantly different between ACLR-SA and standard ACLR: arthrofibrosis/cyclops (6.9% vs 6.5%; OR, 0.96; 95% CI, 0.47-1.96; $P = .917$; $I^2 = 0\%$; moderate-certainty evidence), subsequent meniscal surgery (3.0% vs 7.0%; OR, 1.72; 95% CI, 0.61-4.86; $P = .304$; $I^2 = 0\%$; moderate-certainty evidence), and hardware removal (2.5% vs 2.3%; OR, 0.90; 95% CI, 0.20-4.06; $P = .893$; $I^2 = 0\%$; moderate-certainty evidence) (Figures 4-6).

Two studies^{46,56} reported no cases of synovitis in their ACLR-SA groups, while von Essen et al⁵⁸ and Ramadan et al⁴⁸ each documented 2 cases. Overall, synovitis was observed in 4 of 150 patients receiving ACLR-SA (2.7%). In the nonaugmented ACLR group, Parkes et al⁴⁶ reported 1 infection requiring arthroscopic irrigation and debridement, and Tavakoli Darestani et al⁵⁵ noted 1 infection managed with arthroscopic joint lavage. In the ACLR-SA group, Kitchen et al³¹ documented 1 superficial infection successfully treated with oral antibiotics.

Patient-Reported Outcomes. There was no difference between groups in both PROs analyzed: IKDC score (MD, -3.29; 95% CI, -7.94 to 1.36; $P = .166$; $I^2 = 79\%$; very low-certainty evidence) and Lysholm score (MD, -2.01; 95% CI, -6.21 to 2.20; $P = .350$; $I^2 = 82\%$; very low-certainty evidence) (Figures 7 and 8).

Return to Sport. In the ACLR-SA group, there was a higher rate of return to preinjury activity level as compared with nonaugmented ACLR (72.5% vs 54.0%; OR, 0.44; 95% CI, 0.21-0.91; $P = .027$; $I^2 = 0\%$), while both groups had an equivalent return to any sport (89.8% vs 87.3%; OR, 0.79; 95% CI, 0.33-1.86; $P = .588$; $I^2 = 0\%$). Data are available in Figure 9.

Subgroup and Sensitivity Analyses

Five subgroup analyses emerged from 2 patient subsets (graft and augmentation types):

Subgroup A: HT autograft with or without FiberTape

Subgroup B: HT autograft with or without FiberWire

Subgroup C: HT autograft with or without InfinityLock

Subgroup D: BTB with or without FiberTape

Subgroup E: QT with or without FiberTape

Subgroup A: HT Autograft With or Without FiberTape. FiberTape augmentation of hamstring autografts in ACLR significantly reduced failure rates as compared with nonaugmented techniques (3.1% vs 8.5%; OR, 2.86; 95% CI, 1.03-7.90; $P = .043$; $I^2 = 0\%$) (Figure 3). As seen in the pooled analysis, hamstring autografts with or without FiberTape also showed equivalent rates of arthrofibrosis/cyclops and subsequent meniscal surgery (Figures 4 and 5).

IKDC scores were comparable between groups (MD, -1.20; 95% CI, -3.06 to 0.06; $P = .206$; $I^2 = 0\%$; low-certainty evidence). With subgroup analysis, heterogeneity decreased from 79% (pooled analysis) to 0% (subgroup A), indicating that it might not be important (Figure 7). Similarly, for the Lysholm score, no significant differences were found (MD, -0.96; 95% CI, -4.53 to 2.61; $P = .597$; $I^2 = 65\%$; very low-certainty evidence). Although subgrouping reduced heterogeneity from 82% (pooled analysis) to 65% (subgroup A), substantial heterogeneity persisted (Figure 8). A Baujat plot identified an outlier,³⁹ and a leave-1-out analysis estimated that removing this study reduced heterogeneity to 29% (Appendix 1, Figures A1 and A2, available in the online version of this article). Meta-regression demonstrated with statistical significance that sex ($P = .0154$) and age ($P = .0419$) did not fully account for the residual heterogeneity.

Subgroups B-D: Other Augmentation Devices and Graft Types. Subgroup B (HT autograft with or without FiberWire) included 2 studies with 275 patients; subgroup C (HT autograft with or without InfinityLock), 1 study with 181 patients; subgroup D (BTB with or without FiberTape), 1 study with 114 patients; and subgroup E (QT with or without FiberTape), 2 studies with 117 patients. No statistically significant differences in failure rates were observed between augmented and nonaugmented techniques in any of these subgroups (B, $P = .899$; C, $P = .453$; D, $P = .121$; E, $P = .279$). Data are available in Figure 3.

Reporting Biases

The funnel plots showed no evidence of potential publication bias for complications and RTS. However, there was visual asymmetry for the IKDC and Lysholm funnel plots, indicating publication bias. Egger test values ($P = .2559$ and $P = .4406$) did not confirm visual assumptions (Appendix 2, available online).

Certainty of Evidence

A synthesis based on the GRADE approach (Table 3) rated failure rates as high-certainty evidence, complications and RTS as moderate, and PROs as low/very low.

A RoB 2 Tool

		Risk of bias domains					
		D1	D2	D3	D4	D5	Overall
Study	Ramadan 2022						
	Domains: D1: Bias arising from the randomization process. D2: Bias due to deviations from intended intervention. D3: Bias due to missing outcome data. D4: Bias in measurement of the outcome. D5: Bias in selection of the reported result.						Judgement Some concerns Low

B ROBINS-I Tool

		Risk of bias domains							
		D1	D2	D3	D4	D5	D6	D7	Overall
Study	Bodendorfer 2019								
	Daniel 2023								
	Daniel 2024								
	Kitchen 2022								
	Meng 2024								
	Mohan 2023								
	Parkes 2021								
	Tavakoli Darestani 2023								
	Tensho 2024								
	von Essen 2022								
Domains: D1: Bias due to confounding. D2: Bias due to selection of participants. D3: Bias in classification of interventions. D4: Bias due to deviations from intended interventions. D5: Bias due to missing data. D6: Bias in measurement of outcomes. D7: Bias in selection of the reported result.						Judgement Moderate Low			

Figure 2. Risk-of-bias assessment of included studies. RoB-2, Cochrane Risk-of-Bias 2 tool.

DISCUSSION

This systematic review and meta-analysis, encompassing 11 studies and 1179 patients, compared ACLR-SA with nonaugmented ACLR. The main findings of this meta-analysis are that ACLR with hamstring autografts

augmented with FiberTape significantly reduced failure rates from 8.5% to 3.1% when compared with nonaugmented techniques, while maintaining equivalent PROs (IKDC and Lysholm scores) and complication rates for arthrofibrosis/cyclops and subsequent meniscal surgery. Conversely, when FiberWire was utilized for HT SA, no

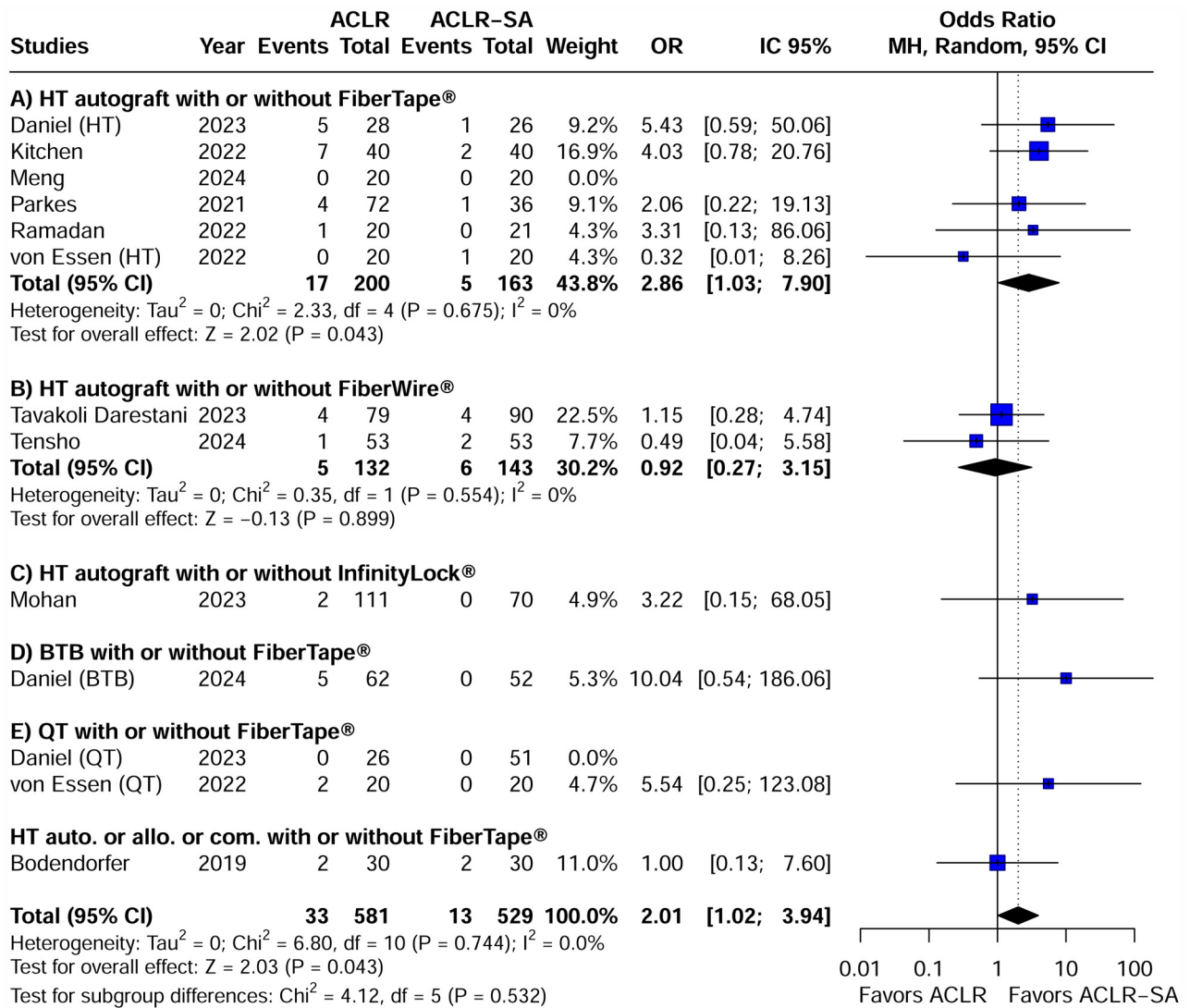


Figure 3. ACLR performed with hamstring autograft augmented with FiberTape reduced failure rates as compared with standard nonaugmented ACLR. ACLR, anterior cruciate ligament reconstruction; BTB, bone–patellar tendon–bone; HT, hamstring; OR, odds ratio; QT, quadriceps tendon; SA, suture augmentation.

significant differences were observed in failure rates. For other graft and augmentation combinations, only a small number of studies were available for inclusion, limiting the statistical power of the analysis and emphasizing the need for future research. However, a pooled analysis on return to preinjury activity level was possible and showed that ACLR-SA increased rates from 54.0% to 72.5%.

ACLR-SA consists of bridging the ACL graft with a non-absorbable suture or tape, offering additional protection against excessive strain while supporting the healing and ligamentization process.^{1,16} A scoping review synthesizing biomechanical studies concluded that suture-augmented grafts are 12.2% to 73.0% stronger and exhibit 17.0% to 60.2% less elongation than nonaugmented grafts.³⁵ One of the studies reported that FiberTape SA increased the

load to failure from 473 ± 169 N to 744 ± 219 N (mean ± SD).³⁸

These biomechanical advantages likely underpin the main finding of the present meta-analysis—that ACLR with FiberTape-augmented HT autografts reduced failure rates from 8.5% to 3.1%. ACLR failure rates in the literature vary considerably, ranging from 3% to 25%,^{2,6,27,62} primarily depending on the studied population. In this meta-analysis, the failure rates align with previously reported data. Moreover, for all graft and augmentation types, the pooled failure rate of 2.5% in the ACLR-SA group falls below this range, highlighting its protective effect against graft failure.

A subgroup analysis of 363 patients demonstrated that FiberTape SA significantly reduced failure rates in

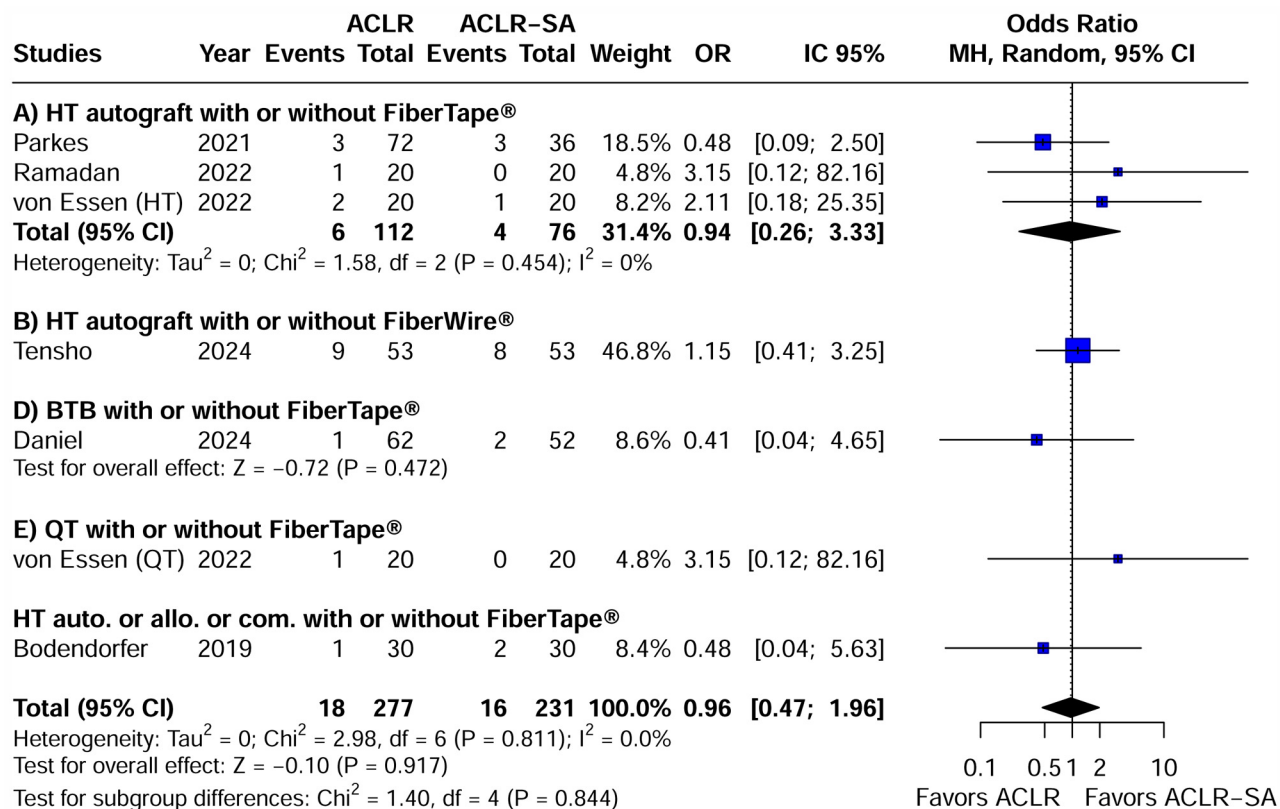


Figure 4. There was no significant difference in arthrofibrosis/cyclops between the groups. ACLR, anterior cruciate ligament reconstruction; BTB, bone-patellar tendon-bone; HT, hamstring; OR, odds ratio; QT, quadriceps tendon; SA, suture augmentation.

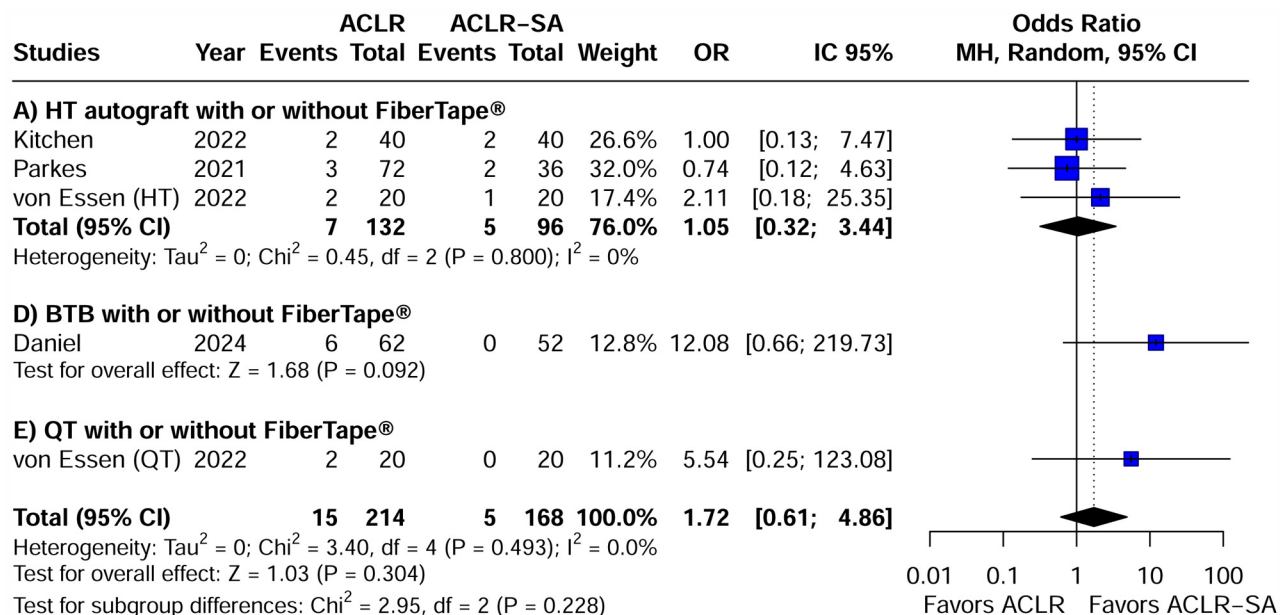


Figure 5. There was no significant difference in subsequent meniscal surgery between the groups. ACLR, anterior cruciate ligament reconstruction; BTB, bone-patellar tendon-bone; HT, hamstring; OR, odds ratio; QT, quadriceps tendon; SA, suture augmentation.

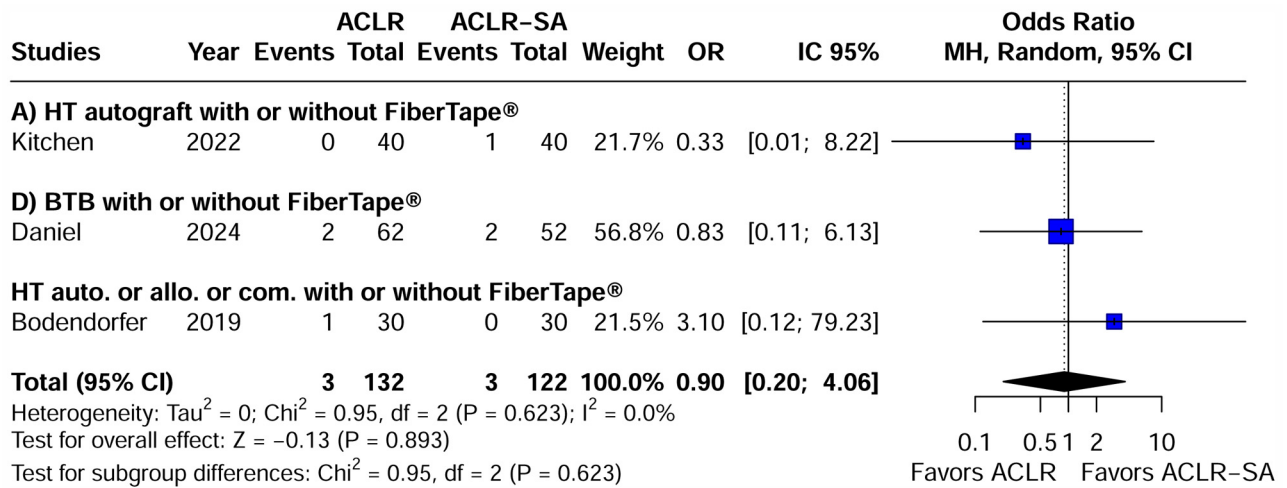


Figure 6. There was no significant difference in hardware removal between the groups. ACLR, anterior cruciate ligament reconstruction; BTB, bone–patellar tendon–bone; HT, hamstring; OR, odds ratio; SA, suture augmentation.

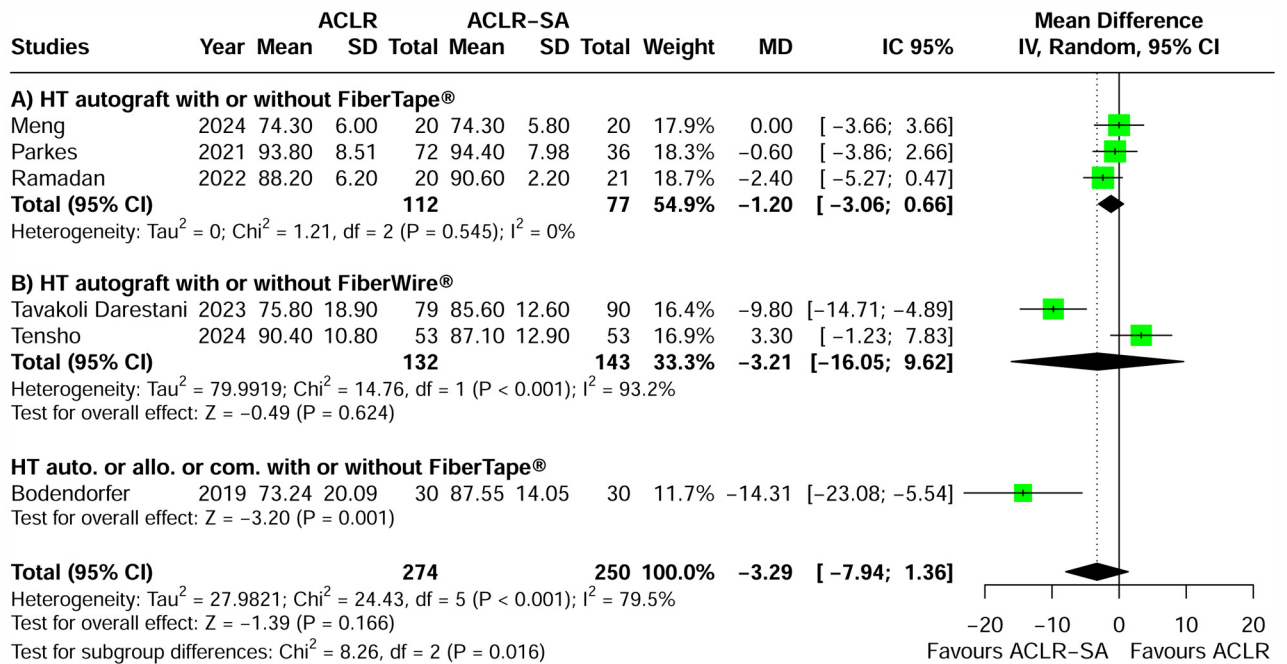


Figure 7. There was no significant difference in IKDC score between the groups. ACLR, anterior cruciate ligament reconstruction; HT, hamstring; IKDC, International Knee Documentation Committee; MD, mean difference; SA, suture augmentation.

reconstructions with HT autografts. Individually, most studies lacked the statistical power to confirm this finding.^{31,39,46,48,58} However, by pooling data, this meta-analysis was the first to have the statistical power to demonstrate this association. In contrast, no statistically significant differences between groups were found in the subgroup analyses for reconstructions with BTB and QT grafts. Yet, the smaller sample sizes of these subgroups

(114 and 117 patients, respectively) may not have sufficient statistical power to detect a significant difference.

Unlike the significant reduction in failure rates observed when FiberTape was used to suture augment HT autografts, FiberWire augmentation showed no significant difference when compared with nonaugmented ACLR. Although studies detailing the ACLR-SA technique have proposed that No. 2 FiberTape and No. 5 FiberWire

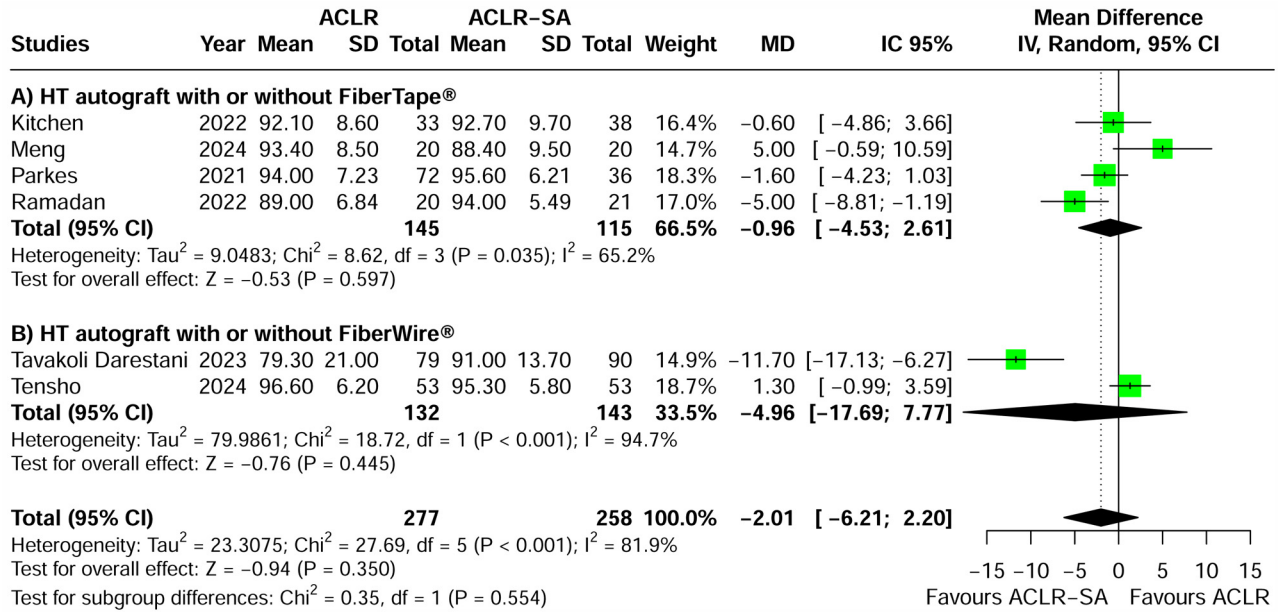


Figure 8. There was no significant difference in Lysholm score between the groups. ACLR, anterior cruciate ligament reconstruction; HT, hamstring; MD, mean difference; SA, suture augmentation.

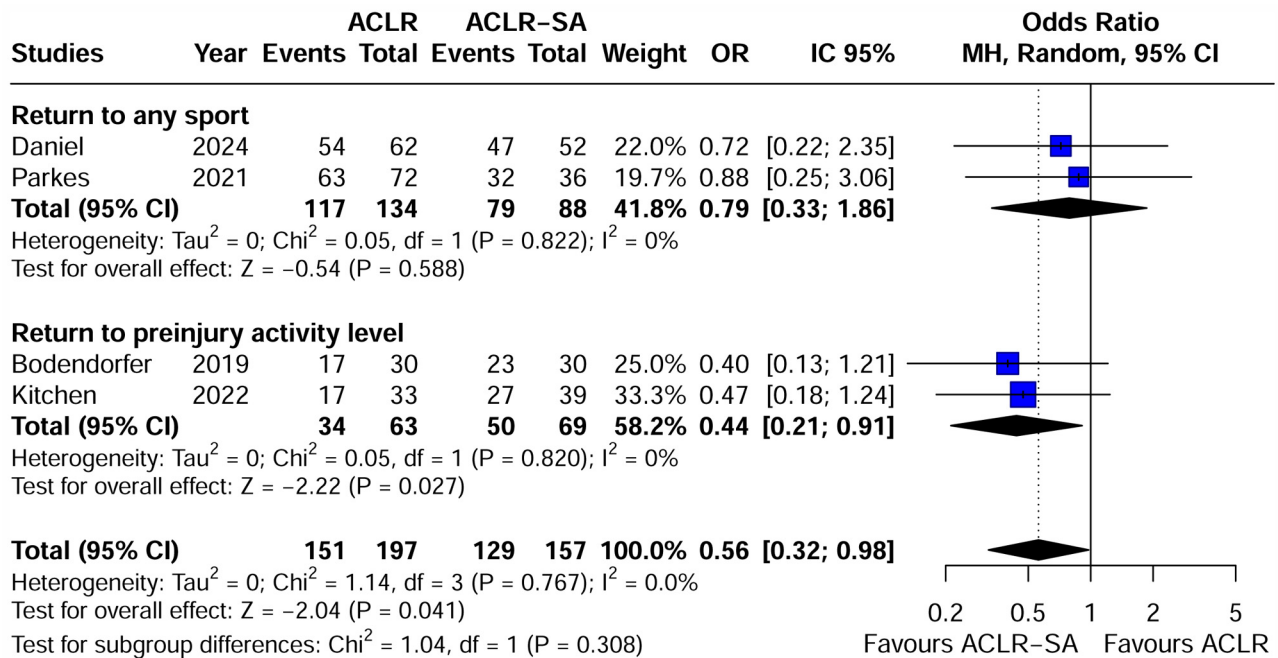


Figure 9. Return to sport was significantly higher after ACLR-SA. ACLR, anterior cruciate ligament reconstruction; OR, odds ratio; SA, suture augmentation.

can be used for SA,^{1,50} the findings of the present meta-analysis suggest that FiberWire may be less effective in preventing failures. This discrepancy may be attributed to differences in thickness and elongation resistance between the materials.

Age is a known risk factor for graft rupture after ACLR, with younger patients being at higher risk.^{36,51,60} Three articles in this meta-analysis focused on populations with a mean age <21 years.^{18,19,31} Pooled data from these studies showed 17 failures among 156 patients (10.9%) in the

TABLE 3
GRADE Summary of Findings and Certainty of Evidence^a

Outcomes: No. (Articles)	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication Bias	Certainty	Relative Effect (95% CI)	What Happens
Graft failures: 1110 (11)	×	×	×	×	×	⊕⊕⊕⊕: High	OR, 2.01 (1.02-3.94)	ACLR-SA decreases graft failure rate.
Subsequent meniscal repairs: 382 (4)	×	×	×	–	×	⊕⊕⊕○: Moderate	OR, 1.72 (0.61-4.86)	ACLR-SA probably results in little to no difference in subsequent meniscal repairs.
Arthrofibroses: 508 (6)	×	×	×	–	×	⊕⊕⊕○: Moderate ^c	OR, 0.71 (0.22-2.28)	ACLR-SA probably does not increase arthrofibroses.
IKDC–subgroup A: 189 (3)	–	×	×	–	×	⊕⊕○○: Low ^{b,d}	MD, –1.20 (3.06-0.66)	Evidence suggests that ACLR-SA results in little to no increase in IKDC.
Lysholm–subgroup A: 260 (4)	–	–	×	–	×	⊕○○○: Very low ^{b,d,e}	MD, –1.20 (3.06-0.66)	Evidence suggests that ACLR-SA results in little to no increase in Lysholm.
Return to sport: 354 (4)	×	×	×	–	×	⊕⊕⊕○: Moderate ^f	OR, 0.56 (0.32-0.98)	ACLR-SA may result in higher rate of return to sport.

^aGRADE criteria: ×, no serious limitations; –, serious limitations. Subgroup A: hamstring autograft with or without FiberTape. ACLR-SA, anterior cruciate ligament reconstruction with suture augmentation; IKDC, International Knee Documentation Committee.

^bNot upgraded for imprecision owing to sample size <400, and confidence intervals included no effect and moderate benefits.

^cNot upgraded for imprecision owing to confidence intervals including a small effect for benefits and disadvantage.

^dNot upgraded for risk of bias owing to moderate risk in the domains of confounding and measurement of outcomes.

^eNot upgraded for inconsistency owing to substantial heterogeneity ($I^2 \geq 50\%$)

^fNot upgraded for imprecision owing to sample size <400, and confidence intervals included small and large effects that benefit ACLR-SA.

nonaugmented ACLR group, as opposed to 3 failures among 169 patients (1.8%) in the ACLR-SA group (OR, 5.72; 95% CI, 1.73-18.89; $P = .004$; $I^2 = 0\%$). This finding suggests that the protective effect of SA may be greater for younger patients, who are at higher risk for failure. However, as these studies did not exclusively include individuals aged <21 years but only reported the mean age as <21 years, definitive conclusions cannot be drawn, and more evidence is needed to confirm this observation. Similarly, athletes of pivoting sports such as soccer, football, and basketball are at higher risk of graft rupture after ACLR.^{25,59} Webster et al⁶¹ reported that 40% of the evaluated players sustained a subsequent ACL injury. As with younger patients, other groups with a high risk of failure, such as pivoting sports practitioners, may benefit from greater protection with SA. Future studies focusing on high-risk groups are needed.

Previous synthetic intra-articular augmentations for ACL grafts have been associated with high rates of complications, such as synovitis and effusions,^{8,30,32,57} raising concerns that SA materials might lead to similar issues.¹⁸ However, preliminary findings from early animal studies indicated no increase in inflammation or adverse events related to foreign body reactions.^{35,54} While cases of complications were reported in the clinical studies in this meta-analysis, there were no significant differences in rates of arthrofibrosis/cyclops (6.9% vs 6.5%), subsequent meniscal surgery (3.0% vs 7.0%), and hardware removal

(2.5% vs 2.3%) observed between the ACLR-SA and non-augmented ACLR groups. For synovitis, a meta-analysis was not feasible because of limited available data. Yet, pooled data indicated a 2.7% incidence (4/150) in ACLR-SA cases, while no cases (0/60) were reported in the non-augmented ACLR group. These findings suggest that SA materials are tolerated within the knee.

Regarding knee function, Bodendorfer et al¹¹ and Daniel et al¹⁹ reported that the SA technique did not overconstrain knee extension, as they observed an equivalent range of motion between knees treated with ACLR with and without SA. Regarding functionality and clinical outcomes, HT autograft with and without FiberTape demonstrated equivalent PRO scores. Overall RTS rates were significantly higher in the ACLR-SA group than in the nonaugmented ACLR group (82.2% vs 76.6%; $P = .041$). However, RTS definitions varied across studies. Two articles^{18,46} defined RTS as a return to any sport, and when these data were pooled, no significant difference was observed between groups (89.8% vs 87.3%; $P = .588$). These rates were higher than those in a meta-analysis of 69 publications by Ardern et al,⁴ which found that 81% (95% CI, 74%-87%) of patients returned to some level of sport after ACLR. Two other studies^{11,31} defined RTS as a return to preinjury activity levels. In this subgroup, ACLR-SA demonstrated a significantly higher RTS rate (72.5% vs 54.0%; $P = .027$). Ardern et al reported that 65% (95% CI, 59%-72%) of patients returned to their

preinjury levels of sport after ACLR. In this meta-analysis, the ACLR-SA group showed higher RTS rates, while the nonaugmented ACLR group had lower rates.

Finally, SA techniques have been safely used in various other ligament and tendon procedures, including medial collateral ligament repair,^{10,34} lateral ankle instability reconstruction,¹⁴ ulnar collateral ligament repair and reconstruction,^{29,44} and posterior cruciate ligament.⁴⁷ For ACL tears, SA has been applied to ACL repair,^{23,41} although a meta-analysis¹⁵ reported higher failure rates in patients who underwent repair with SA versus standard ACLR. In contrast, the present study demonstrates that ACLR-SA results in lower failure rates while preserving functional outcomes and maintaining acceptable complication rates as compared with nonaugmented ACLR. These findings reinforce ACLR-SA as a promising approach for ACL tear management.

Limitations

This study has limitations to acknowledge. Most studies had a retrospective design, introducing an inherent risk of bias attributed to the lack of randomized data. Additionally, baseline demographic and clinical characteristics varied across studies. Subgroup analyses were based on key variables such as SA material and graft type to address this limitation. Definitive conclusions could not be drawn for subgroups other than A and B owing to limited statistical power, emphasizing the need for further research. For PROs, subgrouping did not reduce heterogeneity, prompting meta-regression analysis. Still, much of the heterogeneity remained unexplained after adjusting for sex and age. For instance, 3 studies^{39,40,48} did not assess meniscal injuries as a baseline characteristic, making meta-regression for this variable unfeasible. Another potential limitation is that in 3 articles,^{11,18,19} the surgeons changed their practice by initially not performing SA and later adopting it at a certain point. This resulted in cohorts that were not contemporary, which may introduce performance bias attributed to increased surgeon experience and the evolving use of devices. Future research should evaluate other graft options, such as BTB and QT, and prioritize large-scale RCTs targeting high-risk populations, such as athletes and young adults, to confirm the trends observed in this meta-analysis.


CONCLUSION


This systematic review and meta-analysis, comprising 11 studies with 1179 patients, demonstrated that ACLR with HT autografts augmented with FiberTape results in lower failure rates while maintaining comparable functional outcomes and complication rates as compared with nonaugmented techniques. FiberWire-augmented HT ACLR, in turn, failed to demonstrate differences in failure rates versus nonaugmented reconstructions. The small number of studies available for other graft and

augmentation types limited the reliability of the subgroup analyses, highlighting the importance of further research. However, when data were pooled from all subgroups, ACLR-SA was associated with an increased return to pre-injury activity level.

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