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SCOPING REVIEW PAPERS

From Biology-Limited to Mechanics-Driven Rehabilitation: A Graft-Specific Framework After Artificial Ligament Reconstruction in ACL, PCL, and Multiligament Knee Injuries

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Abstract

Artificial ligament reconstruction introduces a paradigm shift in postoperative rehabilitation by reducing biologic constraints and increasing reliance on mechanical load tolerance. This scoping review aimed to develop a clinically applicable, graft-specific rehabilitation framework across ACL, PCL, and multiligament knee injuries. A structured search of PubMed, Cochrane, and Google Scholar (2010–2025) was conducted following PRISMA guidelines. Eleven studies were included and appraised for methodological quality. A consistent transition from biology-driven to mechanics-driven rehabilitation was identified, enabling earlier weight bearing, muscle activation, and strength progression under controlled conditions. Based on these findings, we propose a rehabilitation velocity framework, integrating graft-specific constraints, neuromuscular readiness, and load tolerance to guide progression. Despite accelerated early-phase rehabilitation, return-to-sport decisions remain dependent on objective functional criteria rather than graft type alone. This framework provides clinicians with a structured, criteria-based approach to safely optimize recovery following artificial ligament reconstruction.

Keywords: *Artificial ligament reconstruction; Graft-specific rehabilitation; Rehabilitation velocity; Multiligament knee injury; Return to sport*

Introduction

The anterior cruciate ligament (ACL) is a ligament that stabilizes the knee. Injury to the ACL causes mechanical instability in the knee, which can seriously impact overall quality of life and athletic performance (Sanders et al., 2016). The incidence of ACL injuries is 68.6 per 100,000 people, especially in people who participate in sports that involve cutting, jumping, and sudden landings, such as football and basketball (Montalvo et al., 2019; Sanders et al., 2016). Epidemiologically, women have a risk of injury reaching 2.10/10,000 athletes, especially in collision sports (Montalvo et al., 2019). Meanwhile, in football, the average number of injuries in women reaches 3% and in men 1.6% (Bloch et al., 2025). ACL injuries can occur alone or with multiple ligament injuries, such as those involving the Posterior Cruciate Ligament (PCL). The prevalence of multiple ligament ACL and PCL injuries is 0.072–0.2% of all orthopaedic injuries, but this figure is often underreported because they frequently occur in conjunction with knee dislocations (Ferré-Aniorte et al., 2025; Ng et al., 2020). Reconstructive surgery is a treatment to restore the stability and functional ability of the knee by installing a graft to reconstruct the ACL and PCL (Ostojic et al., 2024). Graft options for the ACL and PCL can come from autografts (tissue from the patient themselves), allografts (donor tissue), and the use of arti-

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ficial grafts (Ostojic et al., 2024). This artificial graft is here to provide an alternative graft with the potential for faster recovery (Ardern et al., 2011). The advantages of synthetic grafts include: the absence of another surgical wound at the donor site, unlimited availability, consistent and uniform strength and size, and the potential for shorter rehabilitation times because they do not require extensive biological integration like autografts (Ardern et al., 2011). These synthetic grafts are also used for patients who have previously failed autografts and have the potential to accelerate rehabilitation. Although surgical management can improve mechanical stability in up to 80-90% of cases, the risk of complications such as joint stiffness (arthrofibrosis) and secondary graft failure remains a serious threat. Long-term success depends heavily on precise surgical technique and adherence to an aggressive but measured rehabilitation protocol (Ardern et al., 2011). These conditions collectively result in lost playing and training time of up to 8.7-12.4 months (DeFroda et al., 2021). The success rate of athletes achieving Return to Play (RTP) after multiple ligament injuries and having to undergo combined ACL and PCL reconstruction is lower compared to isolated ACL reconstruction (D'Ambrosi et al., 2024). Studies show that only about 22% to 58% of athletes can return to their original competitive sport level after a multiple ligament injury (D'Ambrosi et al., 2024). This success also depends on the accuracy of surgical technique and adherence to appropriate rehabilitation protocols (van Haren et al., 2025). Therefore, this paper aims to compare and synthesize rehabilitation frameworks following biologic and artificial ligament reconstruction across anterior cruciate ligament, posterior cruciate ligament, and multiple ligament knee injury, and to examine how graft type influences rehabilitation philosophy and progression.

Method

This study was conducted as a scoping review to systematically map and synthesize the available evidence on rehabilitation and conditioning following artificial ligament reconstruction in anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and multiligament knee injuries (MLKI). The review methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).

Clinical Questions

Do rehabilitation and conditioning exercise programs following multiple ligament knee reconstruction involving the ACL and PCL using artificial grafts differ from conventional rehabilitation protocols after ACL and PCL reconstruction?

P = Patient ACL, PCL, or MLKI reconstruction
I = Artificial graft
C = Conventional biologic graft
O = Rehab and conditioning exercise protocol (characteristics, progression, and return to sport)

Evidence-based search

A systematic literature search was conducted in PubMed, Cochrane Library, and Scholar for studies published between January 2010 and December 2025 using the PRISMA-ScR flow chart by T.F-R and S.S-R (Figure 1) (Liberati et al., 2009). The search strategy combined Medical Subject Headings (MeSH) and free-text terms as follows: ACL, PCL, multiple ligament knee injury, and artificial graft. Keyword searches were performed using single or combined keywords using the Boolean operators AND and OR, across three article databases (Table 1). For Google Scholar, the first 200 results sorted by relevance were screened. Additionally, reference lists of included studies were manually screened to identify further relevant articles. The conventional rehabilitation protocol, added by the sports medicine team, chose to use the Fowler Kennedy ACL-PCL-Multiple Ligament Injury protocol. (Fowler Kennedy, 2015, 2016a, 2016b), ASPETAR ACL Rehab Protocol (Kotsifaki et al., 2023), and ACL Melbourne Rehab Guide 2.0. Article inclusion and exclusion criteria are based on: (i) article title and abstract containing synthetic graft for multiple ligament injury 2010-2025, (ii) article title and abstract containing treatment and rehabilitation after ACL and PCL reconstruction surgery with synthetic graft, (iii) the article can be accessed in full and uses English, and (iv) the manuscript contains information about the rehabilitation protocol used. Exclusion criteria are based on: (i) the article is a seminar article, (ii) it is not a textbook.

Table 1. Search Strategy

Database	Key Words	Amount
Pubmed	((((((((Artificial graft) AND (multiligament knee injury)) OR (Artificial graft)) AND (ACL)) OR (Artificial graft)) AND (PCL))) OR (Artificial graft)) AND (ACL)) AND (PCL)	18
Cochrane	Artificial graft Multiligament AND / OR Knee AND / OR Injury "ACL PCL."	0
Shcolar	Artificial graft Multiligament OR Knee OR Injury "ACL PCL."	210

All identified records were imported into a reference manager, and duplicates were removed. Two authors screened titles and abstracts, followed by full-text screening. Disagreements were resolved through discussion and agreement with the 3rd and 4th author. Although critical appraisal is not mandatory in scoping reviews according to PRISMA-ScR recommendations, methodological quality assessment will be performed to provide the strengths and limitations of all selected articles. The selected articles will be critically reviewed based on the study design. AMSTAR-2 will be used for systematic reviews, ROBINS-I for cohort studies, JBI critical appraisal checklist for case series, and SANRA for narrative review and clinical commentaries. C.C and S.A-H conducted all assessments. All the selected articles will undergo data extraction, which includes the researcher's name, year of publication, study type, risk of bias, clinical outcome, applicability, and implications for the rehabilitation phase. A narrative synthesis was performed on rehab and conditioning protocols, focusing on rehab phases, progression criteria, graft-specific differences, and rehab velocity and constant shifts. No data analysis or statistical calculations were performed in this study.

Result

The initial search yielded 228 records (Figure 1). Following the screening and eligibility assessment, 11 studies met the predefined inclusion criteria and were included in the critical appraisal (Table 2). These studies consisted of systematic reviews, cohort studies, case series, narrative reviews, and expert opinion reports, indicating a heterogeneous evidence base with varying methodological rigor and levels of evidence (Table 2).

The methodological quality of the included studies ranged from moderate to high. The systematic reviews and meta-analyses appraised using AMSTAR-2 generally demonstrated moderate methodological quality, primarily limited by heterogeneity in rehabilitation protocols, outcome measures, and the inclusion of predominantly non-randomized studies. The cohort studies assessed using ROBINS-I exhibited a moderate risk of bias, mainly due to selection

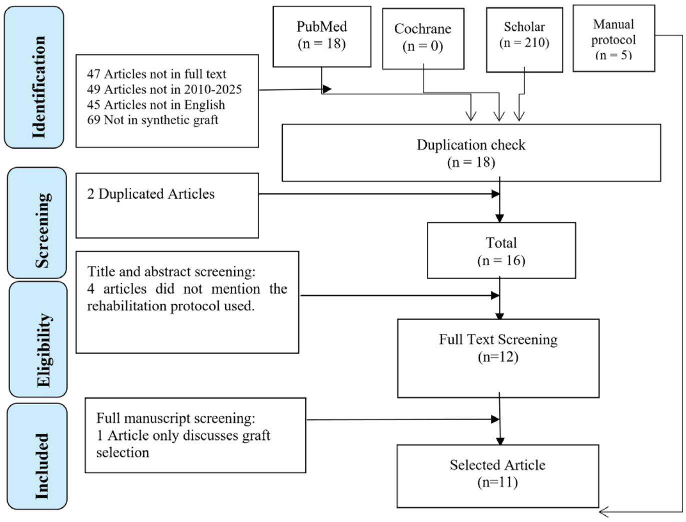

FIGURE 1. Literature Search and Selection Strategy (Prisma Flow Chart)

bias, confounding, lack of randomization, and absence of blinding. The case series evaluated using the JBI Critical Appraisal Checklist demonstrated moderate methodological quality but was limited by small sample size and lack of a comparator group. Narrative reviews and clinical commentaries assessed using SANRA provided valuable conceptual frameworks for rehabilitation but inherently carried a moderate risk of bias because of non-systematic evidence selection and reliance on expert interpretation (Table 2).

Table 2. Critical appraisal table and data extraction

Author (Year)	Study Design & Level of Evidence	Population & Intervention	Internal Validity / Risk of Bias	Clinical Importance (Key Outcomes)	Applicability to Practice	Implications for the Rehabilitation Phase
Arias et al. (Arias et al., 2023)	Systematic review; Level 2a	Patients with multiple ligament knee injury (MLKI) undergoing surgical reconstruction	Moderate risk of bias; limited high-quality comparative trials	Evidence supports the need for prolonged protection and slower progression compared with isolated ACL	Highly applicable for MLKI, including Artificial or hybrid reconstructions	Early: strict protection & controlled ROM; Mid: delayed strengthening; Late: conservative RTS
Migliorini et al. (Migliorini et al., 2022)	Systematic review & meta-analysis; Level 1a	Artificial ACL reconstruction (predominantly LARS)	Low–moderate risk of bias; heterogeneity across included studies	Patient-reported outcomes comparable to autograft; higher incidence of synovitis reported	Supports accelerated but monitored rehabilitation after an Artificial ACL	Early: early ROM & weight-bearing; Mid: faster strength progression; Late: RTS criteria-based
Lee et al. (Lee et al., 2022)	Systematic review; Level 2a	ACL reconstruction, rehabilitation, and return-to-sport criteria	Moderate heterogeneity; rehabilitation protocols varied	Functional and strength-based criteria outperform time-based RTS decisions	Directly applicable to Artificial and biological graft rehabilitation	Late: running, RTS, RTP decisions guided by objective testing
McDonald et al. (McDonald et al., 2021)	Clinical commentary; Level 5	Principles of ACL rehabilitation progression	High risk of bias; non-comparative expert opinion	Highlights the importance of milestone- and criteria-based progression	Useful as a conceptual overlay rather than an evidence driver	All phases: progression based on ROM, strength, and neuromuscular control milestones
Keeling et al. (Keeling et al., 2021)	Narrative review; Level 5	Rehabilitation following multiple ligament knee injury	High risk of bias; narrative synthesis	Emphasizes staged protection and neuromuscular control	Applicable as framework guidance for MLKI rehabilitation	Early: joint protection; Mid: motor control; Late: gradual RTS
Simhal et al. (Simhal et al., 2021)	Retrospective cohort study; Level 3b	Artificial ligament reconstruction of the knee	Moderate risk of bias; lack of randomization and a control group	Demonstrated acceptable stability and early functional improvement	Supports cautious acceleration of rehabilitation	Early–Mid: earlier ROM and closed-chain strengthening with effusion control

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Table 2. Critical appraisal table and data extraction

Author (Year)	Study Design & Level of Evidence	Population & Intervention	Internal Validity / Risk of Bias	Clinical Importance (Key Outcomes)	Applicability to Practice	Implications for the Rehabilitation Phase
Sun et al. (Sun et al., 2020b)	Retrospective cohort study; Level 3b	Artificial PCL reconstruction compared with autograft	Selection bias present; non-randomized design	Comparable stability with earlier functional recovery in the artificial group	Relevant for tailoring PCL Artificial rehabilitation	Early: anterior-biased ROM; Mid: quadriceps dominance; Late: delayed running
Moreira et al. (Moreira, 2020)	Systematic review; Level 2a	Artificial versus biologic ligament reconstruction	Moderate heterogeneity across included studies	Artificial ligaments tolerate earlier loading than biologic grafts	Strong support for modified, accelerated rehab timelines	Early: earlier weight-bearing & ROM; Mid: accelerated strength progression
Ranger et al. (Ranger et al., 2018)	Case series; Level 4	Artificial PCL reconstruction	High risk of bias; small sample size	Reported safe early ROM and improved posterior stability	Informative for early-phase PCL rehabilitation	Early: controlled ROM; Mid: avoid posterior shear forces
Batty et al. (Batty et al., 2015)	Expert review; Level 5	Biomechanics and clinical considerations of Artificial ligaments	High risk of bias; expert opinion	Describes mechanical behavior and potential complications	Provides a mechanistic rationale rather than protocol guidance	All phases: understand graft load tolerance
Beecher et al. (Beecher et al., 2010)	Prospective cohort study; Level 2b	Artificial ACL reconstruction with early functional rehabilitation	Moderate risk of bias; non-randomized	Demonstrated faster return of function and knee stability	Foundational evidence for accelerated Artificial ACL rehab	Early: early weight-bearing & ROM; Mid: earlier strengthening

Despite differences in study design, a consistent focus was observed on rehabilitation structure, progression criteria, and return-to-sport considerations following artificial ligament reconstruction. All included studies described rehabilitation and conditioning protocols using a phase-based progression model, consistently divided into six phases. Phases I: protection and early activation, phase II: early strength and controlled motion, phase III: progressive strengthening, phase IV: speed and plyometric initiation, phase V: advanced agility and sport-specific training (RTP), and phase VI: return to sport (RTS). The included studies also revealed consistent differences between artificial and biologic graft rehabilitation protocols, particularly in the early phases of recovery. Artificial ligament reconstruction allows earlier progression of loading, motion, and muscle activation under controlled conditions, indicating a shift in rehabilitation constraints from biological healing toward mechanical load tolerance. Based on these findings, a concept of rehabilitation progression velocity is proposed to guide graft-specific rehabilitation strategies. The protocols are structured by time, primary rehabilitation goal, strength, neuromuscular emphasis, and progress criteria. The re-

Table 3. Protocol Reh and Conditioning Exercise After Artificial Graft ACL-R

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase I: Protection and Early Activation (Batty et al., 2015; Beecher et al., 2010; Moreira, 2020; Ranger et al., 2018)	Postoperative weeks 0 to 2	Protect the Artificial anterior cruciate ligament graft, control pain and joint effusion, restore full knee extension, and initiate early neuromuscular activation.	Weight bearing as tolerated from the early postoperative period. Knee range of motion progressed toward full extension and flexion up to approximately one hundred and twenty degrees as tolerated.	Quadriceps activation exercises, straight leg raises without extension lag, hip and core stabilization, and early proprioceptive input.	Minimal joint effusion, full passive knee extension, and effective quadriceps activation without extension lag
Phase II: Early Strength and Controlled Motion (Keeling et al., 2021; McDonald et al., 2021; Simhal et al., 2021)	Postoperative weeks 2 to 6	Restore full functional knee range of motion, normalize gait mechanics, and improve early lower limb strength.	Full weight bearing without assistive devices. Progressive achievement of full knee flexion with no restrictions if swelling is controlled	Closed kinetic chain strengthening, bilateral to unilateral lower limb strengthening, and basic balance training	Full knee range of motion, symmetrical gait pattern, and absence of reactive joint effusion

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Table 3. Protocol Reh and Conditioning Exercise After Artificial Graft ACL-R

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase III: Progressive Strengthening (Beecher et al., 2010; Moreira, 2020; Sun et al., 2020a)	Postoperative weeks 6 to 12	Develop symmetrical lower limb strength and enhance neuromuscular control in multiple planes.	Full unrestricted knee range of motion and full weight bearing	Progressive resistance training, unilateral strengthening, frontal and transverse plane neuromuscular training	Quadriceps and hamstring limb symmetry index of at least 70-80% with no post-exercise swelling
Phase IV: Speed and Plyometric Initiation (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022)	Postoperative months 3 to 4	Introduce running mechanics, speed exposure, and controlled plyometric loading.	Initiation of linear running and acceleration drills with a continued unrestricted range of motion	Low to moderate intensity plyometric exercises, deceleration drills, and reactive neuromuscular training	Hop test performance of at least 75-80% and good movement quality
Phase V: Advanced Agility and Sport-Specific Training (Arias et al., 2023; Migliorini et al., 2022; Simhal et al., 2021)	Postoperative months 4 to 6	Develop advanced agility, cutting ability, and sport-specific movement control.	No restrictions in range of motion or weight bearing	High-intensity plyometric training, change of direction drills, and sport-specific neuromuscular loading	Strength and hop test symmetry of at least 90% with no reactive joint effusion
Phase VI: Return to Sport (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022)	Postoperative months 6 to 9	Achieve safe and sustainable return to unrestricted sports participation	Full unrestricted participation based on sport-specific demands	Sport-specific conditioning, fatigue-based functional testing, and psychological readiness assessment	Strength and hop performance symmetry of at 90-95%, stable knee function, and confident movement execution

habilitation and conditioning protocols for post-ACL-R with artificial grafts are shown in Table 3.

This also applies to the rehab-conditioning protocols for artificial PCL-R and MLKI (ACL-PCL). Rehab and conditioning protocols after PCL-R and MLKI (ACL-PCL) with Artificial graft are presented in Tables 4 and 5.

Table 4. Protocol Reh and Conditioning Exercise After Artificial Graft PCL-R

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase I: Protection and Early Activation (Batty et al., 2015; Beecher et al., 2010; Moreira, 2020; Ranger et al., 2018)	Postoperative weeks 0 to 2	Protect the Artificial posterior cruciate ligament graft, control pain and joint effusion, and prevent posterior tibial sag while initiating early neuromuscular activation.	Weight bearing as tolerated with a brace locked in full extension. Knee range of motion limited to zero to sixty degrees using prone or gravity-minimized positions. Active hamstring contraction is avoided.	Priority quadriceps activation, straight leg raises without extension lag, hip and core stabilization exercises, and ankle pump exercises.	Minimal joint effusion, full passive knee extension, and effective quadriceps activation without extensor lag
Phase II: Early Strength and Controlled Motion (Keeling et al., 2021; McDonald et al., 2021; Simhal et al., 2021)	Postoperative weeks 2 to 6	Restore controlled functional range of motion, improve gait stability, and maintain protection against posterior tibial translation.	Progressive knee range of motion up to ninety degrees. Gradual brace unlocking during ambulation. Full weight bearing with controlled gait mechanics	Closed kinetic chain quadriceps-dominant strengthening, basic balance training, and trunk stability exercises	Knee range of motion of at least 90°, symmetrical gait pattern, and absence of posterior tibial sag

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Table 4. Protocol Reh and Conditioning Exercise After Artificial Graft PCL-R

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase III: Progressive Strengthening (Beecher et al., 2010; Moreira, 2020; Sun et al., 2020b)	Postoperative weeks 6 to 12	Develop symmetrical lower limb strength and improve sagittal and frontal plane neuromuscular control.	Full knee range of motion and unrestricted weight bearing without a brace if posterior stability is maintained	Progressive resistance training with quadriceps dominance, unilateral strengthening, and neuromuscular perturbation training	Quadriceps limb symmetry index of at least 70-80% and no reactive joint effusion following exercise
Phase IV: Speed and Plyometric Initiation (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022)	Postoperative months 3 to 4	Introduce controlled dynamic loading, impact activities, and linear speed while protecting posterior knee stability.	Initiation of linear running when objective posterior stability is confirmed, with a continued unrestricted range of motion	Low to moderate intensity plyometric exercises, deceleration training, and advanced neuromuscular re-education	Initial hop test performance of at least 75-80% limb symmetry and stable posterior drawer examination
Phase V: Advanced Agility and Sport-Specific Training (Return to Play) (Arias et al., 2023; Migliorini et al., 2022; Simhal et al., 2021)	Postoperative months 4 to 6	Develop high-level agility, cutting ability, and multiplanar sport-specific movement control.	No restrictions in range of motion or weight bearing	Advanced plyometric training, change of direction drills, and reactive neuromuscular control exercises	Strength and hop test symmetry at 90%, and symmetrical performance on dynamic balance testing
Phase VI: Return to Sport (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022)	Postoperative months 6 to 9	Safe and sustainable return to unrestricted sports participation	Full unrestricted sports participation according to the demands of the specific sport	Sport-specific conditioning, fatigue-based functional testing, and assessment of psychological readiness	Strength and hop performance symmetry of at 90-95%, no joint effusion, and confident sport-specific movement

Table 5. Protocol Reh and Conditioning Exercise After Artificial Graft MLKI (ACL-PCL)

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase I: Protection and Early Activation (Batty et al., 2015; Beecher et al., 2010; Moreira, 2020; Ranger et al., 2018)	Postoperative weeks zero to two	Protect the Artificial anterior cruciate ligament and posterior cruciate ligament grafts and control pain and joint effusion.	Weight bearing as tolerated with the brace locked in full extension. Knee range of motion, zero to sixty degrees, using gravity-minimized positions. Active hamstring contraction was avoided.	Priority quadriceps activation, hip and trunk stabilization, straight leg raises without extension lag.	Minimal joint effusion, full passive knee extension, effective quadriceps activation
Phase II: Early Strength and Controlled Motion (Keeling et al., 2021; McDonald et al., 2021; Simhal et al., 2021)	Postoperative weeks two to six	Restore controlled knee range of motion and normalize gait	Progressive knee flexion up to ninety degrees. Gradual brace unlocking. Full weight bearing with controlled gait	Closed kinetic chain quadriceps-dominant strengthening, balance training	Knee range of motion at least ninety degrees, symmetrical gait, no posterior sag
Phase III: Progressive Strengthening (Beecher et al., 2010; Moreira, 2020; Sun et al., 2020b)	Postoperative weeks six to twelve	Develop symmetrical strength and neuromuscular control	Full knee range of motion and unrestricted weight bearing if stability is maintained	Progressive resistance training, unilateral strengthening, and neuromuscular perturbation	Strength symmetry 70-80%, with no reactive joint effusion

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Table 5. Protocol Reh and Conditioning Exercise After Artificial Graft MLKI (ACL-PCL)

Phase	Approximate Timeframe	Primary Rehabilitation Goals	Range of Motion and Weight Bearing Strategy	Strength and Neuromuscular Emphasis	Criteria to Progress to Next Phase
Phase IV: Speed and Plyometric Initiation (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022)	Postoperative months three to four	Introduce dynamic loading and controlled impact	Initiate linear running with confirmed anterior and posterior stability	Low to moderate plyometric exercises, acceleration, and deceleration drills	Hop test symmetry 75-80% with stable drawer tests
Phase V: Advanced Agility and Sport-Specific Training (Return to Play) (Arias et al., 2023; Migliorini et al., 2022; Simhal et al., 2021)	Postoperative months four to six	Restore agility and sport-specific control	No restrictions in range of motion or weight bearing	Advanced plyometrics, change of direction drills, and reactive training	Strength and hop symmetry at 90%
Phase VI: Return to Sport (Arias et al., 2023; Keeling et al., 2021; Lee et al., 2022; Migliorini et al., 2022)	Postoperative months six to nine	Achieve safe and sustainable return to sport	Full unrestricted participation according to the sport's demands	Sport-specific conditioning, fatigue-based testing, and psychological readiness	Strength and hop symmetry 90-95% with a stable knee

Comparative synthesis with established biologic graft rehabilitation protocols (Fowler Kennedy, ASPETAR, and Melbourne frameworks) demonstrated that artificial graft protocols are mechanics-driven and response-based, and biologic graft protocols remain biology-driven and time-constrained. Artificial ligament rehabilitation enables earlier exposure to loading and movement and increased rehabilitation velocity in early phases. However, this acceleration requires: strict monitoring of joint response, careful workload progression, and maintenance of movement quality. Comparison of ACL-R rehab protocol between artificial grafts and conventional ACL-R graft from Fowler Kennedy ACL, ASPETAR ACL Rehab Protocol, and ACL Melbourne Rehab Guide 2.0, and the comparison results are shown in Table 6.

Table 6. Comparison of Rehab-Conditioning Protocol Post ACL-R Artificial Graft and Conventional

Phase	Approximate Time Frame	Artificial ACL (Evidence-Synthesized Framework)	Fowler Kennedy ACL Rehabilitation	Melbourne ACL Rehabilitation Guide 2.0	Aspetar ACL Rehabilitation Protocol 2023–2024	Key Clinical Contrast
Phase I: Protection and Early Activation	0–2 weeks	Immediate mechanical stability allows early weight bearing as tolerated, rapid quadriceps activation, and early range of motion progression guided by joint response.	Protection-oriented approach emphasizing effusion control, full extension restoration, and cautious early activation.	Permits weight bearing as tolerated but regulates the range of motion and early loading based on swelling and movement quality.	Highly criteria-driven early phase with progression dependent on pain, effusion, and neuromuscular control.	Artificial ACL rehabilitation is mechanics-driven, whereas biologic protocols remain biology-limited.
Phase II: Early Strength and Controlled Motion	2–6 weeks	Accelerated closed kinetic chain strengthening and earlier attainment of functional range of motion under strict monitoring of joint response.	Gradual strength progression with conservative external loading and predefined time milestones.	Hybrid model combining time-based guidance with movement-quality checkpoints.	Strict criteria are required for progression of strength and loading.	Artificial ACL tolerates earlier controlled loading compared with biologic graft protocols.
Phase III: Progressive Strengthening	6–12 weeks	Earlier neuromuscular and resistance training with rapid progression toward strength symmetry.	Progressive strengthening with delayed exposure to high external loads.	Objective strength testing guides progression but assumes biologic graft vulnerability.	Explicit limb symmetry and strength thresholds are required before advancing intensity.	Limiting factor shifts from graft healing to neuromuscular capacity in artificial ACL.

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Table 6. Comparison of Rehab-Conditioning Protocol Post ACL-R Artificial Graft and Conventional

Phase	Approximate Time Frame	Artificial ACL (Evidence-Synthesized Framework)	Fowler Kennedy ACL Rehabilitation	Melbourne ACL Rehabilitation Guide 2.0	Aspetar ACL Rehabilitation Protocol 2023–2024	Key Clinical Contrast
Phase IV: Speed and Plyometric Initiation	3–4 months	Earlier initiation of linear running and controlled plyometrics once mechanical stability and movement quality are confirmed.	Running and plyometrics were introduced later, following conservative biologic milestones.	Running is initiated based on movement quality and symptom response.	Running and plyometrics are introduced only after meeting strict biomechanical criteria.	Artificial ACL increases rehabilitation velocity, requiring precise load control.
Phase V: Advanced Agility and Sport-Specific Training (RTP)	4–6 months	Earlier exposure to change-of-direction and sport-specific loading with close workload surveillance.	Conservative progression of agility and sport-specific drills.	Gradual sport-specific exposure with careful volume management.	Highly structured, criteria-based sport progression.	Artificial ACL allows earlier performance exposure but not unrestricted training volume.
Phase VI: Return to Sport (RTS)	≥6–9 months	Potential for earlier return to sport if strict objective criteria are met, although conservative clearance is recommended.	Return to sport is commonly recommended at nine months or later.	Return to sport is guided by functional readiness, but rarely before nine months.	Return to sport requires comprehensive physical and psychological clearance.	All protocols converge on criteria-based return to sport rather than time alone.

The results of the comparison between PCL-R rehabilitation and conditioning with artificial grafts and conventional protocols, as well as the comparison between artificial and conventional ML-KI (ACL-PCL) protocols, are shown in Tables 7 and 8.

Table 7. Comparison of Rehab-Conditioning Protocol Post PCL-R Artificial Graft and Conventional

Phase	Approximate Time Frame	Fowler Kennedy PCL Reconstruction Rehabilitation	Synthetic PCL Reconstruction Rehabilitation (Evidence-Synthesized)	Key Clinical Differences
Phase I: Protection and Early Activation	Postoperative weeks 0–2	Brace locked in extension for ambulation, feather-touch or partial weight bearing, assisted range of motion limited to approximately zero to ninety degrees, strict avoidance of active hamstrings.	External protection recommended with early weight bearing as tolerated, early quadriceps activation, cautious range of motion progression guided by joint response rather than fixed biologic timelines.	Biologic protocol is biology-driven and rule-based, whereas synthetic protocol is mechanics-driven and response-based.
Phase II: Early Strength and Controlled Motion	Postoperative weeks 2–6	Continued bracing, gradual range of motion progression, closed kinetic chain strengthening in limited flexion ranges, hamstrings still restricted.	Earlier restoration of functional range of motion, confident progression of quadriceps-dominant closed kinetic chain strengthening, and hamstrings progressed by criteria.	The synthetic framework allows earlier controlled loading while maintaining posterior shear protection principles.
Phase III: Progressive Strengthening	Postoperative weeks 6–12	Weight bearing as tolerated with normalized gait, full range of motion targeted, cautious introduction of active hamstrings often with brace support.	Accelerated resistance and neuromuscular training, earlier hamstring activation based on posterior tibial control, and movement quality.	Biologic protocol introduces hamstrings based on time rules, synthetic protocol uses control- and tolerance-based criteria.
Phase IV: Speed and Plyometric Initiation	Postoperative months 3–4	Running is delayed until the full range of motion, minimal effusion, and adequate neuromuscular control are achieved.	Linear running and controlled plyometrics may begin earlier once mechanical stability and joint response are acceptable.	Synthetic PCL permits earlier velocity exposure but demands strict monitoring of cumulative load.

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Table 7. Comparison of Rehab-Conditioning Protocol Post PCL-R Artificial Graft and Conventional

Phase	Approximate Time Frame	Fowler Kennedy PCL Reconstruction Rehabilitation	Synthetic PCL Reconstruction Rehabilitation (Evidence-Synthesized)	Key Clinical Differences
Phase V: Advanced Agility and Sport-Specific Training	Postoperative months 4–6	Advanced strengthening and agility progressed conservatively, and brace use often continued during higher-demand tasks.	Earlier progression to multidirectional drills and sport-specific loading with close fatigue and workload surveillance.	Synthetic framework accelerates performance exposure but requires tighter workload governance.
Phase VI: Return to Sport	Postoperative months 9–12 or later	Return to sport is commonly delayed beyond nine months, emphasizing graft maturation, reinjury prevention, and psychological readiness.	Potentially earlier return to sport if strict objective criteria are met, although conservative clearance remains recommended.	Despite mechanical advantages, return to sport remains criteria-based in both approaches.

Table. 8 Comparison of Rehab-Conditioning Protocol Post MLKI (ACL-PCL) Artificial Graft and Conventional

Phase	Approximate Timeframe	Fowler Kennedy MLKI Rehabilitation	Synthetic MLKI Rehabilitation Framework	Key Clinical Differences
Phase I: Protection and Early Activation	Postoperative weeks zero to two	Strict protection with brace use and restricted weight bearing depending on ligament combination. Early activation is cautious to protect healing grafts.	Early weight bearing as tolerated with rigid external protection. Immediate quadriceps activation with emphasis on joint effusion control.	Biologic protocol is healing-driven; synthetic protocol permits earlier activation due to immediate mechanical stability.
Phase II: Early Strength and Controlled Motion	Postoperative weeks two to six	Gradual progression of the range of motion with restrictions to protect grafts. Strengthening the largely closed kinetic chain.	Earlier restoration of the functional range of motion and more confident progression of closed kinetic chain strengthening.	Synthetic framework allows earlier controlled loading compared with conservative biologic progression.
Phase III: Progressive Strengthening	Postoperative weeks six to twelve	Cautious strengthening progression with delayed limb symmetry expectations.	Accelerated strength and neuromuscular progression with earlier attainment of limb symmetry indices.	Limiting factor shifts from tissue healing to neuromuscular capacity in synthetic MLKI.
Phase IV: Speed and Plyometric Initiation	Postoperative months three to four	Running and plyometrics are delayed or highly restricted due to reinjury risk.	Earlier initiation of linear running and controlled plyometrics if the joint response is stable.	Synthetic MLKI supports earlier speed exposure with strict movement quality control.
Phase V: Advanced Agility and Sport-Specific Training	Postoperative months four to six	Multidirectional and sport-specific drills are introduced cautiously and often later.	Earlier progression to change-of-direction and sport-specific tasks with close fatigue and load monitoring.	Synthetic framework accelerates performance exposure but requires tight workload surveillance.
Phase VI: Return to Sport	Postoperative months nine to twelve or later	Return to sport is delayed with strong emphasis on biological healing, psychological readiness, and reinjury prevention.	Potentially earlier return to sport if objective criteria are met, although conservative clearance remains advised.	Despite mechanical advantages, return to sport should remain criteria-based in both frameworks.

A key thematic pattern identified across all included studies is the transition from a biology-limited to a mechanics-limited rehabilitation model. These findings provide the basis for a clinically applicable, graft-specific rehabilitation framework integrating progression criteria and load management principles.

Discussion

This scoping review demonstrates a consistent shift in rehabilitation principles following artificial ligament reconstruction, characterized by a transition from biologically constrained to mechanically driven rehabilitation. This shift represents not merely a modification of existing protocols but a fundamental change in the underlying rehabilitation paradigm. The comparison between biologic and synthetic anterior cruciate ligament rehabilitation reveals a fundamental philosophical divergence driven by differences in graft biology, mechanical stability, and acceptable rehabilitation velocity (Beecher et al., 2010; Van Melick et al., 2016). Biologic anterior cruciate ligament reconstruction is constrained by ligamentization processes that necessitate cautious loading and delayed exposure to high-velocity activities (Beecher et al., 2010; Van Melick et al., 2016). In contrast, synthetic anterior cruciate ligament reconstruction provides immediate mechanical stability, shifting rehabilitation constraints toward neuromuscular control and load tolerance rather than biological healing (Beecher et al., 2010; Moreira, 2020). This shift permits earlier activation and strengthening when joint effusion and movement quality are adequately controlled (Beecher et al., 2010; Ranger et al., 2018). A key contribution of this study is the introduction of rehabilitation velocity as a conceptual framework to describe the rate of safe progression through rehabilitation phases. Rehabilitation velocity is influenced by: graft type and mechanical properties, neuromuscular readiness, joint response (e.g., effusion, pain), and load tolerance. This concept provides a clinically meaningful way to reconcile differences between biologic and artificial graft protocols. While biologic grafts impose a fixed biological ceiling, artificial grafts allow a variable, criteria-driven progression, where advancement depends on patient-specific responses rather than predefined timelines. Despite early-phase differences, both approaches converge in later rehabilitation phases, where return-to-sport decisions rely on objective functional criteria rather than graft type alone (Ardern et al., 2011; Buckthorpe & Della Villa, 2020; Zaffagnini et al., 2015).

Biologic posterior cruciate ligament rehabilitation is primarily constrained by the need to protect against posterior tibial translation during graft healing (Fowler Kennedy, 2016a). Protocols emphasize prolonged bracing, restricted weight bearing, and delayed hamstring activation to minimize graft elongation (Fanelli, 2018; Fowler Kennedy, 2016a). Synthetic posterior cruciate ligament reconstruction provides immediate mechanical restraint, allowing earlier quadriceps activation and progression of weight bearing under strict movement control (Beecher et al., 2010; Lee et al., 2022). However, accelerated rehabilitation remains sensitive to excessive posterior shear and cumulative mechanical loading (Lee et al., 2022; Migliorini et al., 2022; Sun et al., 2020a). Ultimately, return-to-sport decision-making converges on functional readiness and joint stability irrespective of graft type (Ardern et al., 2011; Buckthorpe & Della Villa, 2020; Zaffagnini et al., 2015).

Rehabilitation following biologic multiple ligament knee injury reconstruction is heavily constrained by the need to protect multiple healing grafts simultaneously. (Batty et al., 2015; Fanelli, 2018). As a result, biologic protocols prioritize prolonged protection, conservative loading, and delayed exposure to sport-specific demands (Monson et al., 2022; Mook et al., 2009). Synthetic multiple ligament knee injury reconstruction shifts the rehabilitation paradigm toward mechanical load tolerance and neuromuscular control due to immediate graft stability (Batty et al., 2015; Beecher et al., 2010). This allows higher rehabilitation velocity during early phases, although progression must remain tightly regulated to avoid mechanical overload (Batty et al., 2015; Migliorini et al., 2022; Simhal et al., 2021). When compared with established protocols such as Fowler Kennedy, ASPETAR, and Melbourne frameworks, artificial ligament rehabilitation aligns with the broader trend toward criteria-based progression, but differs in its increased rehabilitation velocity during early phases. This suggests that artificial ligament protocols should not replace existing frameworks, but rather extend them by incorporating graft-specific considerations, particularly regarding early loading and progression. Across all graft types, late-phase rehabilitation converges on objective performance metrics, such as limb symmetry indices, neuromuscular control, and psychological readiness to guide optimal return to sports. Importantly, graft type does not appear to determine RTS timing independently. Instead, functional readiness remains the primary determinant, reinforcing the importance of criteria-based rather than time-based progression.

Limitation

This review has several limitations. First, the included studies were heterogeneous in design, with a predominance of lower-level evidence such as case series and expert opinion. Second, variability in reported rehabilitation protocols and outcome measures limited direct comparison across studies. Third, the absence of high-quality randomized controlled trials reduces the strength of causal inference. Additionally, this review relied on narrative synthesis without quantitative meta-analysis due to heterogeneity in study design and outcomes.

Practical Applications Key

Rehabilitation following knee ligament reconstruction has traditionally been guided by biologic graft healing timelines, resulting in conservative, time-based progression models. Although contemporary practice increasingly incorporates functional and criteria-based return-to-sport decision-making, most rehabilitation frameworks remain rooted in biologic constraints. Synthetic ligament reconstruction offers immediate mechanical stability, yet its implications for rehabilitation progression and clinical decision-making remain insufficiently defined and inconsistently applied. This study identifies a fundamental paradigm shift in rehabilitation following artificial ligament reconstruction, characterized by a transition from biology-limited to mechanics-driven progression across ACL, PCL, and multiligament knee injuries. It introduces the concept of rehabilitation velocity as a unifying framework to guide phase progression based on graft-specific mechanical properties, neuromuscular readiness, and joint response, rather than fixed timelines. Furthermore, this study provides a clinically integrated, graft-specific rehabilitation framework that supports earlier progression in early phases while maintaining strict criteria-based advancement and workload regulation. This framework enables clinicians to move beyond uniform, time-based protocols toward a personalized, graft-specific rehabilitation strategy, optimizing early functional recovery without compromising long-term joint integrity. By integrating rehabilitation velocity and objective progression criteria, clinicians can better balance accelerated recovery with safety, ultimately supporting more precise and individualized return-to-sport decision-making in complex knee ligament injuries.

Conclusion

Artificial ligament reconstruction redefines rehabilitation by shifting the primary constraint from biological healing to mechanical load tolerance. This transition enables increased rehabilitation velocity, particularly in early phases, while maintaining the need for strict criteria-based progression. We propose that rehabilitation should no longer be uniformly time-based but instead guided by a graft-specific, velocity-informed framework integrating joint response, neuromuscular control, and objective performance metrics. This paradigm may enhance early functional recovery while preserving long-term joint integrity, offering a clinically actionable model for modern sports rehabilitation.

Declaration of conflict of interest
The authors declare no conflict of interest.

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