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Scoping review

Quadriceps and Hamstring Strength Recovery Following Different Anterior cruciate ligament (ACL) Reconstruction Techniques: A Scoping Review of Graft Choices and Rehabilitation Protocols

Strength Recovery After ACL Reconstruction: A Scoping Review

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Background: Although there has been extensive research on anterior cruciate ligament reconstruction (ACLR) outcomes, a comprehensive synthesis of strength recovery and functional performance across different graft choices and rehabilitation protocols is still lacking. Objective: To systematically analyze quadriceps and hamstring strength recovery and functional performance outcomes following different ACLR graft choices (hamstring tendon [HT], quadriceps tendon [QT], bone-patellar tendon-bone [BPTB], anterior tibialis tendon [ATT]) and rehabilitation protocols.

Methods: Following PRISMA-ScR guidelines, systematic searches were conducted across MEDLINE, Embase, Web of Science, SPORTDiscus, and Cochrane databases (January 2017-December 2024). Twenty-eight studies met inclusion criteria, examining strength outcomes in adult patients after primary ACLR using HT, QT, BPTB, or ATT grafts.

Results: Our review revealed that isokinetic dynamometry was the primary assessment method in 82.14% of studies, with testing most frequently performed at 60°/s (46.15%), 180°/s (21.15%), and 240°/s (17.31%). HT autografts were most commonly utilized (47.92%), followed by QT (14.58%), BPTB (12.50%), and ATT (4.17%). At seven months post-ACLR, no surgical group achieved the clinical benchmark of 90% limb symmetry index (LSI) for quadriceps strength. HT recipients demonstrated greater hamstring deficits, while QT and BPTB recipients showed more pronounced quadriceps weakness. Combined eccentric-plyometric training produced superior strength gains compared to either modality alone during early rehabilitation ($p<0.05$). Single-leg hop testing revealed comparable performance between HT and QT recipients, though both groups showed significant deficits versus controls ($p<0.01$).

Conclusion: Different ACLR graft choices demonstrate distinct strength recovery patterns. Combined rehabilitation protocols incorporating progressive strength training and neuromuscular exercises optimize outcomes. Return-to-sport decisions should consider multiple objective criteria including strength symmetry (LSI>90%) and functional performance rather than time alone. Future research should establish comprehensive, evidence-based return-to-sport testing protocols for minimizing reinjury risk.

Keywords: *Biomechanics; dynamometry; exercise therapy; isokinetic testing; joint instability; muscle strength dynamometer; treatment outcome*

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1. INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most devastating knee injuries in sports medicine, significantly affecting sport performance and long-term joint health (1). Recent epidemiological data indicates incidence rates of 0.05 per 1,000 player-hours in team sports, with notably higher rates during competition (0.48 per 1,000 player-hours) compared to training (0.04 per 1,000 player-hours) (2,3). The financial burden associated with ACL injuries, including surgical costs and rehabilitation, exceeds $2 billion annually in the United States alone (4).

Recent studies have shown that the incidence of ACL injuries is higher in certain sports and populations, highlighting the need for effective rehabilitation and return-to-sport strategies (5). While ACL reconstruction (ACLR) has evolved as the gold standard surgical intervention for restoring knee stability (6,7), optimal graft choice remains controversial. The most commonly used autografts include hamstring tendon (HT), bone-patellar tendon-bone (BPTB), quadriceps tendon (QT), and less frequently, anterior tibialis tendon (ATT). Each graft type presents distinct considerations; HT grafts often result in persistent hamstring weakness at deep knee flexion angles, while BPTB grafts frequently lead to quadriceps deficits and anterior knee pain (8,9). Though QT has emerged as a promising alternative, research comparing functional outcomes across graft types remains limited (10,11).

Post-ACLR rehabilitation faces significant challenges in restoring neuromuscular function, regardless of graft choice. Studies indicate that only 19.6% of patients achieve symmetrical knee function at six months post-surgery when comparing operated versus non-operated limbs (12). This deficit is particularly concerning as asymmetrical muscle function has been associated with increased risk of secondary ACL injury and early onset osteoarthritis (13–15).

Given these challenges, objective assessment of recovery becomes crucial. Isokinetic strength testing has emerged as the gold standard for evaluating muscle recovery and informing return-to-sport (RTS) decisions (16,17). The limb symmetry index (LSI), calculated as (operated limb/non-operated limb × 100%), serves as a key metric, with an LSI ≥90% generally considered satisfactory (18,19). Evidence spanning the last decade demonstrates that quadriceps strength symmetry before RTS significantly reduces re-injury risk, while hamstring strength deficits correlate with increased ACL graft rupture rates (20,21). These foundational findings continue to guide current clinical practice.

The timing and criteria for RTS decisions have evolved beyond conventional time-based protocols (22). While clinicians historically cleared athletes at six months post-ACLR, research over the past decade has established a criterion-based approach incorporating objective strength measurements, functional performance tests, and psychological readiness assessments (23,24). This evidence-based shift represents a fundamental change in return-to-sport decision-making. This shift reflects growing recognition that biological healing timeframes may not align with functional recovery milestones.

Rehabilitation paradigms established over the past decade address the intricate recovery trajectories associated with ACL injuries (25), with ongoing refinement based on emerging evidence. Established protocols prioritize the early restoration of range of motion, progressive strengthening exercises, and the re-establishment of neuromuscular control (26), with these fundamental principles remaining consistent despite evolving implementation strategies. Empirical evidence strongly supports the integration of both open and closed kinetic chain exercises to optimize quadriceps strength recovery (27). Furthermore, eccentric training regimens have been shown to yield superior outcomes in terms of muscle mass and strength gains (28,29).

Single-leg hop tests have become established as valuable functional performance measures that complement traditional strength assessments (30). These tests evaluate the intricate interplay of muscular strength, neuromuscular control, and psychological preparedness (31). A growing body of evidence suggests a strong correlation between hop test symmetry and successful return to pre-injury sport participation levels (32,33).

Growing evidence suggests that post-ACLR outcomes are influenced by factors beyond surgical technique and rehabilitation protocols (34). Studies from the last five years have identified biological markers, psychological factors, and pre-operative conditioning as potential moderators of recovery trajectories (35,36).

Furthermore, the efficacy of blood flow restriction training, motor learning principles, and innovative biofeedback technologies in optimizing rehabilitation outcomes warrants further exploration (37).

Despite extensive research on individual aspects of post-ACLR recovery, a comprehensive synthesis of strength and functional outcomes across different graft types and rehabilitation protocols is lacking. This scoping review aimed to systematically analyze evidence regarding quadriceps and hamstring strength recovery and functional performance outcomes following different ACLR graft choices and rehabilitation approaches. Such synthesis will provide clinicians with evidence-based guidance for optimizing graft selection and rehabilitation program design, ultimately improving patient outcomes.

2. METHODS

2.1. Study design and protocol registration Public

This scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines (38). To ensure transparency and reduce potential bias, the review protocol was prospectively registered in OSF (Registration DOI: https://doi.org/10.17605/OSF.IO/R6JTQ). Compliance with ethical guidelines ensures the reliability and validity of research in sports medicine and sports science (39).

2. 2. Research question development

The research questions were developed using the Population, Concept and Context (PCC) framework recommended for scoping reviews (40). The population of interest included patients who underwent primary ACLR. The key concepts examined were quadriceps and hamstring strength outcomes along with functional performance measures. The context encompassed different graft choices (HT, QT, BPTB, ATT) and rehabilitation protocols.

2. 3. Eligibility criteria

The review included randomized controlled trials, prospective cohort studies, and retrospective studies with control groups examining adult patients (≥18 years) who underwent primary ACLR using HT, QT, BPTB, or ATT grafts. Studies needed to report quadriceps and/or hamstring strength measurements as primary outcomes, with functional performance measures as secondary outcomes. A minimum follow-up of six months post-surgery was required. Only English language articles published between January 2017 and December 2024 were considered. Studies involving revision ACLR, concomitant major ligament injuries, case reports, conference abstracts, unpublished data, or non-human subjects were excluded (Table 1).

2.4. Information sources and search strategy

In December 12th, 2024, we conducted a comprehensive literature search across multiple electronic databases, including MEDLINE (via PubMed), Embase, Web of Science, SPORTDiscus, and the Cochrane Central Register of Controlled Trials. The search strategy was developed in consultation with a medical librarian and peer-reviewed using the Peer Review of Electronic Search Strategies (PRESS) checklist (41). The search combined terms related to ACL reconstruction (including specific graft types), strength assessment (including isokinetic testing), functional performance, and rehabilitation protocols. The search strategy employed the following key terms: Population: ["Anterior Cruciate Ligament" OR "Anterior Cruciate Ligament Reconstruction" OR "ACL reconstruction" OR "ACLR" OR "anterior cruciate ligament surgery"] AND Intervention/Assessment: ["Muscle Strength" OR "Muscle Strength Dynamometer" OR "Athletic Performance" OR "isokinetic strength" OR "quadriceps strength" OR "hamstring strength" OR "peak torque" OR "limb symmetry index" OR "LSI" OR "H/Q ratio" OR "muscle function" OR "strength assessment" OR "strength testing" OR "single leg hop test" OR "hop performance" OR "functional performance" OR "dynamometer"] AND Graft Types: ["Transplants" OR "hamstring tendon" OR "quadriceps tendon" OR "bone-patellar tendon-bone" OR "anterior tibialis tendon" OR "HT graft" OR "QT graft" OR "BPTB graft" OR "ATT graft" OR "autograft"] AND Rehabilitation: ["Rehabilitation" OR "Physical Therapy Modalities" OR "Exercise Therapy" OR "postoperative rehabilitation" OR "physical therapy" OR "physiotherapy" OR "exercise program" OR "strength training" OR "neuromuscular training" OR "isokinetic training" OR "open kinetic chain" OR "closed kinetic chain" OR "eccentric training"] AND Outcomes: ["Treatment Outcome" OR "Recovery of Function" OR "return to sport" OR "functional recovery" OR "strength recovery" OR "muscle performance" OR "knee function" OR "clinical outcomes"].

Table 1. Eligibility criteria for scoping review of ACLR studies.

	Inclusion	Exclusion
Population	Male and female patients Age between 18 and 33 years Patients with different activity level Patients with ACL: • Primary ACL injury • Potential concomitant meniscal injuries ACLR: • HT autograft: a quadruple St tendon autograft and a quadruple StG autograft • HT From IL leg • HT From CL leg • QT autograft • ATT allograft • BPTB autograft	Arthritis History of muscle injuries Knee instability Patients with ACLR: • ACL revision surgery • Multi-ligament knee injury • History of contralateral knee injury • Concomitant cartilage injuries Healthy group: History of knee injury or surgery
Outcome	Strength test for knee extensor and flexor with an isokinetic dynamometer (isometric at 20°,60° and 90° for knee flexion and 70°for knee extension) and (Isokinetic at 30°/s,60°/s,90°/s,180°/s,240°/s,300°/s and 330°/s) or with a handheld dynamometer (Isometric at 90°). SLH test: Absolute values or LSI documented as an outcome. Tests conducted at a specific time point during rehabilitation, from 3 months to return to sport.	No isokinetic strength outcomes were reported
Publication type	All original research types Language: English	Meta-analyses, systematic or narrative reviews, conference abstracts, posters

ACL: anterior cruciate ligament; **ACLR**: anterior cruciate ligament reconstruction; **ATT**: tibialis anterior tendon; **St**: semitendinosus; **BPTB**: bone-patella tendon-bone; **CL**: contralateral; **HT**: hamstrings tendon; **IL**: ipsilateral; **LSI**: limb symmetry index; **QT**: quadriceps tendon; **StG**: semitendinosus gracilis.

2. 5. Study selection process

Study selection followed a rigorous two-stage process. Initially, two independent reviewers (WI and WD in the authors' list) were resolved through consensus or consultation with a third reviewer (ID). The entire selection process was documented using the PRISMA flow diagram (42). Structured peer review processes improve the quality and reliability of scientific work in systematic reviews (43).

2. 6. Data extraction and analysis

Data extraction was performed using a standardized, pilot-tested form, with two reviewers (WI and HG) independently extracting data and cross-verifying for accuracy. Extracted information included study characteristics (author(s), year, design, country), population demographics (age, sex, activity level, time from injury to surgery), surgical details (graft type, fixation method), and rehabilitation protocols (timeline, specific interventions). Strength assessment parameters included peak torque (PT), peak torque normalized to body weight (PT/BW), LSI, hamstring-to-quadriceps ratio (H/Q), joint angle at peak torque (JAPT), time to peak torque (TPT), reciprocal delay (RD), and endurance ratio (ER). Functional performance measures, including single-leg hop tests and other validated performance tests, were also recorded.

Methodological quality was assessed using the Cochrane Risk of Bias tool 2. 0 for randomized trials (44) and the Newcastle-Ottawa Scale for non-randomized studies (45). Two reviewers (WI, HG and WM) independently erformed these quality assessments to ensure reliability.

2. 7. Data synthesis and presentation

Results were synthesized narratively and organized by graft type and outcome measure. When sufficient homogeneous data were available, meta-analyses were performed using random-effects models. For continuous outcomes, we calculated standardized mean differences with 95% confidence intervals. To enhance comparability, strength outcomes were standardized using consistent formulas: LSI was calculated as (Involved limb/Uninvolved limb) × 100%, while H/Q ratio was determined as (Hamstring PT/Quadriceps PT) × 100%. Results were presented using tables, forest plots (where applicable), and narrative summaries, with separate analyses for different graft types and time points.

2. 8. Assessment of evidence strength

The overall quality of evidence was evaluated using the grading of recommendations assessment, development and evaluation (GRADE) approach (46). This assessment considered multiple factors including risk of bias, inconsistency, indirectness, imprecision, and publication bias. This comprehensive evaluation provided a structured framework for assessing the strength of evidence supporting our findings and recommendations.

3. RESULTS

The systematic literature search initially identified 279 articles related to knee muscle strength assessment after ACLR, with 104 articles addressing both strength and functional outcomes. Following screening of titles, abstracts, and full texts against the eligibility criteria, 28 articles met the inclusion criteria - all examining strength outcomes, with nine of these also investigating functional capacity. These 28 articles were included in the final data synthesis.

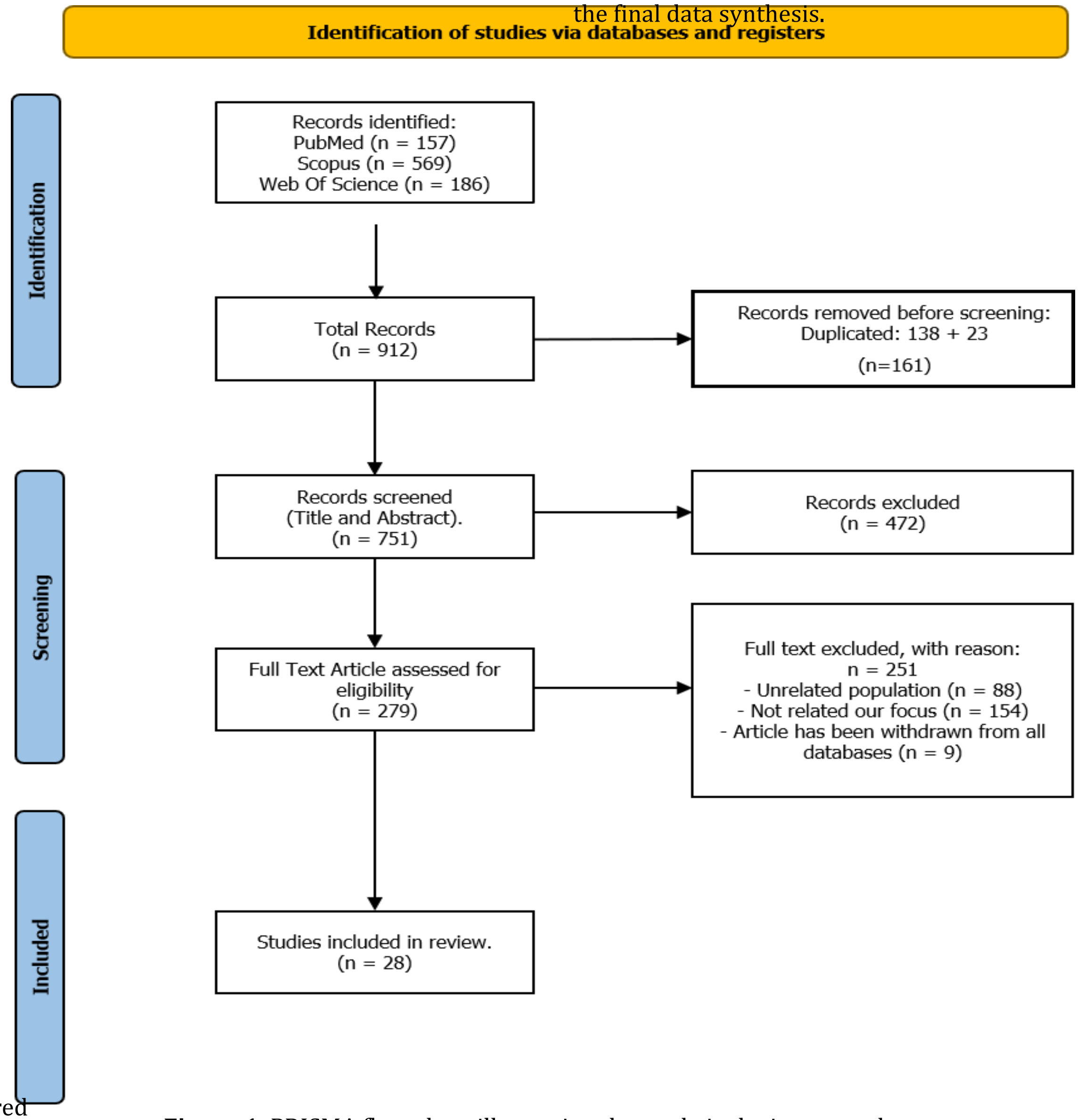

Figure 1. PRISMA flow chart illustrating the study inclusion procedure

3.1. Methodological characteristics of strength assessment

Isokinetic dynamometry was the primary strength assessment method across all included studies. The Humac-Norm dynamometer (CSMI, USA) was most commonly utilized (n=11, 61. 11%), followed by Biodex (Biodex Medical Systems, NY; n=3, 16. 67%) and Con-trex MJ systems (n=3, 16. 67%). One study employed the IsoMed2000 dynamometer (D & R Ferstl GmbH, Germany) (47), while another supplemented isokinetic testing with hand-held dynamometry (Power Track II Commander Echo, JTECH Medical) (48). The majority of studies (n=23, 82.14%) assessed isokinetic strength exclusively, while five studies (17.86%) evaluated both isometric and isokinetic parameters.

3. 2. Standardization of isokinetic testing protocols

Angular velocity protocols varied across studies, with measurements most frequently performed at 60°/s (n=24, 46.15%), followed by 180°/s (n=11, 21.15%), 240°/s (n=9, 17.31%), 90°/s (n=4, 7.69%), 300°/s (n=3, 5.77%), and 330°/s (n=1, 1 92%). Testing protocols typically comprised 3-5 repetitions at 60°/s, 5 repetitions at 90°/s and 180°/s, and 15 repetitions at higher velocities (240°/s and 300°/s). While most studies (n=26) did not specify gravity correction procedures, three studies reported its implementation - one at 45° knee flexion (49), one prior to testing (50), and one as part of their methodology (51). Standard testing range of motion was 0-90° knee flexion with one-minute inter-set rest periods, though some investigators utilized full range of motion (51–54).

3.3. Standardization of isometric testing methodology

Isometric strength assessment protocols demonstrated variability in joint positioning angles. Two investigations employed measurements at 90° knee flexion (51,55), while two others utilized 60° knee flexion (28,56). A differentiated approach was implemented in one study (57), using distinct angles of 70° for knee extensor and 20° for knee flexor assessment. Testing standardization across studies included 3-5 maximal voluntary contractions maintained for 5-second durations.

3.4. Functional performance assessment parameters

Single-leg hop (SLH) testing was implemented in nine studies as a validated functional performance measure. The standardized protocol required unilateral horizontal jumps with hands positioned behind the back to maximize test specificity. Performance assessment involved three trials per limb with standardized one-minute rest intervals, utilizing mean hop distance as the primary outcome measure.

3.5. Post-operative rehabilitation characteristics and progression

Twenty-one studies (75%) detailed specific rehabilitation protocols while seven (25%) provided insufficient protocol information. Rehabilitation durations demonstrated considerable variability, ranging from four weeks to 12 months post-surgery. A comprehensive protocol stratification was reported by Gillet et al. (58), determining RTS timing based on activity demands: four months for non-pivoting sports, six months for non-contact pivoting sports, and 8-9 months for contact pivoting sports. Rehabilitation programs universally incorporated progressive phases targeting muscular strength, joint stability, cardiovascular endurance, proprioception, and range of motion restoration through integrated exercise modalities including isokinetic training, closed kinetic chain (CKC), open kinetic chain (OKC), plyometric, balance, and sport-specific conditioning.

3.6. Distribution of ACLR graft selection and associated outcomes

Graft selection was specified in 27 studies (84.38%), with one study (47) not reporting graft type. HT autografts were most frequently utilized, documented in 23 studies (47.92%), followed by QT autografts in 7 studies (14.58%), BPTB autografts in 6 studies (12.50%), and ATT allografts in 2 studies (4.17%). Functional performance assessment through SLH testing demonstrated a similar distribution pattern: HT autografts (6 studies, 46.15%), QT autografts (3 studies, 23.08%), ATT allografts (2 studies, 15.38%), and BPTB autografts (2 studies, 15.38%).

3.7. Impact of rehabilitation protocols on muscular strength and functional performance

Multiple studies demonstrated significant effects of specialized rehabilitation protocols on strength and functional outcomes following ACLR (Table 2). Isokinetic training emerged as a crucial rehabilitation component, with several key findings:

a- Early post-operative period (0-3 months): Integration of combined eccentric and plyometric training produced superior strength gains compared to either modality alone during the initial six weeks post-ACLR (59). Implementation of early OKC exercises alongside CKC training enhanced isokinetic strength parameters at both three and six months postoperatively in patients with hamstring tendon autografts (27).

b- Intermediate rehabilitation phase (3-6 months): Isokinetic protocols demonstrated significant strength improvements in hamstring tendon autograft recipients at 4-6 months post-ACLR compared to preoperative baselines, particularly following eccentric training (29). The addition of 4-week isokinetic strength training to standard protocols yielded superior outcomes compared to conventional resistance training in bone-patellar tendon-bone autograft recipients (60).

c- Late rehabilitation phase (>6 months): Incorporation of isokinetic strength programs into traditional rehabilitation protocols produced significantly greater strength gains at six months post-ACLR (50). Notably, isokinetic training specifically reduced strength deficits compared to conventional rehabilitation approaches in hamstring tendon autograft patients (61).

Specialized protocols targeting neuromuscular control demonstrated greater effectiveness in minimizing bilateral strength asymmetries compared to standard rehabilitation in anterior tibialis tendon allograft recipients (62). However, functional performance measured by single-leg hop testing showed no significant differences between specialized and conventional protocols (28,62). Additionally, no significant differences in strength recovery or hop performance were observed between standard and accelerated rehabilitation protocols for either hamstring tendon or bone-patellar tendon-bone autografts (63).

3. 8. Comparative analysis of graft selection impact on strength recovery and functional outcomes

Evidence synthesis revealed distinct patterns of strength recovery and functional performance across graft types following ACLR:

Table 2. Comparison of quadriceps and hamstring strength, and functional performance outcomes across different ACLR graft types and rehabilitation protocols.

Author year) Study design	Participants (Sex)	Graft type	Activity level	Rehabilitation procedures	Outcomes measures	Isokinetic strength speed	Evaluation Follow-Up	Measured Parameters	Principal Findings
(Holmgren et al., 2024a) Cross-sectional study	312 patients QT; n = 104; (60 M, 44 F); 27±9.5 years, HT; n = 104; (60 M, 44 F) 26 ±9.7 years, BPTB; n =104; (60 M, 44 F); 26 ±9.4 years	HT StG BPTB QT	Preinjury Tegner QT 7.0 (6.5-8.0)*, Score ≥6; 47 (88.7), HT 7.0 (5.0-9.0)*, Score ≥6; 49 (74.2), BPTB 7.5 (6.0-9.0)*, Score ≥6; 49 (84.5)	The initial rehabilitation included exercises for ROM, balance, coordination, and thigh muscle strength. Open kinetic chain exercises with external weights were introduced after six weeks, between 30° and 90° of knee flexion, and progressed to full ROM by 12-week period.	Isokinetic strength test	Isokinetic Quadriceps test at 90°/s	7±1 months after ACLR	LSI PT LSI TW LSI for torque at 30° of knee flexion LSI for time to PT	**LSI PT and LSI TW and LSI for time to PT:** ↓ in QT compared with HT and BPTB ↓ in BPTB compared with HT **LSI for torque at 30° of knee flexion:** ↓ in QT compared with HT and BPTB NS between HT and BPTB
(Ong et al., 2024) Prospective cohort study	36 patients ECC; n =18; (14M/4F); 26.3±6.7 years, CON; n =18;(17M/1F);25.6±4.3 years	HT	Not reported	4 to 6 months post-surgery, Participants followed 6 weeks isokinetic training program, they performed 10 repetitions at speeds of 60◦/s, 120◦/s, and 180◦/s with a 10-second rest period between each speed progression. the concentric (CON) group used concentric muscle contractions while the eccentric (ECC) group focused on eccentric	Isokinetic strength test SLH test	Isokinetic test at 60◦/s	Pre-training and post-training	PT LSI SHD	↑ PT ↑ PT in ECC than CON ↑Ex LSI NS on Ex LSI between CON and ECC ↑ Flx LSI in ECC ↑ Flx LSI in ECC than CON ↑ SHD in ECC compared with CON ↑ RTS% ECC (55.6%) than CON (27.8%)

				muscle contractions.					
(Forelli et al., 2023) Cohort study	103 recreational athletes OKC+ CKC; n = 51;(34 M/16F); 26.3±5.3 years, CKC; n =52; (36 M/14F) ;30.5±10.2 years	HT; StG	**Tegner score:** OKC+CKC;7.5±1.0 CKC;7.0±2.0 **Marx score:** OKC+CKC;13.5±3.0 CKC;10.2±3.3	closed kinetic chain (CKC) group followed a muscle strengthening protocol three times per week OKC+CKC group followed a combined protocol of CKC and Open kinetic chain (OKC) to strengthen the quadriceps and hamstrings. The OKC protocol was performed on an isokinetic machine for leg extensions and seated leg curls. This routine included 10 sets of 8 repetitions at a speed of 60 degrees per second, along with 8 sets of 8 repetitions, performed three times per week. CKC exercises were initiated immediately after surgery, while OKC exercises began approximately four weeks postoperatively.	Isokinetic strength test knee laxity	Isokinetic test at 60°/s	3 and 6 months after ACLR	LSI PT/BW Laxity	↑ LSI in OKC+CKC than CKC ↑ PT/BW in OKC+CKC than CKC NS on laxity
(Kasmi et al., 2023) Randomized controlled trial	40 elite athletes (M) CON; n=10; ;20.4±3.34 years, ECC; n=10 ;20.30±2.83 years, PLYO; n=10 ;20.30±2.54 years, COMB; n=10 ;20.60±3.80	BPTB	athletes performed systematic sports on an international level and they were members of the Tunisian	Two weeks post-surgery, participants followed a standardized 12-week rehabilitation	Isokinetic strength test Tampa kinesiophobia score (TSK-CF)	Isokinetic test at 90 °/s, 180 °/s and 240 °/s	pre-and post-training	PT TW H/Q Ratio PT Ratio TW Ratio	↑ IKDC , TSK-CF , KOOS ↑ IKDC, TSK-CF, and KOOS in COMB than PLYO, ECC and CON ↑PT Ratio and TW Ratio in COMB than ECC, CON and PLYO

	Years.		national team in their respective sport	program focusing on controlling edema and inflammation, expanding the range of motion, improving stability, and strength training. In addition, Participants of the eccentric (ECC), plyometric (PLYO), and the combined eccentric and plyometric (COMB) groups performed two 60 min training sessions per week for six weeks. The control group (CON) matched the training volume of the intervention groups	IKDC KOOS			LSI PT LSI TW IKDC score KOOS score TSK-CF score	↑LSI PT and LSI TW in COMB than ECC, PLYO and CON
(Wang et al., 2023) Randomized controlled trial	42 athletes EXP; n = 21 ;(7 M, 14 F); 21.6±3.2 years, CG; n = 20; (7 M, 14 F); 22.2±2.8 years.	BPTB	National athletes (judo, wrestling, kung fu, football, volleyball, basketball, weightlifting, hockey, tennis and taekwondo)	Beginning four weeks post-surgery, the experimental group (EXP) underwent a 4-week isokinetic muscle strength training of knee flexion and extension, conducted five times per week. In parallel, the control group (CG) followed the same exercise	Isokinetic strength Test Kinaesthetic test Positional Tests Balance test	Isokinetic test at 60°/s and 240° /s	Pre-training and post-training	PT Muscular endurance Kinesthesia 30° Position sense 60° Position sense Anterior-posterior (AP) displacement Medial lateral (ML) displacement Anterior-posterior (AP) speed	↑ PT and Flx Muscular Endurance in EXP ↓ Kinesthesia , 30° and 60 position sense , AP + ML displacement and speed in EXP ↑ PT at 60°/s in CG ↓ AP + ML displacement and speed in CG ↑ PT at 60°, Ex PT at 240°/s and Ex Muscular Endurance in EXP compared with CG ↓ Kinasthesia, 30° position sense, AP displacement in EXP compared with CG

				schedule but utilized a knee joint trainer with pneumatic resistance.				Medial-Lateral (ML) speed	
(Cerci et al., 2023a) Retrospectve study	64 patients (M) St; n=32; 26.15±8.48 years, StG; n=32; 22.65±6.17 years	HT; St and StG	not reported	The rehabilitation protocol consisted of four phases over 12 weeks. Patients began with patellar mobilization, followed by isometric and isotonic quadriceps exercises then they engaged in closed kinetic chain exercises, isotonic straight leg raises, lateral step-ups, squats and proprioceptive training. Subsequently, they focused on daily activities, including walking, varied-speed straight-line running, stair climbing, balance exercises, and resistance training. The final phase focused on progressive resistance exercises, endurance, agility, and plyometric exercises.	Isokinetic strength test	Isokinetic test for concentric/concentric contractions (Con/Con) at 60°/s, 180°/s, and 240◦/s	6 months after ACLR	H/Q Ratio PT	↑ PT in HK compared to ACLR side ↑ PT in HK in St compared with StG NS on PT between ACLR sides of St and StG ↑ H/Q Ratio at 60°/s in ACLR compared to HK ↑ H/Q Ratio in ACLR side at 60°/s in St compared with StG
(Wenning et al., 2023)	444 patients	HT	Sports performance levels were	Postoperative treatment	Isokinetic strength Test	Isokinetic test at 60 °/ s	Pre-surgery and 5–7	PT(Nm/Kg) H/Q Ratio	↑ Ex LSI in EARLY than DELAYED and CHRONIC

Retrospective cohort study	EARLY; n=89;(64M/25F)(72%M/28%F); 25.3 (14)* years, DELAYED; n=271; (194M/77F) (72%M/28%F) 26.8 (13) * years, CHRONIC ; n=84; (57M/27F)(68%M/32%F) 27.4 (18)* years.		categorized as sedentary, low-intensity activity, linear sports, and pivoting activity, with patients demonstrating increased participation in higher activity levels	performed a criterion-based rehabilitation protocol and involved mono-articular exercises and passive treatments for 2–4 weeks. Full weight-bearing was permitted once there were no signs of inflammation, effusion, or pain, typically within the first two weeks. Then patients progressively increased their physical activity, aiming to attain a symmetrical gait by six weeks at the latest.			months after ACLR	LSI	↑ PT in EARLY than Delayed and CHRONIC ↑ H/Q ratio in ACLR side compared to HK ↑ H/Q Ratio in CHRONIC than DELAYED and EARLY ↑H/Q ratio
(Genç et al., 2023a) Retrospective cohort study	20 athletes (M); 28.05±6.87 years.	HT; Modified St technique	Tegner pre-operative: Mean±SD; 6.45±1.19, Med (Min–Max); 6.45 (5–9), Tegner post-operative: Mean±SD; 6±1.34, Med (Min–Max); 6 (4–8)	not reported	Isokinetic strength test Lysholm Tegner IKDC	Isokinetic test at 60°/s, 180°/s, 240°/s, and 300◦/s	6 months after ACLR	PT H/Q Ratio H/H Ratio Q/Q Ratio Angle at PT (JAPT) Time to PT (TPT) Reciprocal delay (RD) Endurance ratio (ER) Tegner score Lysholm score IKDC score	↑ Lysholm , Tegner and IKDC ↑ Ex PT at 60°,180° and 300 ◦/s in HK compared toACLR side ↑ H/Q , H/H and Q/Q ratio at 300◦/s in ACLR side compared to HK ↑ Ex JAPT At 300◦/s in ACLR side compared to HK ↓ Flx JAPT at 180◦/s in ACLR side compared to HK ↑TPT 300◦/s in HK compared to ACLR side NS on RD and ER
(Genç & Güzel, 2022) Retrospective cohort	29 athletes (M) 24.65±7.47 years	HT; StG	Tegner Pre operative; 6.48±1.45, Tegner post operative; 6.00±1.64	Not reported	Isokinetic strength Test Lysholm Tegner IKDC	Isokinetic test at 60, 180, and 240◦/s	6 months after ACLR	PT H/Q Ratio Joint angle at peak torque (JAPT)	↑ Flx RD at 60°/s and 180°/s in ACLR side compared to HK ↑ Flx PT at 60°/s in HK compared to ACLR side ↑ Ex PT at 180°/s and 240°/s in HK compared to ACLR side

								Time to peak torque (TPT) Reciprocal delay (RD) Lysholm score Tegner score IKDC score	NS in H/Q Ratio, TPT, and JAPT ↑ Lysholm, Tegner and IKDC
(Felix et al., 2022) Longitudinal observation	74 athletes ACL-G; n= 34 (27 M ,7 F); 25.05±6.82 years, CG; n= 40 (33M ,7 F); 27.7±8.16 years.	Not reported	Professional and amateur players Tegner preoperative; 8±1.3, Tegner post operative; 7.1±1.82, Tegner CG; 7.6±1.2	Not reported	Isokinetic knee strength test SLH test	Isokinetic test at 60º/s	Pre-surgery and 12 months after ACLR	LSI	↑ Ex LSI in ACL-G ↑ LSI in CG than ACL-G NS in Flx LSI
(Ivarsson & Cronström, 2022b) Cross-sectional study	72 participants (35M,37F); 25.8±5.4 years.	HT PT other	Not reported	Not reported	Isokinetic strength test by Isokinetic dynamometer (IKD) Isometric strength test by hand-held dynamometer (HHD)	Isokinetic test at 60°/s	12 months after ACLR	IKD PT HHD PT LSI	↑ PT in IKD and HHD in HK compared to ACLR side ↑ PT with IKD than with HHD HHD 75.3% Flx LSI 94.6% Ex LSI IKD 91.3% Flx LSI 87.7 %Ex LSI ↑ Abnormal Flx LSI in HHD than IKD
(Gillet et al., 2022a) Retrospective cohort study	186 patients (M) StG; n = 119; 25.6±6.1 years, St; n = 67; 26.9±6.4 years.	HT : StG and St	Regular participation (at least 3 times a week) in a sport activity at the time of ACL rupture	Rehabilitation program consists of three postoperative stages. The initial postoperative stage, lasting 45 days, including cryotherapy and activities included thigh muscle contractions, passive range of motion exercises, and walking with crutches.	Isokinetic strength test	Isokinetic test at 90°/s, 180°/s, and 240 °/s for concentric and 30 °/s for eccentric contractions	6 months after ACLR	PT Functional Ratio	↓ PT in ACLR side compared to HK NS on PT between St and StG NS on Functional ratio

				Second Stage (45th to 90th day postoperatively) focused on global closed kinetic chain exercises. The final stage of this protocol involved a progressive return to-sport activity approximately 4 months after surgery for non-pivoting sports, 6 months for pivoting sports without contact, and 8 to 9 months for pivoting sports involving contact.					
(Parpa & Michaelides, 2022) Randomized controlled study	24 elite soccer players (M) EXP; n=12 ;24.25±4.73 years, CG; n=12; 23.83±3.86 years.	HT	soccer players	Following six months ACLR, both groups participated in a supervised rehabilitation protocol three times a week for five weeks. The control group (CG) engaged in a regimen that included running, plyometric exercises, cutting movements, and sports-specific drills. The experimental group (EXP) followed the same regimen	Isokinetic strength test	Isokinetic test at 60°/s	Pre-training and post-training	PT H/Q Ratio Q Deficits H Deficits	↑ PT in ACLR side ↑ Ex PT than Flx PT in ACLR side ↓ Q deficits at post-training ↓ Q deficits in EXP than CG NS on H deficits ↑ H/Q Ratio% in ACLR side in Exp NS on H/Q Ratio % in ACLR side in CG

				but also incorporated an isokinetic training protocol					
(Gerdijan et al., 2022) Randomized controlled study	44 subjects Isokinetic; n=72; 36 M ;29.22±4.61 years and 36 F;27.53±4.26 years. Classic; n=72; 36 M; 27.78±4.59 years and 36 F; 28.28±4.65 years.	HT	Not reported	Four months post-surgery, the isokinetic group underwent in kinesitherapy following an isokinetic exercise program which included 30-minute training sessions, five times a week, for six weeks. the classic group followed a kinesitherapy regimen based on standard isotonic exercises, focusing on muscle strength enhancement through weight training and gym workouts.	Isokinetic strength test	Isokinetic test at 60 º / s	pre-training and 3and 6 weeks post training	Deficit of torque of the knee flexor (FLDEF)	↓ FLDEF ↓ FLDEF in Isokinetic group than in classic group
(Von Essen et al., 2021) Randomized controlled study	137 patients IL; n=68(33F, 35M); 33±9 years, CL; n= 69 (25 F, 44M); 31.1±9 years.	HT; St from Ipsilateral (IL) leg and St from contralateral (CL) leg	Tegner median (range) pre injury: IL; 7 (2–10), CL; 8(4-10)	The rehabilitation protocol was standardized to allow full weight-bearing from the first day after surgery. However, sports activities that involve contact or pivoting were strictly restricted for a duration of nine months post-surgery.	Isokinetic strength test Isometric test at 60°/s SLH test Lysholm Tegner IKDC KOOS	Isokinetic test at 60, 180 and 300°/s,	6, 12 and 24 months after ACLR	Isokinetic PT Isometric torque Total work (TW) ROM Laxity Muscle circumference Distance SLH Tegner score Lysholm score KOOS score IKDC score	↑ Lysholm , KOOS , IKDC and tegner NS Lysholm, KOOS, IKDC, Tegner between groups NS ROM and laxity between IL and CL groups Similar in Distance SLH and muscle circumference between IL and CL groups ↑ Isometric Ex torque in Cl at 6,12 months but NS at 24 months ↓ Isokinetic Flx PT and Flx TW in IL group

(Cristiani et al., 2021) Randomized controlled study	160 patients BPTB/standard rehab; n=40 (25 M, 15 F),;29.3±6.4 years, BPTB/accelerated rehab; n=40 (34 M, 6 F);28.5±5.5 years, HT/standard Rehab; n=40; (29M ,11F);28.0±6.3 years, HT/accelerated rehab; n=40 (27M ,13F); :28.8±6.3 years.	BTPB HT	Not reported	The accelerated rehabilitation program lasts for 4 months, while the standard program continues for 6 months. Patients start rehabilitation with exercises to achieve full ROM and weightbearing followed by closed kinetic chain exercises, balance and proprioceptive training, and using a stationary bicycle. In later stages, patients engage in a running program and plyometric exercises, cutting drills, perturbation training, and sport-specific drills.	Isokinetic strength test SLH test	Isokinetic test at 90°/s	Pre-surgery and 4,6,8,12 and 24 months after ACLR	Ex LSI Flx LSI SLH LSI	↓ Ex LSI at 4 months ↑ Ex LSI from 6 to 24 months ↓ Ex LSI in BPTB compared with HT ↑ Flx LSI in BPTB from 4 to 24 months ↓ Flx LSI in HT at 4 months ↑ Flx LSI in HT from 6 to 24 months ↓ Flx LSI in HT compared with BPTB ↑ SLH LSI from 4 to 24 months ↓ SLH LSI in BPTB compared with HT at 4 months NS on muscle strength and SLH performance between Standard and accelerated rehab groups
(Sinding et al., 2020) Prospective randomized controlled clinical trial	150 patients QT; n = 50 (25 M, 25F) ;28.7±6.4 years, HT; n = 50 (23 M, 27F);28.3±6.2 years, CG: n = 50 (27M ,23 F);28.3±6.2 years.	QT HT; StG	Not reported	The standard rehabilitation program followed a progressive approach. During the initial phase (days 1–14), patients were allowed full weight-bearing up to their pain threshold, encouraged free	Isokinetic strength test SLH test IKDC	0 °/s isometric, 60 °/s and 180 °/s concentric, and − 60 °/s eccentric	12 months after ACLR	PT LSI H/Q Ratio IKDC score SHD	↓ Ex PT and LSI in ACLR side in QT compared with HT and CG ↓ Flx PT and LSI in ACLR side in HT compared with QT ↓ H/Q ratio in ACLR side in HT compared with QT ↓ PT and LSI in ACLR side in HT compared with CG NS H/Q ratio in ACLR side between HT and CG ↑ H/Q ratio in ACLR side in QT compared with CG NS on Muscle strength in HK between groups

				movement, and no bandages were required. In the subsequent phase (weeks 3–12), the regimen included frequent movement exercises with the use of a bicycle ergometer, and continued full weight-bearing. From 4–9 months, patients were permitted to start running. Finally, in the period from 10–12 months, participation in contact sports was allowed.					↑ IKDC in QT and HT groups NS on IKDC between QT and HT groups NS on SHD and SHD LSI between QT and HT groups ↓ SHD and SHD LSI HT and QT compared to CG
(Riesterer et al., 2020) Retrospective study	80 patients (54M, 26 F) ;29±9 years	HT; St	Not reported	The rehabilitation protocol consists of four phases over 26 weeks, Patients began with knee mobilization, quadriceps activation, gait training, proprioceptive training, stationary cycling, and neuromuscular stimulation. Then they incorporated closed kinematic chain coordination and performed hip and core	Isokinetic strength test	Isokinetic test at 60°/s	Pre-surgery and 6 months after ACLR	PT H/Q Ratio LSI	↑ PT in both sides ↑ Ex LSI NS Flx LSI NS H/Q Ratio

				stability training. Subsequently, they progressed to strength development, running, and stretch-shortening exercises.					
(Roger et al., 2020) Randomized controlled trial	60 Patients St; n=33 (78%M ,21.2% F);30.5±8.9 years, StG; n=27(85.2%M,14.8%F) 30.3±8.5years.	HT; St and StG	Sport level before rupture (%) 4ST Intensive ;78.8 Moderate;21.2 StG Intensive;73.7 Moderate;26.3	Rehabilitation began immediately following surgery and lasted for six months. The program was personalized according to the initial passive range of motion (ROM) and weight-bearing capacity.	Isokinetic strength test IKDC knee laxity Postural Balance pain upon kneeling and sensation over the donor site	Isokinetic test at 60°/s and 240°/s	Pre-surgery, 6 and 24 months after ACLR	Side to side deficits (%) IKDC score Return to work (yes/no) side-to-side differential laxity Pain Length-function–surface area (LFS) Loss of flexion/extension	↑ IKDC NS on IKDC , Side to side deficits ,return to work, pain during physical activities, side-to-side diferential laxity, balance, **loss of flexion/extension**, or surgicalcomplications.,between groups ↑ Laxity
(Guney-Deniz et al., 2020) Cross-sectional, case–control study	67 patients with ACLR and 20 healthy individuals. QT; n = 22; (17M, 5F); 27.8±2.8 years, HT; n = 24; (18M ,4F); 26.7±4.6 years, TAA: n = 21 (17M, 4F); 26.4±5.5 years, CG; n = 20;28.7±3.1 years	QT HT ATT	All participants had equal Tegner Knee Score and no patient was professional or elite level athletes	Early rehabilitation emphasized managing joint swelling and controlling pain. Upon meeting specific criteria, the program gradually incorporated strengthening exercises and functional therapeutic activities.	Isokinetic strength test Active joint position sense (JPS) assessments at 15°, 45° and 75° of knee flexion SLH test IKDC	Isokinetic test at 60°/s and 180°/s	12 months after ACLR	PT EX LSI FLX LSI Active JPS IKDC scores SHD LSI SHD	↑ Ex LSI at 60°/s in CG than QT, HT and ATT ↑ Ex LSI at 60°/s in HT than QT ↑ Ex LSI at 180°/s in CG than QT and ATT NS at 180 °/s in Ex LSI betwen CG and HT ↑ Ex LSI in HT than QT and ATT at 180 °/s NS on Ex LSI between QT and ATT NS in Flx LSI between ACLR groups and CG

									NS IKDC and LSI SHD between ACLR groups and CG ↓ Active JPS in QT, HT, and ATT compared to CG at 15° NS on JPS between ACLR groups and CG at 45° and 75° ↓ JPS in QT compared to ATT and HT at 15°
(Vidmar et al., 2020) Randomized controlled trial	30 recreational athletes (M) ;25 years old CG; n = 15, IG; n = 15	HT; StG	Recreational athletes, 33 engaged in a systematic sports practice with minimum frequency of once a week	Approximately 45 days after ACLR, conventional group (CG) or isokinetic group (IG) are engaged in six weeks (2 sessions/week) knee extensor eccentric training program. Participants in the IG began with passive knee flexion to 30°, followed by maximal eccentric of the quadriceps to resist the knee flexion movement generated by the dynamometer at a constant speed of 60◦/however, participants in the CG were encouraged to perform a knee extensor eccentric contraction using an extensor chair, starting from a	Isokinetic strength test SLH test Muscle mass evaluation (magnetic resonance imaging) Lysholm	Isokinetic test at 60°/s	Pre-training and post-training	Isometric PT Eccentric (ECC) PT Concentric (CON) PT Lysholm score Cross-sectional area (ACSA)	↑ Isometric PT and ECC PT in IG than CG ↑ ECC PT in IG than CG ↑ ACSA in IG than CG NS in CON PT and Lysholm and SLH test between groups

				concentric position. An electronic metronome ensured a consistent cadence of 2 s for each phase of movement					
(Batty et al., 2019) Cohort study	100 patients (54 M and 46 F); 26.6±8.0 years.	HT	Not reported	The rehabilitation program extended over a period of 52 weeks, Patients were instructed to reduce knee swelling with rest, ice, compression. Patients were allowed to bear their full weight. they focused on knee flexibility exercises, including using a stationary bicycle, performing wall squats, straight leg raises, lunges, and hamstring curls. Afterward, they engaged in a gym program that involved half squats, using a rowing machine, a cross-trainer, and a step machine. Additionally, they performed bridging, calf raises, exercise ball drills to enhance core	Isokinetic quadriceps strength test Single-leg squat (SLS) test	Isokinetic test at 60°/s	6 and 12 months after ACLR	Knee extensor concentric PT LSI SLS Maximum flexion angle	↑ PT and LSI in both sides Strength deficits in 75% of patients at 6 months and 57%of patients at 12 months ↑ SLS Maximum flexion angle in ACLR side between 6 months and12 months SLS deficits in 31% of patients at 6 Months and 19% of patients at 12 months

				stability, and leg extensions. Subsequently, patients were typically permitted to resume sport-specific drills and activities.					
(Csapo et al., 2019a) Retrospective cohort study	46 athletes (26 F; 20.0±2.7 years and 20 M;21.6±3.2 years) HT; n = 25(15M,10 F) QT; n = 21 (6M,15 F)	HT QT	Professional alpine skiers, Tegner scores indicated high activity levels at all measurement points (0 months; 7.9±0.5, 6 months;8.0±1.0, 12 months; 8.3±0.7, 24 months;7.9±0.5)	Not reported	Isokinetic strength test Lysholm Tegner visual analog scale (VAS) back in action test battery	Isokinetic test at 60°/s	**Lysholm, Tegner and VAS** 0, 6, 12, and 24 months after ACLR **Isokinetic test and back in action test** 161.5±24.2 days after ACLR	Maximum voluntary contraction (MVC) PT MVC Ratio Q deficits H deficits Lysholm score Tegner score	↓ MVC PT in ACLR side ↑ MVC Ratio in ACLR side ↑ Q deficits in ACLR side compared to HK ↑ Q deficits in QT compared with HT NS in H deficits between goups ↑ Lysholm and Tegner
(Kaya et al., 2019) Randomized controlled study	32 patients G1; n=17;29.35±9.71 years, G2; n=15,31.60±8.45 years.	ATT	Not reported	All patients followed a standard rehabilitation program during the first two weeks after surgery. From third week to 12th week following ACLR, neuromuscular control exercises were added to the standard rehabilitation program for patients in G1. Initially, patients began with single leg	Isokinetic strength test knee joint position sense (JPS) tests SLH test Subjective tests	Isokinetic test at 30°/s and 60°/s, 180°/s, and 330°/s	24 months after ACLR	Concentric PT JPS at15°, 45°, and 75° SHD Subjective parameters (The pivot shift, anterior drawer, and valgus stress tests)	↓ PT at 30°/s in ACLR side compared to HK in G1 ↓ PT at 60°/s in G2 in ACLR side compared to HK Ns on PT at 60°/s and 180°/s between both groups ↓ PT at 330°/s in G1 Compared with G2 ↓ JPS at 15°, 45°, and 75° in ACLR side in G1 than G2 ↑ SHD in ACLR side compared to HK NS in SHD in ACLR sides between both groups

				stance, balance exercises, lunges, step-ups, and bilateral squats. Subsequently, patients performed step-downs, single-legged squats, box heel touches, bridges, and ball exercises. finally, patients performed single-leg straight leg deadlifts, sumo squats, and incorporated weights into all exercises. From the 13th to the 24thweek after surgery, patients engaged in running, agility drills, and plyometric exercises.					
(Hunnicutt et al., 2019) Cohort study	30 patients QT; n = 15 (12M, 3F); 25.0 (14.0–41.0) years, BPTB; n = 15 (7M, 8F); 18.0 (15.0–32.0) years.	QT BPTB	Active patients Preinjury Tegner Score: QT;9 (6-10), BPTB; 9 (3-10) Postoperative Tegner score: QT; 6 (4-9), BPTB;8 (3-9)	Not reported	**Neuromuscular outcomes** Isokinetic and Isometric knee strength test Central activation **Functional outcomes** SLH Crossover hop test Step length symmetry IKDC Lysholm KOOS	Isokinetic test at 60°/s and 180°/s	8 months after ACLR	LSI of Neuromuscular outcomes LSI of Functional outcomes IKDC score Lysholm score KOOS score	NS on LSI Isokinetic and Isometric strength between QT and BPTP NS on SLH LSI between QT and BPTP NS on IKDC , Lysholm and KOOS between QT and BTPB

(Martin-Alguacil et al., 2018) Randomized controlled study	51participants QT ; n = 26(23 M, 3F) 18.7±3.6 years, HT; n = 25(16M,9F); 19.2±3.6 years;	QT HT	Soccer players	Rehabilitation program consists of four phases for 24 weeks and focused on muscular strength, endurance, and neuromuscular control. Patients begin by improving ROM through open and closed chain exercises, then progress to cycling, jogging, and performing balance and plyometric activities. The final stage focuses on muscle strength.	Isokinetic strength test Lysholm knee score Cincinnati Knee Rating System knee stability with KT-2000	Isokinetic test at 60°/s, 180°/s, and 300°/s	Pre-surgery and 3, 6,12 and 24 months after ACLR	PT H/Q ratio Lysholm score Cincinnati knee rating system Anteroposterior laxity	↑ H/Q Ratio in QT compared with HT ↑ Ex PT in HT compared with QT ↑ Lysholm and cincinnati
(Almeida et al., 2018) Prospective case-control study	40 Professional soccer players (M) StG: n=20; 21 (18-28) years, CG: n=20; 20.5 (18-34) years	HT; StG	Professional soccer players	Not reported	Isokinetic strength test IKDC Lysholm Cardiopulmonary exercise test	Isokinetic test at 60 °/s and 240°/s	Pre-surgery and 6 months after ACLR	PT (Nm/Kg) PT deficits (%) Lysholm score the maximum oxygen uptake (VO2max) VT1 VT2 Running speed	↑ IKDC and Lysholm ↓ PT in StG compared to CG ↑ PT deficits in StG compared to CG
(Fischer et al., 2018b) Randomized controlled study	124 patients QT; n = 61 (34 M, 27 F) ;21.7±7.4 years, HT; n =63 (47M ,16 F); 21.5±6.9 years	QT HT	Not reported	Physical therapy began on the first day after surgery, with a particular emphasis on knee extension. Isometric and closed chain exercises started after one week, bicycling after three weeks, and running and sport-specific exercises began	Isokinetic strength test	Isokinetic test at 60°/s	5.5±1.2 months and 7.6±1.6 months after ACLR	PT H/Q ratio LSI	↓ Ex PT in the QT ↑ H/Q ratio in QT compared with HT ↑ Ex PT in HT ↑ Flx PT in QT ↑ Ex LSI in HT compared to QT ↑ Flx LSI in QT compared to HT

				three months post-surgery					

ATT = tibialis anterior tendon; HT = hamstring tendon ;QT = quadriceps tendon; BPTB = bone-patella tendon-bone H = hamstrings; Q = quadriceps; Ex = extensor; Flx = flexor; H/Q = Hamstring/quadriceps; IKDC = International Knee Documentation Committee; KOOS = Osteoarthritis Outcome; LSI = limb symmetry index; BW = body weight; PT = peak torque; SHD = single hope distance; HK = healthy knee; SLH = single leg hop; NS = no significant; TW = total work; RTS = return to sport; H/H = hamstrings/hamstrings; Q/Q = quadriceps/quadriceps; St = semitendinosus; StG = semitendinosus gracilis; * = Median (interquartile range); M = Male; F = Female.

a- Temporal changes in muscle strength: Post-operative isokinetic strength demonstrated consistent improvement from preoperative baselines (47), with significant gains observed by 12 months. However, when compared against healthy controls, both HT and QT recipients exhibited persistent strength deficits; HT grafts showing bilateral weakness in quadriceps and hamstrings, while QT grafts primarily affected quadriceps function (57). At seven months post-ACLR, none of the surgical groups achieved the clinical benchmark of 90% LSI for quadriceps strength (64).

b- Graft-specific strength patterns: Direct comparison revealed QT recipients demonstrated greater quadriceps deficits than HT recipients, while HT recipients showed more pronounced hamstring weakness (57). The BPTB group exhibited significantly reduced quadriceps strength through 12 months compared to HT recipients, whereas HT recipients displayed persistent hamstring deficits throughout the follow-up period (63). Notably, HT recipients showed improved quadriceps torque production at six months compared to preoperative values (50), though remaining below control group levels (65).

c- Bilateral strength adaptations: Studies documented significant strength improvements in the uninjured limb following ACLR with HT grafts (66), alongside reduced hamstring deficits in the operated limb (61). A comprehensive analysis of HT, QT, and ATT recipients revealed universal decreases in quadriceps index scores compared to healthy controls, while hamstring indices remained stable (67).

d- Functional performance outcomes: SLH performance showed comparable results between HT and QT recipients, though both groups demonstrated significant deficits compared to controls (57). While SLH performance improved from preoperative levels across all graft types, BPTB recipients demonstrated inferior performance at four months compared to HT recipients (63). Notably, functional outcomes measured by standardized assessment tools showed equivalence among HT, QT, and ATT groups relative to healthy controls (67).

3. 9. Quality assessment and risk of bias

The methodological quality evaluation of included studies revealed important considerations for interpreting the strength of evidence. Randomized controlled trials, comprising 43% of included studies (n=12), demonstrated generally robust methodological quality when assessed using the PEDro scale, with a mean score of 7.2/10 (range 6-9) (68,69). The remaining observational studies (n=16) achieved satisfactory quality ratings on the Newcastle-Ottawa Scale, averaging 6.8/9 (range 5-8) (70).

Several methodological limitations warrant consideration when interpreting results. Only 32% of studies implemented assessor blinding during strength testing protocols, potentially introducing measurement bias (71). Documentation of rehabilitation protocol compliance was incomplete in 36% of studies, limiting assessment of intervention fidelity (72). The heterogeneity in follow-up durations, ranging from six months to two years, created challenges for temporal comparisons across studies (73). Additionally, variations in strength testing protocols and outcome reporting methods complicated direct comparisons between investigations (16).

Systematic risk of bias assessment revealed predominantly favorable methodological characteristics across studies. Selection bias was minimized in 78% of studies through clear eligibility criteria and appropriate sampling methods. While complete blinding of surgical interventions was inherently challenging, studies implemented various strategies to reduce performance bias, including standardized rehabilitation protocols and objective outcome measures (74). Detection bias was effectively controlled in studies utilizing calibrated isokinetic dynamometry under standardized conditions (74). Participant retention was robust, with 82% of studies reporting dropout rates below 15% (75). Furthermore, comprehensive reporting of pre-specified outcomes aligned with registered protocols demonstrated low risk of reporting bias (76).

These quality considerations provide essential context for interpreting the synthesized evidence while highlighting specific methodological aspects requiring attention in future research. The overall quality assessment suggests sufficient methodological rigor to support the main findings while acknowledging limitations inherent to surgical intervention study (77).

4. DISCUSSION

4. 1. Strength testing modes

Isokinetic dynamometry (IKD) remains the gold standard for objective muscle strength assessment following ACLR (48). However, recent studies have highlighted the potential limitations of IKD, such as its high cost and limited availability in some clinical settings. We determined to report reference values at 60°/s, 180°/s, 240°/s and 300°/s. This was founded on a recent Delphi survey in which specialists such as physical therapists, orthopedic surgeons, and scientists suggested a protocol for the evaluation of concentric knee movements, consisting of five repetitions at 60°/s, 20 repetitions at 180°/s, and 15 repetitions at 300°/s, with one minute of rest interval between sets (78). Recent systematic reviews have validated the use of these specific testing velocities for comprehensive strength evaluation. Unfortunately, IKD is only available to a limited number of clinicians because of its expense and lack of portability (26). In case access to IKD is limited, hand-held dynamometer (HHD - belt-stabilized) can act as a reliable substitute for assessments of quadriceps and hamstrings strength (79,80). In our scoping review, HHD strength measurements can be evaluated against Maximum voluntary isometric contraction (MVIC) reference values. Our review includes MVIC reference values obtained through both IKD and HHD, the validity of HHD measurements in relation to IKD measurements continues to be a topic of discussion (79,81). While IKD provides precise isokinetic strength measurements through computerized assessment, its clinical utility is limited by high cost and space requirements. Hand-held dynamometry offers a valid, reliable and practical alternative for isometric strength testing when IKD is unavailable (82–87). However, HHD measurements can be influenced by tester strength and experience, whereas IKD testing is operator-independent but requires patient familiarization to achieve maximal output (86,87). Given these considerations, both IKD and HHD have important roles in strength assessment after ACLR, with protocol selection guided by clinical setting, resources, and specific testing objectives.

4. 2. Early rehabilitation

Current evidence supports implementation of comprehensive early rehabilitation protocols after ACLR that emphasize restoration of full knee extension range, progressive weight-bearing, and a combination of CKC and OKC exercises (88). While traditional protocols favored CKC exercises due to concerns about graft strain, recent systematic reviews demonstrate that early introduction of progressive OKC exercises enhances quadriceps strength recovery without compromising graft healing or knee stability (89–92). However, the optimal timing and progression of OKC exercise introduction remains debated, as accelerated protocols have not consistently demonstrated superior outcomes in strength symmetry or functional performance (63).

Early rehabilitation must address both local and global movement strategies, as research demonstrates that patients often develop compensatory mechanisms using trunk and hip musculature to overcome quadriceps weakness (93,94). While these compensations may allow early return to function, they could potentially increase injury risk if not properly addressed through targeted neuromuscular training (91,95).

4. 3. Strength training

Restoring symmetric quadriceps and hamstring strength is crucial following ACLR, as persistent deficits increase risk of graft failure, contralateral ACL injury, and suboptimal return to sport outcomes (96–98). Systematic reviews have identified quadriceps strength deficits exceeding 20% at six months post-surgery, while hamstring deficits may persist even after return to sport, particularly following hamstring autograft procedures (98,99). Contemporary rehabilitation protocols emphasize progressive strength training combined with neuromuscular and plyometric exercises to optimize functional outcomes (100–102). Recent evidence demonstrates that properly periodized strength training induces both morphological and neural adaptations that enhance muscle function (28,59,101). These adaptations include muscle fiber hypertrophy, shifts in fiber type composition, and improvements in neuromuscular activation patterns (101,103). The integration of both concentric and eccentric training modalities appears particularly important, as the mechanical tension and controlled tissue damage from eccentric loading provides potent stimuli for muscle adaptation and hypertrophy (28,104).

4. 4. Isokinetic training programs

Isokinetic resistance training provides unique advantages in ACLR rehabilitation through controlled loading across the full range of motion (105,106). The constant velocity movement pattern allows safe progressive strengthening while accommodating to patient fatigue and pain levels (107). Recent systematic reviews demonstrate that integrating isokinetic training into comprehensive rehabilitation programs accelerates strength recovery, with significant improvements documented as early as 4 weeks post-surgery (28,108,109).

Modern isokinetic protocols typically incorporate both concentric and eccentric contractions at varying velocities, complemented by functional exercises targeting balance, proprioception and power development (84). This multi-modal approach appears particularly effective for restoring sport-specific function and confidence in athletic populations (107).

4. 5. ACLR choices and muscle strength

The HT is frequently utilized as a graft for ACLR, often resulting in long-term muscle strength deficits and decreased function in patients (110,111). Studies have demonstrated decreased hamstring strength at greater knee flexion angles in individuals following ACLR with HT grafts (112,113). Notably, deficits in flexion strength persist for up to two years post-surgery (113–115). Our scoping review encompassed research utilizing HT grafts from both the semitendinosus and gracilis tendons (StG), potentially influencing the observed outcomes. While harvesting both hamstring tendons may exacerbate hamstring strength weakness compared to using only the semitendinosus, the gracilis may contribute to functional compensation (32). However, a systematic review indicated that gracilis harvesting led to only a 3.85% decrease in hamstring strength compared to semitendinosus harvest alone (116). Furthermore, persistent hamstring strength deficits have been observed for three to five years following ACLR with HT grafts (117). Literature suggests a trend of quadriceps strength decline for BPTB autografts and hamstring strength decline for HT autografts after ACLR (118). This weakness in hamstring strength may contribute to higher ACL re-rupture rates observed with HT grafts compared to BPTB grafts (119). Issaoui et al. (1) reported that BPTB group had more pronounced quadriceps deficits than HT group. However, some studies have observed a greater increase in quadriceps strength compared to hamstrings following StG ACLR in athletes (120). Furthermore, Chen et al. (121) identified that knee extensor strength was relatively lower but comparable between the ATT and HT groups around 2.5 years post-surgery. These strength variations between the HT and ATT groups could be attributed to ongoing quadriceps femoris atrophy and central inhibition, despite mechanical adjustments (122).

4. 6. Role of strength assessment in RTS decision making

RTS decisions following ACLR should be based on a series of tests (123). Recent systematic reviews have emphasized that comprehensive, criterion-based RTS protocols incorporating multiple objective measures demonstrate superior outcomes compared to time-based protocols alone (124). However, the exact components of such a battery remain a topic of ongoing and intense debate. Contradictory research in the ACL field adds complexity to this discussion. Isometric and isokinetic strength assessment represents a cornerstone of objective rehabilitation monitoring and RTS decision making, with high reliability and validity for detecting between-limb asymmetries (125). According to the literature, a muscle strength difference of less than 10–15% between legs is considered satisfactory for patients with an ACL tear when resuming intense activities (126). Simultaneously, isokinetic dynamometers are commonly used to assess quadriceps and hamstring strength in RTS evaluations (16,17). quadriceps strength test outcomes are linked to ACL and knee reinjuries and should be considered a crucial element of a RTS evaluation process (17,127–129).

4. 7. Isokinetic testing parameters and RTS criteria

IKDs are commonly used to obtain objective data on knee strength, assisting in making RTS decisions and tracking the rehabilitation process after ACLR (10,130,131). PT assessment using isokinetic dynamometry provides insight into both force-generating capacity and neuromuscular control. Recent evidence suggests that quadriceps strength symmetry >90% correlates with reduced secondary ACL injury risk (132). After ACLR, IKDs offer objective data on PT values, particularly for knee extension and flexion movements (133). PT is a standard variable for assessing muscle strength and is measured with the limb symmetry index, which serves as a guideline for assessing rehabilitation and RTS readiness (16). PT is a crucial outcome of isokinetic strength assessments in patients following ACLR (78). The H/Q ratio is the most often used parameter to evaluate muscular strength balance, which considers the function of two opposing (agonist-antagonist) muscle groups (134,135). Asymmetries between the operated and non-operated leg, along with the H/Q ratio, are commonly determined using maximum torque values (21,136). Research has demonstrated that greater quadriceps strength symmetry before returning to sports significantly lowers the risk of re-injury (20). Deficits in the H/Q ratio are linked to a higher risk of ACLR tear (18). It has been suggested that returning to sports participation requires an isokinetic strength ratio greater than 80% of the contralateral knee, along with the effective completion of all functional tasks (88).

Genç et al. (137) have evaluated APT, TPT, RD, and ER values in addition to PT and H/Q ratio values. Researchers view the JAPT value as a crucial indicator of muscle injury risk, as it reflects the relationship between muscle length and force (138,139). The significance of data on muscle reaction time, such as TPT and RD, in assessing determining the likelihood of joint injuries following abrupt movements is also highlighted (140,141). These comprehensive strength parameters, including PT timing and angle-specific torque production characteristics, provide crucial information about both muscle function and injury risk that should inform individualized RTS decisions. A LSI greater than 90% is regarded as satisfactory and is commonly used as a criterion before permitting a patient to RTS (142,143). Recent evidence suggests that meeting objective strength criteria, particularly quadriceps symmetry >90% LSI, correlates with improved patient-reported outcomes and reduced reinjury risk after return to sport (132). Grondin et al. (144) demonstrated that incorporating the hamstring strength symmetry index could slightly improve the estimation of return to running. Additionally Krzemińska and Czamara (145) emphasized that restoring the hamstring strength symmetry index and H/Q ratio can lower the risk of ACL graft failures.

4. 8. SLH test as part of RTS

SLH symmetry has been established as a crucial predictor of successful RTS outcomes and reduced reinjury risk following ACLR (32). Literature indicates that a LSI of 90% or higher in single-leg hopping performance should be considered as a key criterion for RTS (18,20). Recent systematic reviews and meta-analyses demonstrated that achieving LSI ≥90% in hop testing, combined with adequate quadriceps strength, reduced secondary ACL injury risk by up to 84% compared to not meeting these criteria (34,146–148). The SLH LSI, calculated as the ratio of operated to uninjured limb hop distance, provides an objective and normalized functional performance measure that accounts for individual anthropometric variations (130). Additionally, it provides a useful indicator for comparing the two limbs together (19). Logerstedt et al. (33) identified that limb symmetry in the SLH test at six months post-surgery is a predictor of favorable function. Gustavsson et al. (31) reported 6% asymmetry in a healthy group, 21% in the non-operated ACL group, and 20% in the group that underwent surgery six months post-ACLR. Felix et al. (47) noted that one year after ACLR, improvements in symmetry are considered to reach levels that enable a safe RTS activity. However, recent evidence suggests that SLH testing alone may not be sufficient, as athletes can achieve LSI >90% despite persistent quadriceps strength deficits. A comprehensive RTS test battery incorporating strength, power, and neuromuscular control assessments is recommended. This data strongly implies that a safe RTS is influenced by multiple factors and while the time since surgery is important, it should not be the only factor considered.

4. 9. Limitations

Several methodological limitations warrant consideration. While LSI remains the most widely used metric for assessing post-ACLR outcomes, its validity as a sole criterion has been questioned (146). Recent evidence demonstrates bilateral deficits following ACLR, with the uninvolved limb experiencing detraining effects during the early rehabilitation phase and potential compensatory strengthening during later phases (149). This bilateral adaptation phenomenon may mask true deficits when using LSI alone (12,18,19,31,33,63,117,150). Additionally, absolute strength values compared to pre-injury baseline or matched healthy controls may provide more accurate assessments of recovery (151).

4. 10. Practical recommendations

Based on the synthesized evidence, several key recommendations emerge for clinicians working with post-ACLR patients. Strength assessment protocols should incorporate both isokinetic and isometric testing when available, with testing at multiple angular velocities (60°/s, 180°/s, and 240°/s) to comprehensively evaluate muscle function. When isokinetic testing is unavailable, belt-stabilized hand-held dynamometry provides a valid alternative for isometric strength assessment.

Rehabilitation programming should begin early with a focus on restoring full knee extension range of motion and progressive weight-bearing. The integration of both OKC and CKC exercises is recommended, with OKC exercises introduced progressively from 4-6 weeks post-surgery. Strength training should emphasize both concentric and eccentric contractions, with particular attention to eccentrics for enhancing muscle hypertrophy and function.

RTC decisions should be based on multiple objective criteria rather than time alone. A minimum LSI of 90% for both quadriceps and hamstring strength, combined with symmetrical SLH performance, should be achieved before clearing athletes for RTS. However, clinicians should recognize that LSI may mask bilateral deficits and should consider absolute strength values compared to pre-injury baseline or matched controls when available.

Graft-specific considerations should inform rehabilitation progression. Patients with HT grafts require particular attention to hamstring strength restoration at deep knee flexion angles, while those with BPTB grafts need focused quadriceps strengthening. Regular monitoring of both limbs throughout rehabilitation is essential to identify and address potential compensatory mechanisms that may develop.

The integration of neuromuscular training alongside conventional strength training is crucial for optimizing outcomes. This should include progressive balance, proprioception, and sport-specific movement training to address both local and global movement strategies. Patient education regarding realistic recovery timeframes and the importance of achieving objective strength criteria before return to sport is essential for ensuring compliance with rehabilitation protocols.

5. CONCLUSION

This review synthesizes the current evidence regarding quadriceps and hamstring strength recovery patterns and functional performance outcomes across different ACLR graft choices and rehabilitation protocols. The findings highlight the importance of objective strength and hop testing using both absolute values and LSI for comprehensive athlete monitoring. Future research should focus on developing more comprehensive and standardized rehabilitation protocols to optimize muscle strength recovery and functional performance following ACLR. While LSI remains a valuable clinical tool, rehabilitation specialists should consider multiple objective and subjective criteria when making RTS decisions. Future research should focus on establishing more comprehensive, evidence-based RTS testing batteries that can better predict successful outcomes and minimize reinjury risk.

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DECLARATION

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