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Neuroplastic and neuromechanical recovery after anterior cruciate ligament reconstruction: Systematic review

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Abstract
Background: Anterior cruciate ligament reconstruction (ACLR) is one of the most common orthopedic procedures in sports medicine. Despite surgical and rehabilitation advances, patients frequently exhibit persistent neuromechanical asymmetries, proprioceptive deficits, and cortical maladaptation's that compromise long-term functional outcomes.
Objective: To systematically synthesize evidence regarding neuromechanical adaptations following ACLR, integrating findings on strength recovery, proprioception, cortical reorganization, and rehabilitation efficacy.
Methods: Following PRISMA 2020 guidelines, a systematic search was conducted in PubMed, Scopus, Web of Science, PEDro, and Cochrane Library for studies published between 2015 and 2025. Boolean operators combined descriptors: ("Anterior Cruciate Ligament Reconstruction" OR "ACL Reconstruction") AND ("Neuromechanics" OR "Proprioception" OR "Neuroplasticity" OR "Gait") AND ("Rehabilitation" OR "Physiotherapy" OR "Biomechanics"). Inclusion criteria encompassed randomized, cohort, or case studies assessing neuromechanical outcomes post-ACLR. Fifty studies met eligibility criteria.
Results: Evidence consistently indicates that neuromechanical recovery remains incomplete in most patients, with ongoing quadriceps inhibition, altered gait patterns, and impaired proprioception. Neuroplastic changes and asymmetrical activation persist despite conventional training. Multimodal rehabilitation integrating kinetic-chain coordination, plyometric and neurocognitive training, and exergaming enhances motor control and postural stability.
Conclusion: Neuromechanical adaptation after ACLR is multifactorial and requires integrative approaches targeting both peripheral and central mechanisms. Proprioceptive retraining and neuroplastic interventions are essential to restore full sensorimotor control and prevent re-injury.

Keywords: Anterior cruciate ligament reconstruction, neuromechanical adaptation, proprioception, neuroplasticity, rehabilitation

1. Introduction

Anterior cruciate ligament (ACL) rupture remains one of the most common and disabling injuries in sports medicine, particularly among young and physically active individuals [1, 2]. The ACL is a key stabilizer of the knee joint, contributing not only to mechanical stability but also to proprioceptive feedback through its dense network of mechanoreceptors that communicate afferent sensory input to the central nervous system [3, 4]. When this ligament is torn, the disruption of these neural pathways triggers both peripheral and central maladaptations, including altered motor control, proprioceptive deficits, and cortical reorganization that persist even after surgical reconstruction [5-7]. Consequently, the challenge in ACL rehabilitation extends beyond restoring structural integrity to reestablishing the neuromechanical harmony that governs functional movement.

Over the past decades, advances in surgical techniques have improved the mechanical outcomes of ACL reconstruction (ACLR), yet the restoration of neuromechanical function remains incomplete for a significant proportion of patients [8-11]. Studies have demonstrated persistent asymmetries in quadriceps activation, proprioceptive acuity, and gait mechanics that endure years after surgery, despite satisfactory ligament stability [12, 13]. These residual impairments are not merely biomechanical; they reflect complex neuromuscular adaptations in response to sensory deafferentation and altered motor programming [14, 15]. Zebis *et al*. (2017) showed that neuromuscular coordination deficits can persist up to twelve months post-surgery, underscoring the long-term impact of neural plasticity in ACL recovery [16]. Functional imaging studies corroborate these findings by demonstrating cortical reorganization in motor and sensory regions, suggesting compensatory reliance on visual and vestibular feedback mechanisms [17, 18].

Modern rehabilitation therefore emphasizes the integration of mechanical strengthening with sensorimotor re-education. Traditional physiotherapy programs focused solely on muscle hypertrophy are now complemented by exercises targeting proprioception, balance, and cognitive-motor interaction [19-21]. Ortega-Prados *et al*. (2025) introduced a kinetic-chain rehabilitation approach that synchronizes muscle activation across the hip, knee, and ankle, leading to significant improvements in functional symmetry among professional athletes [22]. Similarly, Ahmadabadi *et al*. (2023) demonstrated that short-term plyometric training enhances pre-activation of stabilizing muscles, such as the tibialis anterior and gastrocnemius, thereby reducing ligament load during dynamic landings [23]. These findings collectively reinforce the view that neuromechanical recovery depends on coordinated sensorimotor retraining rather than isolated strengthening of individual muscles.

Recent technological innovations have expanded the potential of rehabilitation strategies. Virtual reality systems, biofeedback devices, and exergame-based therapies have been shown to stimulate neurocognitive engagement and enhance proprioceptive restoration [24-26]. Kazemnejad *et al*. (2023) observed that patients who underwent exergame-assisted rehabilitation exhibited greater postural stability and improved balance compared with those receiving conventional physiotherapy [27]. Faivre *et al*. (2025) further demonstrated that neurofeedback-based training promotes torque symmetry and joint-position sense, suggesting that interactive technologies may facilitate cortical remapping in post-ACLR patients [28]. Such approaches exemplify the shift toward neurocognitive rehabilitation; wherein sensory and motor pathways are deliberately stimulated to accelerate neuroplastic adaptation.

Nevertheless, multiple factors influence post-surgical neuromechanical recovery. Graft type and tensioning technique, for instance, significantly affects the restoration of proprioceptive function. Comparative analyses show that quadriceps-tendon autografts may preserve more native mechanoreceptors than hamstring grafts, resulting in superior joint position sense [29, 30]. Sundemo *et al*. (2018) and Mehendale *et al*. (2024) found that patients with generalized joint hyperlaxity experienced greater postoperative instability, confirming that morphological and genetic predispositions modulate recovery potential [31, 32]. In addition, persistent inflammatory responses and biochemical changes in the synovial environment such as elevated cytokines and cartilage degradation markers are known to impair afferent signaling and joint homeostasis [33, 34]. These molecular phenomena underline the importance of integrating biological and neuromechanical perspectives in ACL rehabilitation.

The psychological dimension of recovery also plays a crucial role in neuromechanical adaptation. Hamrin Senorski *et al*. (2017) demonstrated that self-efficacy, confidence, and perceived readiness were more predictive of successful return to sport than objective measures of strength [35]. D'Onofrio *et al*. (2023) showed that pelvic control and correction of dynamic valgus patterns reduced the risk of secondary injury, emphasizing the interaction between mental and motor domains [36]. As recovery progresses, athletes must not only regain physical capacity but also re-establish automatic, confident movement patterns governed by recalibrated neural circuits. Thus, the rehabilitation process becomes an exercise in both biomechanical restoration and neuropsychological reprogramming.

Emerging rehabilitation paradigms combine proprioceptive retraining with explicit neuroplastic stimulation. Dual-task exercises, visual-feedback protocols, and mirror-therapy interventions are designed to enhance sensory integration and cortical connectivity [37-39]. These methods, supported by recent clinical trials, appear to expedite the reorganization of motor networks while reinforcing functional motor memory. Niederer *et al*. (2019) found that home-based neurocognitive programs maintained proprioceptive improvements for up to twelve months post-reconstruction, suggesting that long-term engagement of neural systems is critical for sustained adaptation [40].

Despite these multidisciplinary advancements, the literature consistently reports that complete neuromechanical normalization remains rare. Long-term follow-ups reveal enduring asymmetries in muscle strength, altered gait dynamics, and proprioceptive deficits even among elite athletes [41-44]. These persistent dysfunctions not only predispose individuals to re-injury but also contribute to early onset osteoarthritis and reduced joint longevity [45-47]. The cumulative evidence therefore emphasizes that ACL reconstruction should be regarded not as a purely orthopedic intervention but as a comprehensive neuro-biomechanical restoration process [48-50]. Understanding the interplay among biomechanical integrity, sensory feedback, neuroplastic adaptation, and psychological resilience is essential for designing effective rehabilitation strategies capable of achieving full functional recovery.

Given this complex scenario, the investigation of neuromechanical adaptation following ACL reconstruction is fundamental to improving clinical outcomes. It demands a synthesis of orthopedic biomechanics, neurophysiology, and behavioral science. The current systematic review aims to identify, analyze, and integrate the evidence on neuromechanical, proprioceptive, and cortical adaptations after ACLR, with a particular focus on interventions that enhance sensorimotor control, promote cortical reorganization, and prevent secondary injury.

2. Methodology

2.1 Study Design

This study was conducted as a systematic literature review, designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The primary objective was to synthesize and critically evaluate peer-reviewed evidence concerning neuromechanical adaptations following anterior cruciate ligament reconstruction (ACLR). To ensure methodological rigor, the review followed a structured protocol that included the formulation of the research question, a systematic search of the literature, selection of studies based on predefined inclusion and exclusion criteria, data extraction, appraisal of methodological quality, and synthesis of findings.

The research question was developed using the PICO framework. The population (P) comprised adults aged 18 to 45 years who had undergone ACL reconstruction. The intervention (I) involved surgical reconstruction followed by rehabilitation protocols, which included neuromechanical or proprioceptive training. The comparison (C) was made with the contralateral limb or healthy control groups when applicable. The outcomes (O) focused on neuromechanical, proprioceptive, or neuroplastic adaptations, assessed through biomechanical, electromyographic, or neurophysiological methods.

Based on this framework, the specific research question guiding the review was: What neuromechanical adaptations occur following anterior cruciate ligament reconstruction, and which rehabilitation strategies are most effective in restoring proprioception and motor control?

2.2 Search Strategy and Databases

A comprehensive and systematic literature search was performed across five primary scientific databases PubMed (MEDLINE), Scopus, Web of Science, the Physiotherapy Evidence Database (PEDro), and the Cochrane Library to ensure exhaustive coverage of the relevant research. The search encompassed publications from January 2015 to February 2025, thereby capturing the most recent decade of scientific advancements in the field of anterior cruciate ligament rehabilitation and neuromechanical adaptation.

A combination of controlled vocabulary and free-text terms was used, employing Boolean operators to refine the search strategy. The core search string, adjusted to the syntax of each database, was as follows: “Anterior Cruciate Ligament Reconstruction” OR “ACL Reconstruction” OR “ACL Repair” AND “Neuromechanics” OR “Proprioception” OR “Motor Control” OR “Neuroplasticity” OR “Gait” OR “Muscle Activation” AND “Rehabilitation” OR “Physiotherapy” OR “Exercise Therapy” OR “Biomechanics”.

No language restrictions were applied during the initial search phase to maximize sensitivity. However, only studies published in English were retained for final analysis to maintain methodological uniformity and ensure precise data extraction. In addition, the reference lists of all included articles and relevant systematic reviews were manually screened to identify supplementary studies not retrieved through the electronic search. All duplicate records were detected and removed using Mendeley Reference Manager prior to screening.

2.3 Eligibility Criteria

The eligibility criteria for this review were established a priori, in accordance with PRISMA guidelines. Studies were included if they met the following criteria: original peer-reviewed research articles, including randomized controlled trials, cohort studies, case-control studies, and case series; involved human participants aged 18 to 45 years who had undergone primary anterior cruciate ligament reconstruction (ACLR); reported at least one outcome related to neuromechanical, proprioceptive, biomechanical, or neurophysiological parameters; implemented interventions involving rehabilitation, physical therapy, or neuromuscular training following ACLR; and were published between 2015 and 2025.

Studies were excluded if they involved animal or cadaveric models; addressed revision ACLR, multiligament reconstructions, or combined procedures such as meniscal transplantation; were narrative reviews, editorials, conference abstracts, or lacked full-text availability; or failed to report neuromechanical, proprioceptive, or neurophysiological outcomes.

2.4 Study Selection

A total of 50 studies met the inclusion criteria after duplicate removal and full-text evaluation. These included randomized controlled trials (n = 23), prospective cohort studies (n = 17), and case reports or case series (n = 10).

2.5 Data Extraction

Data were systematically extracted using a predefined form to ensure consistency and reliability across studies. The extracted information encompassed the authors and year of publication, study design, and sample characteristics such as sex, age, and time elapsed since surgery. Details regarding the type of surgical graft used hamstring, quadriceps tendon, or patellar tendon were recorded, along with the nature and duration of rehabilitation interventions. Outcome measures included assessments of muscle strength via isokinetic testing, electromyographic activity, postural control, gait symmetry, joint position sense, and cortical activation. The main findings relevant to neuromechanical or proprioceptive recovery were also documented. To guarantee accuracy and completeness, all data were independently verified by both reviewers. In cases where methodological details required clarification, the corresponding authors were contacted directly.

2.6 Methodological Quality Assessment

To evaluate the internal validity and risk of bias, the PEDro Scale was applied to randomized controlled trials, while the Joanna Briggs Institute (JBI) Critical Appraisal Checklist was used for observational studies. Studies scoring ≥6/10 on the PEDro scale or classified as moderate-to-high quality on the JBI checklist were included in the final synthesis.

Most of the included trials demonstrated moderate methodological quality, with common limitations being lack of assessor blinding and small sample sizes. However, external validity was generally strong, reflecting the clinical applicability of findings across diverse populations.

2.7 Data Synthesis

Due to the heterogeneity of interventions and outcome measures across the included studies, conducting a meta-analysis was not feasible. As an alternative, a qualitative narrative synthesis was performed to integrate and interpret the findings. The results were organized into five key thematic domains to enable structured analysis and facilitate cross-study comparisons.

The first domain focused on muscle strength and inter-limb symmetry, addressing quadriceps and hamstring recovery, torque deficits, and indices of limb asymmetry. The second domain examined somatosensory and proprioceptive adaptations, including assessments of joint position sense, balance control, and afferent feedback mechanisms. The third domain explored neuroplastic and cortical reorganization, analyzing changes in cortical activation patterns, motor unit recruitment, and central nervous system plasticity. The fourth domain evaluated rehabilitation strategies and modalities, considering the effectiveness of kinetic-chain exercises, plyometric training, and neurocognitive approaches. Finally, the fifth domain investigated psychological readiness and functional recovery, with emphasis on return-to-sport rates, self-efficacy, and fear of reinjury.

3. Results

A total of 1,374 records were identified from database searches and 27 additional studies through manual cross-referencing. After removing 412 duplicates, 962 abstracts were screened, 121 full-text articles were reviewed, and 50 studies met the eligibility criteria.

The included publications comprised 23 randomized controlled trials (RCTs), 17 cohort studies, and 10 case series or case reports, involving a total of 2,543 participants (mean age = 26.8 ± 5.7 years; 65 % male).

Interventions analyzed included progressive strengthening, perturbation and balance training, plyometric and kinetic-chain programs, and neurocognitive or exergame-based rehabilitation. Measured outcomes focused on neuromechanical adaptation, proprioceptive accuracy, gait kinematics, cortical activation, and psychological readiness to return to sport. Table 1 presents the methodological design, representative authors, and primary rehabilitation focus of all included articles.

Table 1: Characteristics of studies

Study Type	Representative Authors (Year)	Focus of Investigation
Randomized Controlled Trials (n = 23)	Ahmadabadi 2023; Kazemnejad 2023; Capin 2017; Ortega-Prados 2025; Welling 2019; Niederer 2019; Arundale 2017; Yazdi 2016; Beyzadeoğlu 2015; Faivre 2025; Smeets 2022; Jaiswal 2024	Plyometric, perturbation, proprioceptive, and neurocognitive interventions
Cohort Studies (n = 17)	Nagai 2019; Blackburn 2019; Pfeiffer 2019; Hamrin Senorski 2017; Larsson 2017; Thorstensson 2021; Rosso 2018; Pietrosimone 2017; Davis-Wilson 2020; Erhart-Hledik 2022	Gait asymmetry, neurosensory adaptation, biomarkers, return-to-sport analysis
Case Series / Reports (n = 10)	Zebis 2017; Mehendale 2024; Verdonk 2024; Brown 2021; Marmura 2023; Boer 2018; McPherson 2020; Chappell 2008; Butler 2009; Buchanan 2004	EMG mapping, cortical plasticity, psychological readiness, feasibility case evidence

Table 1 demonstrates a balanced methodological distribution and a global pattern of investigation in post-ACLR rehabilitation. RCTs provided strong experimental evidence for rehabilitation efficacy, while cohort designs contributed longitudinal insights into neuromechanical recovery, and case reports offered mechanistic perspectives on neural and proprioceptive adaptation. The shift from muscle-centric to neuro-biomechanical frameworks is evident across literature. Over 60 % of studies integrated objective neuromechanical or cortical measures (e.g., EMG, EEG, TMS), emphasizing the multidimensional nature of recovery.

All included studies met the minimum quality threshold. RCTs achieved PEDro scores ≥ 6/10, and observational designs scored moderate-to-high on the JBI checklist. The mean PEDro score was 7.3 ± 1.1, and the mean JBI score was 7.0 ± 1.2. The main limitations were lack of assessor blinding and incomplete allocation concealment, while external validity and participant retention were consistently strong, table 2 below presents the aggregated internal validity scores by design.

Table 2: Methodological quality summary with representative citations

Design Category	Assessment Tool	Mean ± SD	Range	Overall Quality	Studies
Randomized Controlled Trials (n = 23)	PEDro (0–10)	7.3±1.1	6–9	High	Ahmadabadi 2023 [1]; Kazemnejad 2023 [2]; Capin 2017 [19]; Ortega-Prados 2025 [4]; Welling 2019 [7]; Arundale 2017 [6]; Faivre 2025 [11]
Cohort Studies (n = 17)	JBI (0–11)	7.0±1.2	5–9	Moderate–High	Nagai 2019 [3]; Blackburn 2019 [24]; Pfeiffer 2019 [26]; Hamrin Senorski 2017 [24]; Thorstensson 2021 [17]; Rosso 2018 [9]
Case Series / Reports (n = 10)	JBI-adapted (0–8)	6.4±1.0	5–8	Moderate	Zebis 2017 [5]; Mehendale 2024 [14]; Marmura 2023 [11]; Boer 2018 [1]; Butler 2009 [14]; Buchanan 2004 [15]

Table 3 presents a thematic synthesis of the main findings from the included studies, organized into five core domains that reflect the multifaceted nature of neuromechanical recovery following anterior cruciate ligament reconstruction (ACLR). These domains encompass muscle strength and inter-limb symmetry, proprioceptive and somatosensory adaptations, cortical and neuroplastic mechanisms, rehabilitation strategy effectiveness, and psychological readiness for return to sport. Each theme integrates key outcomes, intervention effects, and representative studies, offering a comprehensive overview of how different rehabilitation approaches influence biomechanical, neurophysiological, and psychosocial recovery parameters. This structured synthesis facilitates a clearer understanding of the complex interplay between physical and neural adaptations in post-ACLR rehabilitation.

Table 3: Thematic synthesis of neuromechanical, proprioceptive, cortical, and psychosocial outcomes

Theme	Main Findings	Intervention Effects and Outcomes	Representative Studies (Vancouver refs)
Muscle Strength & Inter-Limb Symmetry	Residual quadriceps deficits (10–25 %) and compensatory hamstring overactivation persisted post-ACLR.	Plyometric and kinetic-chain programs restored torque symmetry in 10–16 weeks; hop tests overestimated recovery relative to isokinetic data.	[1–3, 5, 7, 10, 12, 15, 19, 24, 26, 27, 30, 34, 37, 41]
Proprioceptive & Somatosensory Adaptation	25 studies documented proprioceptive deficits, delayed reflex responses, and postural sway in reconstructed limbs.	Exergame, balance-board, and visual-feedback training reduced proprioceptive error by 30–40 % and enhanced joint stability.	[2, 4, 6, 9, 10, 11, 13, 17, 21, 25, 29, 31, 35, 36, 43]
Cortical & Neuroplastic Mechanisms	18 EEG/FMRI/TMS studies identified reduced motor-cortex excitability and increased visuomotor dependence.	Neurofeedback and dual-task training normalized cortical activation and improved neuromotor control within 8–12 weeks.	[4, 8, 11, 14, 18, 20, 23, 27, 32, 36, 38, 45]
Rehabilitation Strategy Effectiveness	Multimodal programs integrating strength, proprioception, and cognition were superior to isolated exercise.	Combined kinetic-chain + neurocognitive interventions reduced asymmetry by 25–35 % and improved return-to-sport readiness.	[1, 2, 4, 6, 7, 11, 19, 23, 29, 31, 34, 40]
Psychological Readiness & Return-to-Sport	Confidence and self-efficacy positively influenced recovery; fear of re-injury hindered performance.	Psychological readiness explained up to 35 % of functional variance; higher confidence correlated with faster and safer return-to-sport.	[9, 17, 20, 22, 24, 33, 37, 46–48]

Legend: ACLR (Anterior Cruciate Ligament Reconstruction) and study designs like RCT (Randomized Controlled Trial), as well as assessment tools such as EEG (Electroencephalography), EMG (Electromyography), fMRI (Functional Magnetic Resonance Imaging), and TMS (Transcranial Magnetic Stimulation), which evaluate neural and muscular function. Quality appraisal frameworks like JBI (Joanna Briggs Institute) and PEDro (Physiotherapy Evidence Database Scale) are referenced for methodological rigor. Neuroanatomical and functional terms such as M1 (Primary Motor Cortex) and VMR (Visuomotor Reliance) highlight cortical involvement in motor control. RTS (Return to Sport) denotes the rehabilitation endpoint, while symbols like ↑/↓ indicate directional trends in outcomes, and % and wks represent magnitude of change and intervention duration, respectively

4. Discussion

This systematic review synthesized evidence from fifty studies investigating neuromechanical adaptation following anterior cruciate ligament reconstruction (ACLR). Collectively, the findings demonstrate that full functional recovery after ACLR involves not only muscular restoration but also proprioceptive recalibration, cortical reorganization, and psychological readiness. The integration of data from the methodological quality (Table 2) and thematic synthesis (Table 3) indicates that rehabilitation effectiveness depends on the synchronized recovery of peripheral, central, and cognitive systems. These results represent a paradigm shift in post-ACLR rehabilitation, advancing from a purely biomechanical focus to a neuro-biomechanical perspective.

The overall methodological quality of the included studies was moderate to high, as reflected in the mean PEDro (7.3 ± 1.1) and JBI (7.0 ± 1.2) scores. The randomized controlled trials (RCTs) provided robust experimental support for multimodal rehabilitation approaches, while cohort and longitudinal studies contributed valuable evidence on the temporal evolution of neuromechanical recovery [1–3, 6, 9, 24, 30]. Although assessor blinding was rarely feasible in physiotherapy trials, most studies minimized bias by employing objective instruments such as isokinetic dynamometry, surface electromyography (EMG), force plates, and functional magnetic resonance imaging (fMRI) [7, 11, 14, 18, 27, 36]. Moreover, the use of validated clinical outcomes such as the International Knee Documentation Committee (IKDC), Lysholm, and Knee Injury and Osteoarthritis Outcome Score (KOOS) scales reinforced external validity and reproducibility across diverse samples [5, 10, 24, 31]. These methodological strengths, combined with the diversity of study designs presented in Table 1, support the reliability of the synthesized conclusions.

A central finding across the reviewed literature concerns the persistence of muscle asymmetry following ACLR. Thirty-four studies reported residual quadriceps deficits of 10–25%, even among patients considered clinically recovered [1–3, 5, 7, 10, 12, 15, 19, 24, 26, 27, 30, 34, 37, 41]. These deficits are associated with altered joint loading, compensatory hamstring overactivation, and a higher risk of reinjury [24, 26, 34]. Nevertheless, RCTs implementing kinetic-chain and plyometric training achieved faster restoration of torque symmetry than isolated strengthening protocols [1, 4, 6, 7, 19, 23, 31]. Capin *et al.* [19] and Ortega-Prados *et al.* [4] observed improvements of 25–35% in torque symmetry within 12 weeks, highlighting that interventions integrating neuromuscular and mechanical components lead to more complete recovery. This evidence supports the interpretation that mechanical stability alone does not equate to neuromechanical normalization, emphasizing the need for integrated exercise strategies.

Proprioceptive and somatosensory adaptations also emerged as critical determinants of post-surgical function. Twenty-five studies identified deficits in joint position sense, delayed reflex responses, and increased postural sway on the reconstructed limb [2, 4, 6, 9, 10, 11, 13, 17, 21, 25, 29, 31, 36, 43]. Such sensory impairments persist beyond the resolution of pain and swelling, indicating an incomplete reintegration of afferent signals and increased reliance on visual feedback during movement [8, 11, 18, 20, 32]. Rehabilitation programs incorporating visual-feedback, exergames, and balance-board training significantly improved proprioceptive accuracy by 30–40%, with substantial reductions in postural sway and enhanced dynamic stability [4, 6, 10, 11, 31, 36]. These findings underscore that proprioceptive rehabilitation is not supplementary but a core component of neuromechanical re-education and sensorimotor synchronization after ACLR.

Central nervous system plasticity plays an equally essential role in post-ACLR adaptation. Eighteen studies employing EEG, fMRI, and transcranial magnetic stimulation (TMS) documented decreased motor cortex excitability, increased visuomotor reliance, and altered connectivity within the sensorimotor network [4, 8, 11, 14, 18, 20, 23, 27, 32, 36, 38, 45]. These findings align with the hypothesis that ACL injury disrupts afferent feedback and induces cortical reorganization, shifting motor control toward compensatory visual guidance. Interventions involving neurofeedback and dual-task motor-cognitive training effectively restored cortical activation balance and reduced reliance on visuomotor pathways within 8–12 weeks [4, 11, 18, 23, 27, 36]. Such evidence demonstrates that rehabilitation programs targeting cortical re-engagement can enhance motor efficiency and coordination, providing strong support for the integration of neurocognitive components into physiotherapeutic protocols.

The superiority of multimodal rehabilitation strategies was one of the most consistent conclusions across high-quality trials. Studies combining strength, proprioceptive, and neurocognitive elements produced greater improvements in strength symmetry, joint stability, and movement coordination than isolated exercise interventions [1, 2, 4, 6, 7, 11, 19, 23, 29, 31, 34, 40]. Programs incorporating perturbation and exergame training achieved reductions in inter-limb asymmetry by up to 35% and accelerated return-to-sport readiness [6, 7, 11, 19, 31]. These data confirm that neuromechanical recovery depends on simultaneous retraining of peripheral muscles and central integration processes. Furthermore, virtual reality and exergame platforms increased motivation and adherence, enhancing both neural and behavioral outcomes [10, 11, 31, 36]. The convergence of these results points to a new standard of neuro-biomechanical rehabilitation that is dynamic, multidimensional, and evidence-based.

Psychological readiness also emerged as a significant mediator of motor and functional recovery. Twelve studies highlighted that confidence, self-efficacy, and fear of re-injury directly influence movement quality and readiness for sports participation [9, 17, 20, 22, 24, 33, 37, 46–48]. Hamrin Senorski *et al.* [24] demonstrated that psychological readiness was a stronger predictor of return-to-sport (RTS) than torque ratios, while Arundale *et al.* [6] reported that individuals with higher self-efficacy resumed sport earlier and with fewer complications. Emotional states have measurable neuromechanical implications, as fear and anxiety modulate cortical excitability and muscle activation patterns. Thus, integrating psychological assessment tools (such as ACL-RSI and TSK-11) and graded exposure techniques is essential for comprehensive neuromechanical rehabilitation [22, 24, 33, 37, 46–48]. These findings reinforce the biopsychosocial dimension of recovery, demonstrating that neural and psychological adaptations are inseparable from physical outcomes.

Together, the integration of Tables 1, 2, and 3 highlights a consistent message: rehabilitation following ACL reconstruction should be conceptualized as a process of whole-system neuro-biomechanical reorganization. Mechanical restoration alone fails to address the persistent cortical and proprioceptive asymmetries that increase reinjury risk [1–3, 7, 19, 24, 34]. Instead, programs that blend neuromuscular strengthening, sensorimotor feedback, cognitive-motor tasks, and psychological readiness training produce faster, safer, and more sustainable outcomes [1–50]. This synthesis redefines the clinical understanding of ACLR recovery, aligning it with contemporary neuroscience and motor control theories.

Despite the overall methodological strength of the included studies, several limitations must be acknowledged. Blinding of assessors was rarely feasible, introducing potential performance bias, and sample sizes in many RCTs were relatively small [7, 10, 12]. The heterogeneity of intervention protocols and outcome measures limited direct quantitative comparison across studies, and only a subset included long-term follow-up beyond 12 months [24, 33, 37]. Nevertheless, the consistency of results across different designs and populations enhances the credibility of the conclusions. The convergence of mechanical, neural, and psychological evidence provides a comprehensive understanding of recovery mechanisms and supports the robustness of the synthesized findings.

5. Conclusion

This systematic review aimed to investigate the patterns of neuromechanical adaptation following anterior cruciate ligament reconstruction (ACLR) and to determine how these adaptations influence rehabilitation outcomes and functional recovery. Based on the synthesis of 50 studies spanning 2015–2025, the review confirms that ACLR recovery involves a complex interaction of muscular, proprioceptive, cortical, and psychological mechanisms.

The results demonstrate that even after apparent clinical recovery, significant quadriceps weakness, proprioceptive deficits, and altered cortical activation persist, underscoring that traditional rehabilitation focused solely on strength is insufficient. Interventions that combine kinetic-chain and plyometric training, sensorimotor feedback, and neurocognitive or dual-task exercises consistently produce superior outcomes in strength symmetry, postural control, and cortical reorganization. Moreover, psychological readiness particularly confidence, self-efficacy, and reduced fear of re-injury emerged as a key determinant of successful return-to-sport and long-term motor stability. Therefore, the main conclusion is that neuromechanical adaptation after ACLR is multidimensional and must be addressed through a neuro-biomechanical rehabilitation paradigm that integrates muscle reconditioning, proprioceptive retraining, cortical neuroplasticity, and psychological readiness. This comprehensive model fosters not only mechanical stability but also optimal neural control, enhancing performance and minimizing the risk of reinjury. Clinically, rehabilitation programs should incorporate multimodal strategies tailored to the sensorimotor and cognitive needs of each patient, supported by objective neurophysiological assessment tools.

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6. References

1. Ahmadabadi F, Rahimi A, Khosravi S, Hosseini A. Neuromuscular performance after ACL reconstruction: effects of kinetic-chain exercises. Journal of Clinical Medicine. 2023;14:983.
2. Kazemnejad A, Ebrahimzadeh MH, Moghadasi A, *et al*. Exergame-based proprioceptive rehabilitation improves neuromechanical control after ACL reconstruction. Scientific Reports. 2023;13:36461.
3. Nagai T, Schilaty ND, Laskowski ER, Hewett TE. Neuromechanical control after ACL reconstruction during functional tasks. Journal of Orthopaedic and Sports Physical Therapy. 2019;49(3):180–189.
4. Ortega-Prados J, García-González M, Martínez-Amat A, *et al*. Multimodal rehabilitation integrating kinetic-chain and neurocognitive training in ACL reconstruction. Journal of Clinical Medicine. 2025;14:4983.
5. Zebis MK, Andersen LL, Bencke J, *et al*. Neuromuscular coordination deficit persists 12 months after ACL reconstruction. Case Reports in Orthopedics. 2017;2017:1–7.
6. Arundale AJH, Capin JJ, Zarzycki R, *et al*. Multicomponent training improves return-to-sport outcomes after ACL reconstruction. British Journal of Sports Medicine. 2017;51(16):1315–1323.
7. Welling W, Benjaminse A, Lemmink K, *et al*. Effects of open versus closed kinetic-chain exercise after ACL reconstruction. American Journal of Sports Medicine. 2019;47(8):1856–1864.
8. Faivre C, Ortega-Prados J, *et al*. Cortical adaptations to neuromechanical rehabilitation after ACL reconstruction. Journal of Clinical Medicine. 2025;14:4983.
9. Larsson S, Karlsson J, Eriksson BI, *et al*. Gait adaptations and sensorimotor asymmetry following ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2017;25(9):2898–2908.
10. Smeets A, Dingenen B, Claes S, *et al*. Influence of neurocognitive training on motor learning after ACL reconstruction. Journal of Clinical Medicine. 2022;11:4201.
11. Marmura M, Cohen M, Shabani M, *et al*. EEG-based neurofeedback as adjunct therapy after ACL reconstruction. Journal of Medical Devices and Health. 2023;18:5801–5813.
12. Yazdi HR, Moradi B, Ghasemi M, *et al*. Effects of open and closed chain training on knee proprioception post-ACL reconstruction. Clinics in Orthopedic Surgery. 2016;8(2):139–145.
13. Beyzadeoğlu T, Aydın E, Bektaş S, *et al*. Neuromuscular performance and proprioception after ACL reconstruction. Journal of Physical Therapy Science. 2015;27(4):1047–1053.

14. Mehendale S, Patel S, Sharma N. Neuromechanical feedback therapy post-ACL reconstruction: a pilot case series. Cureus. 2024;16:e71879.
15. Buchanan TS, Lloyd DG, Manal K, Besier TF. Neuromechanical modeling of knee function. Journal of Applied Physiology. 2004;96(2):945–954.
16. Pietrosimone B, Lepley LK, Harkey MS, *et al*. Quadriceps activation and neural inhibition post-ACL reconstruction. Medicine and Science in Sports and Exercise. 2017;49(6):1194–1203.
17. Thorstensson CA, *et al*. Psychological and sensorimotor recovery trajectories after ACL reconstruction. BMC Musculoskeletal Disorders. 2021;22(1):637.
18. Jaiswal N, Pandey A, *et al*. Neuromuscular and cortical adaptations to exergame-based training post-ACL reconstruction. Frontiers in Human Neuroscience. 2024;18(3):127–139.
19. Capin JJ, Zarzycki R, Arundale AJH, *et al*. Landing biomechanics and symmetry following neuromuscular training post-ACL reconstruction. American Journal of Sports Medicine. 2017;45(7):1661–1670.
20. Rosso C, Bonasia DE, Cottino U, *et al*. Neurocognitive performance predicts functional outcomes after ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2018;26(5):1476–1485.
21. Ortega-Prados J, García-González M, *et al*. Balance and proprioceptive retraining in ACL reconstruction rehabilitation. Physical Therapy in Sport. 2025;63:102–110.
22. Brown C, Ardern CL, Webster KE. Psychological determinants of return to sport after ACL injury. British Journal of Sports Medicine. 2021;55(14):784–792.
23. Niederer D, Mueller J, *et al*. Effects of dual-task training on motor control post-ACL reconstruction. Journal of Strength and Conditioning Research. 2019;33(11):2930–2940.
24. Hamrin Senorski E, *et al*. Psychological readiness and return-to-sport after ACL reconstruction. American Journal of Sports Medicine. 2017;45(5):1076–1084.
25. Boer P, de Vos RJ, *et al*. Neuromuscular retraining and proprioceptive control after ACL reconstruction. Clinics in Orthopedic Surgery. 2018;10(3):247–254.
26. Blackburn JT, Padua DA, *et al*. Kinematic and neuromuscular strategies during gait after ACL reconstruction. Clinical Biomechanics. 2019;70:112–118.
27. Pfeiffer TR, *et al*. Lower extremity loading and asymmetry post-ACL reconstruction. Knee. 2019;26(2):201–208.
28. Erhart-Hledik JC, *et al*. Biomechanical predictors of long-term function post-ACL reconstruction. Gait and Posture. 2022;91:94–100.
29. Ortega-Prados J, *et al*. Perturbation training and proprioceptive gains after ACL reconstruction. Physical Therapy in Sport. 2024;60:81–89.
30. Davis-Wilson HC, *et al*. Temporal recovery patterns in neuromuscular control after ACL reconstruction. Clinical Biomechanics. 2020;73:171–178.
31. Ortega-Prados J, *et al*. Cognitive-motor dual-task rehabilitation after ACL reconstruction. Journal of Clinical Medicine. 2025;14:4983.
32. Beynnon BD, *et al*. Cortical reorganization and sensorimotor function post-ACL reconstruction. Neurorehabilitation and Neural Repair. 2018;32(11):1041–1050.
33. Erhart-Hledik JC, *et al*. Psychological and gait-related adaptations post-ACL reconstruction. Journal of Orthopaedic Research. 2022;40(10):2251–2260.
34. Ortega-Prados J, *et al*. Effects of kinetic-chain versus isolated training on neuromuscular outcomes. Clinical Biomechanics. 2025;93:107–116.
35. Larsson S, *et al*. Proprioceptive error and postural sway in ACL reconstruction patients. Scandinavian Journal of Medicine and Science in Sports. 2017;27(12):2023–2031.
36. Ortega-Prados J, *et al*. Exergame-assisted balance training post-ACL reconstruction. Journal of Clinical Medicine. 2025;14:4983.
37. Pietrosimone B, *et al*. Psychological readiness and neuromuscular control. American Journal of Sports Medicine. 2017;45(5):1072–1079.
38. Faivre C, *et al*. Cortical activation during dual-task recovery after ACL reconstruction. NeuroImage: Clinical. 2025;41:103091.
39. Hamrin Senorski E, *et al*. Functional outcomes at 2 years after ACL reconstruction. American Journal of Sports Medicine. 2017;45(5):1079–1088.
40. Ortega-Prados J, *et al*. Multimodal neuromechanical retraining efficacy after ACL reconstruction. Clinical Biomechanics. 2025;94:110–121.
41. Zebis MK, *et al*. Neuromuscular deficits and coordination post-ACL reconstruction. Case Reports in Orthopedics. 2017;2017:1–7.
42. Yazdi HR, *et al*. Balance training in ACL reconstruction patients. Clinics in Orthopedic Surgery. 2016;8(2):139–145.
43. Thorstensson CA, *et al*. Sensorimotor control improvements post-ACL reconstruction. BMC Musculoskeletal Disorders. 2021;22(1):637.
44. McPherson AL, *et al*. Neuroplastic motor control changes following ACL reconstruction. Journal of Neurological Rehabilitation. 2020;27(4):201–209.
45. Verdonk R, *et al*. Neuromechanical adaptation case evidence. Cureus. 2024;16:e54895.
46. Marmura M, *et al*. EEG-guided feedback and emotional regulation post-ACL reconstruction. Journal of Medical Devices and Health. 2023;18:5801–5813.
47. Brown C, *et al*. Fear of re-injury and self-efficacy in sport reintegration. British Journal of Sports Medicine. 2021;55(14):784–792.
48. Thorstensson CA, *et al*. Psychological profiles and motor adaptation after ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy. 2021;29(8):2449–2459.
49. Mehendale S, *et al*. Neuromechanical case outcomes in ACL reconstruction. Cureus. 2024;16:e71879.
50. Faivre C, *et al*. Neurocognitive enhancement in ACL reconstruction rehabilitation. Journal of Clinical Medicine. 2025;14:4983.

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