Rehabilitation After ACL Injury: Advancements in Motor Control and Sensorimotor Training for Optimizing Musculoskeletal Function

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Abstract*—B: Anterior cruciate ligament (ACL) injuries compromise knee stability and proprioceptive feedback due to disruption of ligamentous mechanoreceptors. Despite surgical reconstruction and conventional rehabilitation, many patients exhibit persistent deficits in neuromuscular control and joint proprioception, increasing the risk of reinjury. O: To explore and summarize emerging motor control and sensorimotor training interventions and their clinical relevance in post-ACL injuries rehabilitation. M: A narrative review of literature from databases including PubMed, Google Scholar, and Frontiers was conducted. Included sources encompassed experimental studies, clinical trials, pilot studies, systematic reviews, and meta-analyses. Emphasis was placed on motor control–based strategies targeting sensory and motor restoration post-reconstruction. R: Findings indicate that innovative approaches-such as perturbation training, external focus strategies, visual-motor feedback, task-specific exercises, and dual-task cognitive-motor training-significantly enhance proprioception, dynamic stability, and functional movement control. These interventions show promise in minimizing reinjury risk and facilitating return to sport by targeting residual neuromuscular deficits. C: Motor control and sensorimotor training represent essential evidence-supported strategies in ACL rehabilitation. Their integration into post-operative protocols may enhance recovery outcomes, reduce reinjury rates, and support safer return to high-level functional activities. K:ACL Injuries, motor control training, sensorimotor training, proprioception, neuromuscular control, rehabilitation.

***Index Terms*—ACL Injuries, motor control training, neuromuscular control, proprioception, rehabilitation, sensorimotor training.**

I. INTRODUCTION

Approximately 37% of individuals undergoing anterior cruciate ligament reconstruction fail to return to their preinjury activity levels. The risk of repetitive injury post ACL Injuries exceeds 30%, with the incidence of secondary injury estimated at 1 in 4 athletes returning to sport. Persistent alterations in neuromuscular control, lasting up to two years post-surgery, are identified as key contributors to this high reinjury rate. This emphasizes the need for effective tertiary prevention strategies during the return to sport phase to mitigate reinjury risk and optimize functional recovery.

Anterior Cruciate Ligament (ACL) injuries are among the most prevalent and challenging musculoskeletal conditions, often requiring surgical reconstruction followed by a structured rehabilitation process (Dhillon et al., 2011). Conventional rehabilitation protocols have primarily focused on restoring joint stability, muscle strength, and range of motion. However, despite achieving these biomechanical goals, many individuals continue to experience persistent impairments in proprioception, motor control, and neuromechanical efficiency, which significantly contribute to suboptimal functional outcomes and a heightened risk of re injury (Kaya et al., 2019; Gholami et al., 2023).

Anterior cruciate ligament (ACL) injuries are a significant concern in both athletic and general populations, leading to compromised knee stability, proprioception, and functional performance. Rehabilitation approaches focus not only on restoring physical strength but also on enhancing neuromuscular control to prevent re injury. Recent

literature emphasizes that neuromuscular training plays a crucial role in improving sensorimotor control and optimizing movement patterns, thereby contributing to ACL injury prevention (Pangestuputra & Changestu, 2024).

Additionally, growing evidence suggests that incorporating cognitive demands, such as dual task balance exercises, can further enhance postural stability compared to single task training in individuals following ACL Injuries (Eslami et al., 2024).

Emerging research indicates that ACL injuries extend beyond localized mechanical disruptions and result in broader dysfunctions in the human movement system, including impairments in sensorimotor integration, cortical reorganization, and cognitive motor processing (Chaput et al., 2024; Wilk et al., 2024).

This evolving understanding has shifted rehabilitation paradigms from traditional strength dominated approaches towards interventions that holistically target motor control, sensorimotor retraining, and neurocognitive function. Progressive techniques such as visuomotor training (Gholami et al., 2023), differential learning (Gholami et al., 2023), suspension-based exercises (Huang et al., 2021), eccentric plyometric interventions (Kasmi et al., 2021), and core stabilization strategies (Saki et al., 2023) have demonstrated promising outcomes in enhancing functional recovery, neuromechanical coordination, and long-term joint stability.

Furthermore, evidence emphasizes that neglecting motor control and sensorimotor pathways during rehabilitation may compromise the restoration of dynamic joint stability, movement quality, and functional performance (Fukuda et al., 2013; Kaya et al., 2019). Rehabilitation models that integrate physical, sensorimotor, and neurocognitive components show better outcomes in reducing neuromuscular deficits and mitigating the risk of future injuries (Chaput et al., 2024; Wilk et al., 2024).

The importance of motor control exercises lies in their ability to bridge the gap between mechanical recovery and functional movement efficiency. Following ACL Injuries, the disruption in afferent input from the injured ligament affects not only local joint stability but also alters the central nervous system's control over movement patterns (Chaput et al., 2024). Motor control-based interventions facilitate the reestablishment of efficient neuromuscular patterns, improve sensorimotor integration, and enhance feedback mechanisms essential for dynamic joint stability (Fukuda et al., 2013).

Moreover, incorporating neurocognitive challenges, perturbation-based tasks, and visuomotor demands into rehabilitation fosters adaptability, resilience, and prepares the athlete or patient for real world, unpredictable functional demands.

This makes motor control training an indispensable component for optimizing rehabilitation outcomes and long-term injury prevention (Gholami et al., 2023).

This narrative review combines the studies on neuromuscular motor control and sensorimotor training approaches following ACL Injuries. The primary aim is to explore the clinical relevance of these interventions and how they influence functional recovery, improve motor control, and contribute to injury prevention in post ACL Injuries rehabilitation.

II. METHODOLOGY

This narrative review was conducted with the objective of synthesizing and evaluating current evidence on innovative motor control and sensorimotor training strategies in post anterior cruciate ligament (ACL) reconstruction rehabilitation. A comprehensive literature search was performed across electronic databases, including PubMed, Scopus, Web of Science, Google Scholar, and Pedro, targeting peer reviewed articles published between 2010 and 2024. The search strategy utilized a combination of relevant keywords such as “ACL Injuries,” “anterior cruciate ligament rehabilitation,” “motor control,” “sensorimotor training,” “neurocognitive rehabilitation,” and “neuromuscular control,” with filters applied to include only studies published in English involving human participants.

Articles were included if they focused on rehabilitation following ACL Injuries incorporating motor control, neurocognitive, or sensorimotor training interventions, and if they were randomized controlled trials, quasi experimental studies, systematic reviews, meta-analyses, or high quality narrative reviews evaluating outcomes related to functional recovery, proprioception, neuromechanical efficiency, motor control, and injury prevention. Studies were excluded if they solely addressed surgical techniques without rehabilitation components, were case reports, opinion pieces, non-peer reviewed literature, or if they focused on

musculoskeletal injuries unrelated to ACL. These selected studies provided the fundamental evidence for this review, offering necessary knowledge into the emerging rehabilitation protocols that emphasize the combination of neuromuscular, cognitive, and sensorimotor components in improving post ACL Injuries outcomes.

Study Inclusion Criteria- The studies included in this review primarily focused on individuals who had undergone anterior cruciate ligament (ACL) reconstruction, with participants mostly ranging from young adults to middle aged individuals actively engaged in sports or physically demanding activities. The selected studies commonly involved participants in the post-surgical rehabilitation phase, typically between 18 and 45 years of age, who were undergoing structured physiotherapy aimed at restoring functional capacity and preventing re injury. The sample sizes varied across studies, ranging from smaller randomized controlled trials with around 30 to 60 participants to larger systematic reviews and meta-analyses that analyzed data from several hundred individuals. All included studies specifically examined rehabilitation protocols that incorporated motor control strategies, sensorimotor training, or neurocognitive components as part of post ACL Injuries recovery.

Intervention Modalities- The interventions covered in this review included a combination of motor control exercises, sensorimotor training, and neurocognitive rehabilitation, all implemented alongside traditional physiotherapy following anterior cruciate ligament (ACL) reconstruction. These approaches aimed to address not only strength and joint stability but also improve neuromuscular control, proprioception, and cognitive motor integration. Techniques such as visuomotor training, which involved tasks requiring visual tracking and coordinated limb movement, were commonly used to enhance sensorimotor processing. Differential learning strategies introduced varied, unpredictable movements to challenge the motor system and improve adaptability. Suspension based exercises and core stabilization tasks were included to improve postural control, dynamic stability, and kinetic chain efficiency. Additionally, eccentric plyometric training was employed to improve neuromuscular power, movement quality, and reactive strength. Some studies also incorporated neurocognitive tasks like reaction time drills and decision-making challenges to further enhance motor learning and injury resilience. These comprehensive intervention modalities contributed to improved functional outcomes, better movement efficiency, and reduced risk of re injury.

Duration & Frequency of Intervention- The intervention programs reviewed generally lasted between four to twelve weeks. Most of them involved around three to four sessions per week, with each session typically lasting between 45 to 75 minutes. In total, participants completed anywhere from 16 to 36 sessions throughout the program. This frequency and duration were structured to effectively support improvements in motor control, sensorimotor function, and overall functional recovery, complementing the standard rehabilitation protocols commonly used after ACL Injuries.

Outcome Assessment- Across the reviewed studies, participants recovering from ACL Injuries showed consistent improvements in proprioception, balance, pain levels, and functional strength. Proprioception, assessed through joint position sense tests, improved significantly with targeted neuromuscular training (Busch et al., 2024). Balance enhancements were observed using tools like the Star Excursion Balance Test, particularly following dual task balance exercises (Chaput et al., 2024). Pain reduction, often measured using the Visual Analog Scale (VAS), was a key outcome in interventions focusing on neuromuscular strengthening (Fukuda et al., 2013). Functional outcomes, such as quadriceps strength and hop performance, also improved notably with visuo motor and differential learning approaches (Eslami et al., 2024). Additionally, mobility measures, including Timed Up and Go (TUG) and gait parameters (temporal & spatial gait components), reflected significant progress with suspension based neuromuscular exercises (Gholami et al., 2023). These improvements were further supported by MRI findings, which showed favorable changes in thigh muscle composition following structured exercise programs (Fukuda et al., 2013). Overall, the evidence highlights that incorporating proprioceptive, cognitive, and neuromuscular training strategies is highly effective in restoring joint function, reducing pain, and enhancing overall rehabilitation outcomes after ACL Injuries (Arhos et al., 2025).

III. RESULT

The studies reviewed highlight a shift in post-ACL Injuries rehab toward integrating motor learning, neuromuscular training, and cognitive-motor strategies. Interventions like differential learning, visuomotor training, suspension exercises, and core stabilization were shown to improve neuromuscular control, proprioception, functional performance, and psychological readiness. Many studies reported significant improvements ($p < 0.05$) in outcomes such as strength, balance, and return to sport, using reliable and validated measures. While traditional rehab remains important, emerging approaches, especially those using dual-task and sensorimotor elements appear equally or more effective.

Table 1

S. NO	Author (Year)	Study Design	Study Group & Intervention	Outcome Measures	Significance (Results)
1	Chaput et al. (2024)	Narrative Review	ACL reconstructed individuals; cognitive-motor progression integrating visual and decision-making tasks.	Cognitive dual-task tests: ICC ≥ 0.75; neuromuscular assessments well-established.	Cognitive dual-task tests showed good reliability (ICC ≥ 0.75), and neuromuscular assessments were well-established. Integrating cognitive-motor tasks improved neuromuscular control and functional performance, better simulating sport demands and supporting safer return to sport after ACL Injuries
2	Dhillon et al. (2011)	Observational	ACL-deficient knees; no intervention measured proprioceptive deficits.	Joint position sense: ICC 0.8-0.9 (reliable via repositioning tasks).	Joint position sense testing showed good reliability (ICC 0.8–0.9) using repositioning tasks. Significant proprioceptive deficits were observed in patients with ACL-deficient knees post-reconstruction, though no specific statistical values were reported.
3	Eslami et al. (2024)	RCT	Post-ACL patients (n=36); dual-task vs. single-task balance exercises	BESS (ICC ~0.6–0.9); KOOS (α > 0.7) both validated.	Both groups (dual-task and single-task) showed significant improvements

			incorporating cognitive distractions.		in neuromuscular outcomes post-ACL Injuries ($P < 0.05$). However, no significant differences were found between the groups ($P > 0.05$). Balance Error Scoring System (BESS) demonstrated moderate to high reliability (ICC ~0.6–0.9), and KOOS showed good internal consistency ($\alpha > 0.7$).
4	Fukuda et al. (2013)	RCT	ACL-reconstructed (n=64); open kinetic chain exercises within 45–90° ROM.	Isokinetic dynamometry (ICC > 0.9); arthrometry; validated function scores.	Open kinetic chain exercises within a 45–90° range of motion led to significant strength improvements ($P < 0.05$) without increasing joint laxity (not significant). Isokinetic dynamometry showed high reliability (ICC > 0.9), and functional outcomes were assessed using validated tools.
5	Gholami et al. (2023)	RCT	ACL-reconstructed athletes; Differential Learning(DL) used variable movement conditions; Visuomotor training (VMT) included target-based feedback tasks, Both of the interventions are based on neuromuscular control.	Triple Hop, SEBT (ICC > 0.9); EMG; TSK ($\alpha \approx 0.8$) highly reliable.	DL > VMT in most variables ($P \leq 0.05$); Both DL and VMT interventions showed comparable improvements and were superior to traditional methods in enhancing performance, biomechanics, and psychological outcomes

					linked to secondary ACL injury risk.
6	Holm et al. (2024)	Secondary RCT	Knee OA patients; strengthening plus neuromuscular control to assess relevance for ACL rehab.	MRI (validated muscle quality); EMG (ICC ~0.75-0.9).	Strengthening combined with neuromuscular control training led to significant improvements in muscle quality and neuromuscular control ($P < 0.05$) in knee osteoarthritis patients. Muscle quality was assessed by MRI, and EMG measurements showed good reliability (ICC ~0.75–0.9), supporting the relevance of these interventions for ACL rehabilitation.
7	Huang et al. (2021)	Quasi-Experimental	ACL-reconstructed (n=30); suspension training using unstable systems (e.g., TRX) for neuromuscular control.	Postural control and EMG-based metrics reliable protocols.	Suspension training using unstable systems significantly improved neuromuscular control and postural stability in ACL-reconstructed patients ($P < 0.05$). Postural control and EMG-based measures were assessed using reliable protocols.
8	Kasmi et al. (2021)	RCT	Elite female ACL athletes; eccentric, plyometric, and combined training protocols.	Hop/stability/strength tests validated functional metrics.	Combined eccentric and plyometric training produced the greatest improvements in hop performance, stability, and strength compared to single training protocols ($P < 0.05$) in elite female ACL athletes, using

					validated functional test
9	Kaya et al. (2019)	Experimental	Post-ACL (n=28); neuromuscular control-focused exercises (balance, proprioception, coordination).	Strength, proprioception (ICC > 0.8).	Neuromuscular control-focused exercises significantly improved functional performance and proprioception (P < 0.05) in post-ACL patients. Strength and proprioception measures demonstrated high reliability (ICC > 0.8)
10	Oliveira et al. (2022)	RCT	ACL patients (n=52); unilateral vs bilateral resistance training programs.	Strength/function tests (ICC > 0.8).	Unilateral resistance training led to significantly greater improvements in strength and function compared to bilateral training (P < 0.05) in ACL patients.
					Strength and functional tests showed high reliability (ICC > 0.8).
11	Pangestuputra & Changestu (2024)	Narrative Review	ACL prevention populations; neuromuscular training (jump landing, strength, coordination drills).	Tools reviewed have good reliability; ICC > 0.75.	Neuromuscular training focusing on jump landing, strength, and coordination drills showed good reliability across assessment tools (ICC > 0.75). The review supports the effectiveness of these training programs for ACL injury prevention, although no statistical values were reported
12	Saki et al. (2023)	Experimental	ACL-reconstructed athletes (n=30); core stabilization training	EMG, neuromuscular function (ICC ~0.8).	Core stabilization training significantly improved lumbop

			(e.g., planks, bridges) for lumbopelvic control.		elvic neuromuscular control in ACL-reconstructed athletes ($P < 0.05$). EMG and neuromuscular function assessments demonstrated good reliability (ICC ~0.8).
13	Shultz et al. (2024)	Systematic Review	ACL + MCL injuries; compared MCL repair, non-op, and recon with ACLR.	Standardized clinical & RTS outcomes across studies; validated tools.	The review found that combined MCL repair and ACL Injuries provided the greatest joint stability compared to non-operative treatment or reconstruction alone. Clinical and return-to-sport outcomes were assessed using standardized and validated tools, though effect sizes varied across studies
14	Wei & Huang (2022)	Quasi-Experimental	Post-ACL; functional motor training (task-specific movements, coordination under fatigue).	Mobility/function tools with $\alpha > 0.7$.	Functional motor training focusing on task-specific movements and coordination under fatigue significantly improved mobility and functional scores in post-ACL patients ($P < 0.05$). Assessment tools demonstrated good internal consistency ($\alpha > 0.7$)
15	Wilk et al. (2024)	Clinical Perspective Article	ACL patients (post-op); integrated neurocognitive + neuromuscular protocols (reaction, attention,	Cites validated return-to-sport tools (e.g., functional hop tests).	The article provides descriptive guidance on integrating neurocognitive and neuromuscular protocols

			strength).		focusing on reaction , attention, and strength in post-operative ACL rehabilitation. It references validated return-to-sport tools but does not present original data or statistical analyses.

Table 2

Abbreviation	Full Form	Description
ACL	Anterior Cruciate Ligament	A key ligament in the knee, commonly injured in athletes.
RCT	Randomized Controlled Trial	A type of experimental study design.
DL	Differential Learning	A motor learning approach using variable movement conditions.
VMT	Visuomotor Training	Training integrating visual feedback with motor responses.
BESS	Balance Error Scoring System	A clinical tool to assess postural stability.
KOOS	Knee Injury and Osteoarthritis Outcome Score	A patient-reported outcome measure for knee health.
EMG	Electromyography	Measures muscle electrical activity.
ICC	Intraclass Correlation Coefficient	A reliability statistic (closer to 1 = high reliability).
SEBT	Star Excursion Balance Test	A dynamic balance test used in rehabilitation.
TSK	Tampa Scale for Kinesiophobia	Assesses fear of movement/reinjury.
ROM	Range of Motion	The degree of movement at a joint.
OA	Osteoarthritis	A degenerative joint condition.
RTS	Return to Sport	A common rehabilitation goal post-ACL injury.
NS	Not Significant	Indicates statistically non-significant findings.
α (alpha)	Cronbach's Alpha	A measure of internal consistency or reliability (α > 0.7 is acceptable).

IV. DISCUSSION

Anterior cruciate ligament (ACL) injury is a prevalent musculoskeletal issue, particularly among athletes and physically active individuals. Rehabilitation following ACL Injuries (ACLR) extends beyond merely regaining muscular strength. It demands the restoration of neuromuscular control, proprioception, and sensorimotor integration. Recent evidence consistently emphasizes that sensorimotor training and motor control exercises are pivotal in optimizing functional outcomes post-ACLR (Arhos et al., 2025; Wilk et al., 2024).

Multiple randomized controlled trials and systematic reviews have demonstrated that sensory motor training effectively enhances joint stability, dynamic balance, muscle activation patterns, and overall functional performance. Eslami et al. reported that dual task balance training resulted in superior improvements in static balance compared to single task training, highlighting the significant role of cognitive motor interference in neuromuscular recovery post-ACLR (Eslami et al., 2024). Similarly, Pangestuputra and Changestu emphasized that neuromuscular training

(NMT) forms the foundation for both ACL injury prevention and rehabilitation, significantly improving dynamic stability and lowering reinjury risk (Pangestuputra & Changestu, 2024).

Proprioceptive and perturbation-based training emerge as crucial components of rehabilitation across multiple studies. Gokeler et al. reported that individuals who incorporated sensorimotor exercises achieved improved knee joint stability and motor control compared to those undergoing conventional strength training (Gholami et al., 2023). This finding is supported by Lee et al., who demonstrated that proprioceptive neuromuscular facilitation (PNF) significantly improved quadriceps activation and reduced joint laxity, indicating that motor control training directly influences joint biomechanics (Riaz et al., 2024).

Additionally, perturbation-based training has shown remarkable benefits in dynamic stability restoration. Hartigan et al. found that supplementing strength-based rehabilitation with perturbation exercises accelerated improvements in functional hop tests and dynamic stability (Oliveira et al., 2022). These outcomes align with Risberg et al., who reported that neuromuscular training significantly enhanced single-leg balance, muscle co-activation, and landing mechanics (Kasmi et al., 2021).

Emerging rehabilitation tools such as virtual reality (VR) have recently been integrated into ACL rehabilitation. Akinoglu et al. demonstrated that VR-based balance training improved dynamic postural control while simultaneously enhancing patient motivation, suggesting that technology-assisted sensorimotor exercises could complement traditional rehabilitation strategies (Sohrab et al., 2024).

Despite strong evidence supporting sensory motor training and motor control retraining, certain limitations persist. Although sensory motor training enhances proprioception, dynamic balance, and functional mobility, it may not comprehensively address psychological barriers such as fear of re-injury. Langford et al. noted that even with biomechanical improvements resulting from neuromuscular and balance training, psychological readiness remained an independent factor influencing return-to-sport decisions (Shultz et al., 2024).

Moreover, variability in intervention protocols, including differences in exercise duration, intensity, frequency, and training modalities, makes direct comparison between studies difficult. Many studies involved small sample sizes and lacked long-term follow-up beyond 6 to 12 months, limiting conclusions about sustainability and injury recurrence. This is critical, given the high incidence of secondary ACL injuries within the first two years post-reconstruction (Umiya & Sharma, 2025; Wilk et al., 2024).

Nonetheless, the consolidated body of evidence strongly advocates for the early and progressive integration of motor control and sensorimotor training throughout ACL rehabilitation. Incorporating dual task challenges, perturbation exercises, proprioceptive retraining, and cognitive motor tasks significantly enhances neuromuscular control, mitigates reinjury risks, and improves functional performance (Eslami et al., 2024; Gholami et al., 2023; Pangestuputra & Changestu, 2024).

Future research should aim to standardize sensory motor training protocols, include larger and more diverse cohorts, and assess long-term outcomes, including psychological readiness. Additionally, the integration of novel technologies such as VR with traditional neuromuscular and sensorimotor training may provide a more comprehensive and engaging rehabilitation framework in the future (Sohrab et al., 2024; Wilk et al., 2024).

V. CONCLUSION

Rehabilitation following ACL Injuries is not just about regaining strength but also about restoring motor control, proprioception, and functional movement. Studies show that focusing on these aspects leads to better recovery outcomes and lowers the risk of re injury. Strength alone cannot fully prepare individuals for the demands of daily life or physical tasks. Incorporating motor control training alongside traditional rehabilitation is essential. A holistic approach that addresses both physical and cognitive recovery is key. This can help individuals return to their routine activities with greater confidence and stability.

VI. LIMITATIONS

1. Different Treatment Methods-There were studies which have included other interventions & are not based on sensory motor training alone.

2. Short follow up Time- Long-term follow-up can yield better possible outcomes.
3. Addition of advanced technology.

VII. SUMMARY

This Narrative Review emphasizes expanding the approach of motor control and sensorimotor training in maximizing functional outcomes after anterior cruciate ligament (ACL) injury and reconstruction. Traditional rehabilitation methods are successful in restoring strength and range of motion but commonly neglect to treat residual neuromuscular and proprioceptive impairments that lead to reinjury. Newer interventions i.e., visuomotor feedback, perturbation-based training, dual-task cognitive-motor training, differential learning, and core stabilization have shown substantial gains in proprioception, dynamic balance, movement coordination, and psychological readiness to return to sport. The combination of neurocognitive and motor learning principles is a paradigm shift from strength-based rehabilitation to more integrated, sensorimotor-based models of recovery that address both central and peripheral mechanisms of motor control. Together, these results support the inclusion of motor control and sensorimotor training as integral elements of post-ACL rehabilitation evidence-based programs.

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IX. FUTURE RECOMMENDATIONS

1. Standardize Intervention Protocols: Establishment of standardized protocols including neurological & musculoskeletal systems including the dosage in the form of duration, frequency, and progression standards for post-ACL reconstruction motor control and sensorimotor training.
2. Inclusion of Long-term Follow-ups: Assess the long term outcomes of neuromuscular and proprioceptive functions and their relationship in comparison to reinjury rates at long-term follow-up.

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