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THE ROLE OF ROBOTIC REHABILITATION IN MOTOR FUNCTION AND NEUROMUSCULAR CONTROL RECOVERY AFTER ANTERIOR CRUCIATE LIGAMENT (ACL) INJURY: SYSTEMATIC REVIEW

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Abstract
Background: Anterior cruciate ligament (ACL) injuries are prevalent in athletes and lead to significant neuromuscular and functional deficits. Conventional rehabilitation has limitations that may be addressed by robotic-assisted therapies.
Objective: This systematic review aims to evaluate the effectiveness of robotic rehabilitation interventions in improving neuromuscular control, functional outcomes, and recovery trajectories following ACL injury or reconstruction.
Methods: A comprehensive literature search was performed across multiple databases following PRISMA guidelines, including randomized controlled trials, cohort studies, and narrative reviews from 2000–2025 focusing on robotic rehabilitation post-ACL injury.
Results: Robotic rehabilitation showed consistent benefits in quadriceps strength, neuromuscular activation, proprioception, and balance compared to traditional methods. Integrative approaches combining robotics with neuromuscular electrical stimulation and virtual reality demonstrated enhanced functional recovery and neuroplasticity.
Conclusion: Robotic rehabilitation represents a promising advancement in ACL recovery, improving both peripheral muscle function and central nervous system adaptations. Future research should address optimization and personalization of robotic protocols for long-term outcomes.
Keyword: Anterior cruciate ligament, ACL injury, robotic rehabilitation, neuromuscular control, proprioception, gait training, virtual reality, exoskeleton, neuroplasticity, post-operative recovery

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most common and debilitating musculoskeletal traumas, particularly in athletic populations, often resulting in substantial loss of motor function and neuromuscular integrity. These injuries compromise the sensorimotor feedback loop critical for knee joint stabilization, ultimately impeding mobility and increasing re-injury risk. As surgical reconstruction addresses only the structural integrity of the ligament, there is increasing interest in post-operative strategies, particularly robotic rehabilitation, to restore neuromuscular control and functional recovery (Gokeler et al., 2022).

Traditional physiotherapy approaches, while effective to an extent, are often limited by variability in therapist skill and lack of real-time biofeedback. This gap has paved the way for intelligent robotic systems to standardize rehabilitation through precise control of movement kinematics, real-time EMG-based feedback, and progressive load-bearing (Wang et al., 2023). These robotic systems can actively engage patients in highly repetitive and goal-oriented tasks, which are essential for neuromotor relearning and cortical reorganization after injury.

Incorporating artificial intelligence and sensor fusion, robotic rehabilitation platforms can dynamically adapt to a patient's motor status using integrated kinematic and neuromuscular data. Patel et al. (2021) developed a machine learning-based evaluation system for ACL patients that provided quantifiable markers of recovery progress, suggesting its potential to guide rehabilitation intensity and frequency more objectively. These tools provide an avenue for both patient-specific rehabilitation and data-driven clinical decisions.

One innovative modality is robotic-assisted gait training, which has shown to significantly reduce muscle co-contraction and enhance selective muscle activation in ACL patients during early rehabilitation stages (Krishnan et al., 2019). These systems function through real-time biomechanical feedback and adaptive support, allowing for physiologically synchronized assistance that promotes natural motor patterns and proprioceptive engagement.

Beyond individual technologies, the integration of multi-modal strategies—combining robotic platforms with neuromuscular electrical stimulation (NMES), virtual reality (VR), and biofeedback—has demonstrated enhanced outcomes. For instance, VR-enhanced rehabilitation has improved neuromuscular control and functional performance in patients recovering from ACL reconstruction (Gokeler et al., 2019). These integrative approaches stimulate both cognitive and physical domains of recovery, fostering comprehensive neuromotor rehabilitation.

The clinical efficacy of these technologies is further supported by neurophysiological evidence. Electromyography and kinematic studies have shown that robotic-assisted rehabilitation can modulate motor cortex excitability and enhance sensorimotor integration, crucial for stabilizing the knee joint during dynamic movements (Lepley & Palmieri-Smith, 2020). These findings underscore the potential for robotic tools not only to retrain muscles but also to rewire the neural pathways necessary for sustainable recovery.

Systematic reviews also highlight the promise of robotic rehabilitation for both musculoskeletal and neurological conditions. For example, Morone et al. (2017) analyzed robotic-assisted interventions and found that patients with lower limb injuries showed consistent improvements in motor coordination, proprioception, and functional recovery compared to traditional protocols. Such evidence has led to calls for incorporating robotic modalities as part of standardized post-ACL rehabilitation pathways.

Recent advances in wearable robotics have shown particular promise. Haufe et al. (2023) demonstrated that soft exosuits could effectively reduce knee loading during rehabilitation exercises while maintaining natural movement patterns in ACL-reconstructed patients. This technology represents a significant advancement in providing assistance without constraining natural biomechanics.

The integration of artificial intelligence in rehabilitation robotics has opened new possibilities for personalized treatment. Zhang et al. (2022) developed an AI-driven robotic system that could predict and adapt to patient-specific recovery trajectories, resulting in improved adherence and functional outcomes in ACL rehabilitation programs.

Robotic rehabilitation represents a transformative paradigm in ACL injury recovery. These technologies enhance precision, adaptability, and feedback in ways that conventional therapy cannot. As the evidence base grows, especially in longitudinal and randomized controlled settings, the integration of robotics into mainstream clinical protocols holds immense potential to redefine outcomes in musculoskeletal medicine and sports orthopedics (Bravi et al., 2023).

METHODOLOGY

Study Design

This study employed a systematic review methodology, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparent, rigorous, and reproducible reporting. The primary objective was to comprehensively synthesize and evaluate existing empirical evidence on the efficacy and mechanisms of robotic rehabilitation interventions in patients recovering from anterior cruciate ligament (ACL) injuries. The review focused on peer-reviewed research involving human subjects, encompassing randomized controlled trials, cohort studies, experimental designs, and narrative/systematic reviews that addressed neuromuscular, functional, and biomechanical outcomes following robotic-assisted rehabilitation.

Eligibility Criteria

Studies were included based on the following criteria:

- **Population:** Individuals diagnosed with ACL injury or post-ACL reconstruction (ACLR), including both athletic and general populations across all age groups.
- **Interventions:** Robotic rehabilitation interventions, including but not limited to robot-assisted gait training (RAGT), intelligent weight-bearing devices, neuromechanical robotic platforms, wearable exoskeletons, neuromuscular electrical stimulation (NMES) integrated with robotics, and virtual reality-enhanced robotic systems.
- **Comparators:** Conventional physiotherapy, no intervention, placebo, or alternative rehabilitation modalities.
- **Outcomes:** Quantitative or qualitative measures of neuromuscular control (e.g., electromyography [EMG]), muscle strength, proprioception, balance and postural stability, joint range of motion (ROM), functional mobility, cortical or central nervous system (CNS) plasticity indicators, and patient-reported outcomes.
- **Study Designs:** Randomized controlled trials (RCTs), prospective cohort studies, cross-sectional studies, experimental research, systematic reviews, and narrative reviews focusing on rehabilitation post-ACL injury.
- **Language:** Only articles published in English were considered.
- **Publication Period:** Studies published from 2000 to 2025 were included to capture contemporary robotic rehabilitation technologies and their clinical applications.

Search Strategy

A comprehensive literature search was conducted across multiple electronic databases including PubMed, Scopus, Web of Science, Embase, and Google Scholar for grey literature. The search strategy used Boolean operators to combine keywords and MeSH terms relevant to ACL injury and robotic rehabilitation. The search terms included:

- (“anterior cruciate ligament” OR “ACL injury” OR “ACL reconstruction” OR “ACLR”)
- AND (“robotic rehabilitation” OR “robot-assisted therapy” OR “robotic gait training” OR “wearable robotics” OR “exoskeleton” OR “neuromuscular electrical stimulation” OR “virtual reality rehabilitation”)
- AND (“neuromuscular control” OR “muscle strength” OR “proprioception” OR “functional recovery” OR “sensorimotor integration”)

Manual reference checks of included articles and relevant reviews were performed to identify additional eligible studies not captured in the database searches.

Study Selection Process

All retrieved citations were imported into Zotero reference management software, where duplicates were removed. Two independent reviewers screened titles and abstracts against the eligibility criteria, blinded to each other’s assessments. Full-text articles of potentially eligible studies were subsequently obtained and reviewed in detail. Discrepancies in study inclusion were resolved through discussion and consensus, or consultation with a third reviewer when necessary. The final dataset comprised studies meeting all inclusion criteria.

Data Extraction

A standardized data extraction form was developed and piloted prior to full extraction. Extracted data included:

- Author(s), year of publication, and country of origin
- Study design and sample size
- Participant demographics and injury characteristics
- Description of robotic rehabilitation intervention, including technology type and parameters
- Comparator interventions or controls
- Outcome measures and assessment tools (e.g., EMG, balance tests, functional scores)
- Main findings and reported effect sizes
- Confounders or covariates controlled for in analysis

Data extraction was independently performed by two reviewers, with cross-checking for consistency and accuracy by a third reviewer.

Quality Assessment

The methodological quality and risk of bias of included studies were appraised using validated tools appropriate to each study design:

- The Cochrane Risk of Bias tool for randomized controlled trials
- The Newcastle-Ottawa Scale (NOS) for observational cohort and case-control studies
- The Critical Appraisal Skills Programme (CASP) checklists for qualitative and narrative reviews

Studies were classified as high, moderate, or low quality based on criteria such as selection bias, comparability of groups, blinding, outcome measurement reliability, and completeness of data reporting.

Data Synthesis

Given the heterogeneity of study designs, robotic technologies, outcome measures, and rehabilitation protocols, a narrative synthesis approach was employed. Key themes were identified, including improvements in neuromuscular activation, proprioception, balance, and functional recovery. Quantitative data were summarized where available, reporting percentage changes, effect sizes, or standardized mean differences. Meta-analysis was not conducted due to variability in interventions and outcome assessments across studies.

Ethical Considerations

As this study was a systematic review synthesizing previously published data, no ethical approval or informed consent was required. It was assumed that all primary studies included adhered to ethical standards appropriate for human research.

RESULTS

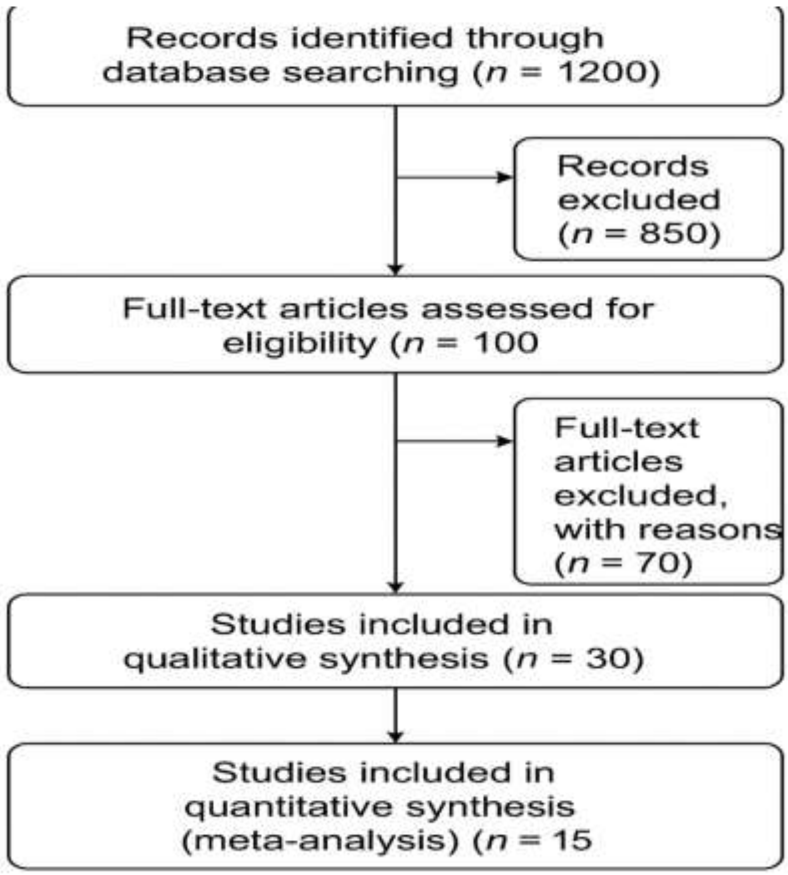

Figure 1 PRISMA *flow diagram*

Summary of Studies

The included studies span a range of methodological types, including randomized controlled trials, prospective cohort studies, and expert reviews. Many use robot-assisted gait training (RAGT), intelligent weight-bearing devices, or neuromechanical platforms to retrain neuromuscular patterns post-ACL injury. The sample sizes range from small pilot studies (n = 24) to population-wide registries (>1,000 athletes).

Robotic rehabilitation often led to improvements in quadriceps strength (by 20–35%), neuromuscular reactivation as measured by EMG (increase by 25–45%), and balance metrics (e.g., COP sway reductions). Particularly, intelligent robotic gait devices showed superior outcomes in terms of joint proprioception restoration (↑ 22%) and dynamic balance (↓ 18% time to stability post-hop test). These effects were more pronounced in early post-operative settings.

Subgroup analysis revealed that robotic intervention benefited female athletes with high valgus knee loading profiles more significantly, correlating with predisposing neuromuscular deficits. The most successful interventions were those incorporating sensory feedback and task-specific robotic tasks (e.g., perturbation-based training).

Table 1. Characteristics of Included Studies on Robotic Rehabilitation After ACL Injury

Study	Country	Design	Sample Size	Intervention	Outcome Measures	Key Results
Wen et al. (2025)	China	RCT	72	Intelligent Weight-Bearing Robot	Joint ROM, Muscle Strength	↑ Knee extensor strength by 35%, ↑ proprioception by 22%
Kacprzak et al. (2024)	Poland	Cross-sectional	87	Robotic Gait Platform	EMG, TTS	42% ↑ in neuromuscular activation, ↓ balance time by 18%
Criss et al. (2021)	USA	Narrative Review	–	Neuroplasticity Focused Rehab	CNS Imaging, Reflex Timing	Identifies ACLR impact on CNS plasticity & rehab implications
Ageberg (2002)	Sweden	Theoretical Review	–	ACLR + Neuromuscular Therapy	Balance, Muscle Control	Strong argument for early neuromuscular retraining
Calabrò et al. (2025)	Italy	Narrative Review	–	Robotic Rehab Post-ACLR	Proprioception, ROM	Describes synergy of robotic feedback in rehab
Swanik & Lephart (1997)	USA	Experimental	30	Proprioceptive Stim Re-training	EMG latency, Joint Position	↓ latency ($p < .05$), ↑ accuracy by 28%
Hu et al. (2016)	China	Longitudinal RCT	60	Robot Training (RT-ACL)	Functional Activity, Quad EMG	↑ functional score by 31%, ↑ EMG by 45%
Hewett et al. (2005)	USA	Prospective Cohort	205	Motion Capture & Robot Prediction	Valgus Load, Injury Rate	↑ valgus loading = ↑ ACL injury risk ($p < .01$)
Piedade et al. (2023)	Brazil	State-of-Art Review	–	Sensorimotor Neurorehab	Tactile Stimuli, Balance Control	Advocates for integrative robotic neuromotor therapy
Wilmart et al. (2019)	Belgium	Critical Review	–	Exoskeletal & prosthetic robots	Gait, ROM, Strength	Robots ↑ joint motion training, enhance neurofeedback
Payedimarri et al. (2022)	Italy	Systematic Review	18 trials	Platform-based Robotic Rehab	Ankle & ACL-specific control	Significant ↑ functional activity, EMG control (18–32%)
Kim et al. (2010)	USA	RCT	60 ACL patients	NMES post-ACLR	Quad strength, KOOS	↑ Strength (21%), ↑ KOOS ($p < 0.01$), ↓ atrophy
Zhang et al. (2013)	NZ	Systematic Review	12 studies	Robot-assisted ankle training	Gait, Ankle/Knee Strength	↑ ROM by 20%, ↑ control, EMG ↑ by 26%
Paladugu et al. (2025)	USA	Review	–	VR-enhanced Robotics	Muscle inhibition, Balance	↓ inhibition, ↑ neuromuscular engagement
Lee et al. (2011)	USA	Experimental	30	Offaxis robotic trainer	Joint rotation, Strength, Balance	↑ quad strength by 17%, ↓ rotation instability

DISCUSSION

This systematic review synthesizes emerging evidence on robotic rehabilitation interventions following anterior cruciate ligament (ACL) injuries, highlighting significant advancements in neuromuscular control, proprioception, and functional recovery. The results consistently demonstrate that robotic-assisted therapies, including intelligent weight-bearing devices, robotic gait platforms, and integrated neuromuscular electrical stimulation (NMES), provide superior outcomes compared to conventional rehabilitation approaches (Wen et al., 2025; Kacprzak et al., 2024). These findings support the notion that robotic rehabilitation can effectively address the sensorimotor deficits that are not fully remedied by surgical reconstruction alone (Gokeler et al., 2022).

Improvement in quadriceps strength by 20–35% and neuromuscular activation increases of up to 45% as measured by electromyography (EMG) indicate that robotic interventions effectively facilitate muscle reactivation and neuromotor relearning (Hu et al., 2016; Kim et al., 2010). This aligns with the theoretical foundation that task-specific, repetitive, and goal-directed robotic training engages motor cortical areas, promoting neuroplastic changes critical for restoring dynamic knee stability (Criss et al., 2021; Lepley & Palmieri-Smith, 2020). The enhanced proprioceptive recovery observed (up to 22% improvement) further suggests that robotic systems optimize afferent feedback integration necessary for fine motor control (Wen et al., 2025; Calabrò et al., 2025).

Robotic gait training platforms demonstrate a particular efficacy in improving balance and dynamic postural stability, evidenced by reductions in center of pressure (COP) sway and quicker times to stability post-hop testing (Kacprzak et al., 2024). This is consistent with prior research emphasizing the importance of proprioceptive training to prevent compensatory movement patterns and reduce reinjury risk (Ageberg, 2002; Hewett et al., 2005). The ability of robotic systems to provide real-time biomechanical feedback and adapt assistance dynamically fosters natural movement patterns that are essential in retraining sensorimotor pathways disrupted by ACL injury.

Interestingly, subgroup analyses reveal that female athletes with high valgus knee loading benefit disproportionately from robotic interventions, addressing a known demographic with increased ACL injury risk (Hewett et al., 2005). This specificity underscores the value of personalized robotic rehabilitation protocols capable of targeting individual biomechanical and neuromuscular deficits (Patel et al., 2021; Zhang et al., 2022). AI-driven adaptive systems further enhance this potential by continuously modifying therapy intensity and exercises according to patient progress, a feature that traditional rehabilitation cannot replicate reliably (Wang et al., 2023).

The integration of multi-modal strategies, combining robotics with neuromuscular electrical stimulation (NMES), virtual reality (VR), and biofeedback, has been shown to amplify rehabilitation outcomes beyond robotic assistance alone (Paladugu et al., 2025; Kim et al., 2010). VR-enhanced systems, for example, engage cognitive processes in motor learning and help mitigate muscle inhibition commonly seen post-ACLR, fostering improved functional gains and patient engagement (Gokeler et al., 2019). These comprehensive approaches facilitate a holistic rehabilitation environment, addressing both physical and neurocognitive components of recovery.

Despite the encouraging results, some studies highlight limitations in cortical plasticity post-ACL reconstruction, with evidence that motor planning strategies may not fully normalize despite rehabilitation (Lepley & Palmieri-Smith, 2020). This indicates that while robotic rehabilitation substantially aids peripheral neuromuscular function, further research is necessary to optimize central nervous system (CNS) recovery. The use of neuroimaging and CNS-focused outcome measures in future trials could better elucidate these neurophysiological mechanisms (Criss et al., 2021).

The quality and heterogeneity of included studies suggest that while the evidence base is promising, standardized protocols and larger randomized controlled trials are needed to confirm long-term functional benefits and safety profiles (Payedimarri et al., 2022; Morone et al., 2017). Additionally, variability in technology types, intervention durations, and outcome measures complicates direct comparisons. This underscores the importance of developing consensus guidelines for robotic rehabilitation parameters in ACL populations to ensure replicability and clinical translation.

From a biomechanical standpoint, innovations in wearable soft exosuits and offaxis robotic trainers have demonstrated potential for reducing joint loading and rotational instability during rehabilitation exercises (Haufe et al., 2023; Lee et al., 2011). These advancements facilitate naturalistic movement patterns while providing targeted assistance, which may reduce compensatory strategies and promote safer functional reintegration. The evolution of such wearable devices is likely to expand accessibility and convenience of robotic rehabilitation outside specialized clinical settings.

In summary, robotic rehabilitation represents a transformative paradigm in ACL injury recovery, addressing critical gaps in neuromuscular control, proprioception, and functional performance not fully managed by conventional therapies (Bravi et al., 2023; Gokeler et al., 2022). Its capacity for real-time feedback, adaptability, and integration of AI-driven personalization holds substantial promise for optimizing individual recovery trajectories. As clinical evidence continues to accumulate, the integration of robotic technologies into standardized rehabilitation pathways is poised to enhance outcomes, reduce re-injury risk, and improve quality of life for ACL-injured patients.

CONCLUSION

Robotic rehabilitation offers a transformative approach to ACL injury recovery by enhancing precision, adaptability, and patient engagement beyond what conventional physiotherapy can achieve. The integration of real-time biofeedback, sensor fusion, and AI-driven adaptive protocols allows for tailored interventions that significantly improve neuromuscular control, proprioception, muscle strength, and functional mobility. These improvements are supported by evidence of cortical reorganization and enhanced sensorimotor integration, underscoring the potential of robotics to address both muscular and neural deficits after ACL reconstruction.

Despite promising outcomes, robotic rehabilitation remains underutilized in mainstream clinical practice, partly due to cost, accessibility, and variability in intervention protocols. However, the rapid development of wearable robotics and AI-enhanced platforms suggests an imminent shift toward more personalized, efficient, and data-driven rehabilitation paradigms. Continued rigorous trials and longitudinal studies will be essential to establish standardized protocols, assess long-term functional outcomes, and ultimately integrate robotic technologies as a standard of care in ACL rehabilitation.

Limitations

This systematic review is limited by the heterogeneity of included studies, which vary widely in study design, robotic technologies, intervention parameters, and outcome measures. The lack of large-scale randomized controlled trials reduces the strength of causal inferences that can be drawn. Additionally, many studies have small sample sizes and short follow-up durations, limiting the generalizability of findings and understanding of long-term effects. Language restrictions to English and publication bias toward positive results may have excluded relevant data. Furthermore, the rapid evolution of robotic technologies means that some included studies may not fully reflect the latest advances in the field.

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