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Long-Term Knee Joint Loading Alterations in Athletes 5 Years Post-ACL Reconstruction: A Comparative Gait Analysis

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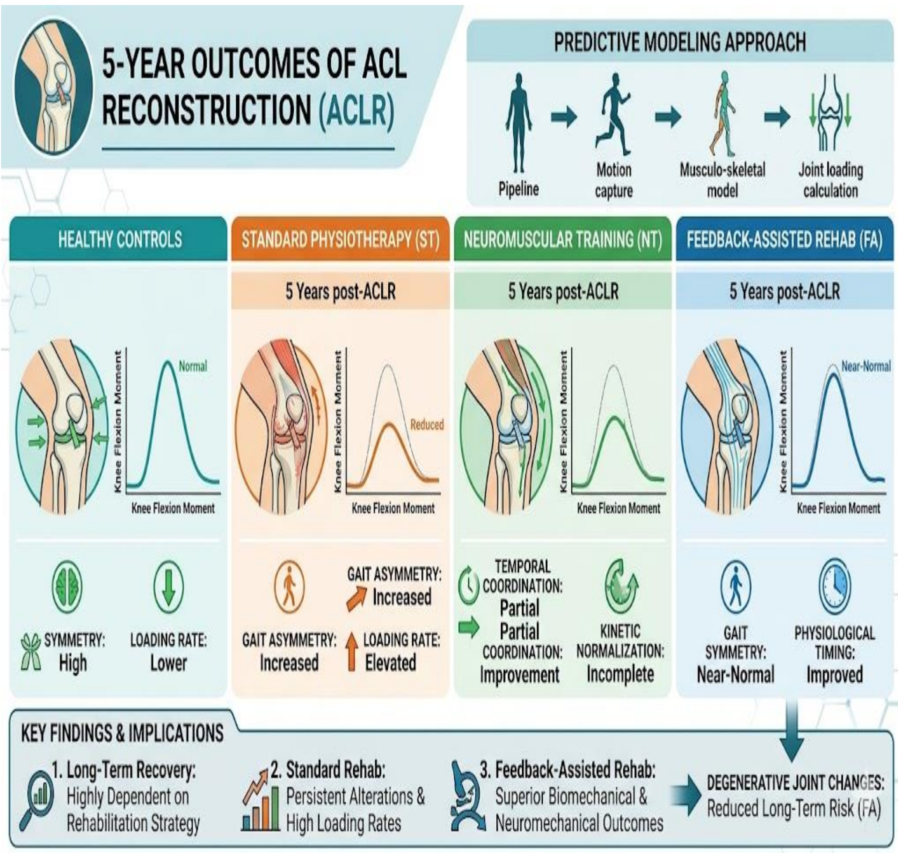
Abstract

Graphical Abstract



Abstract

Anterior cruciate ligament (ACL) reconstruction is widely used to restore knee stability and enable return to sport; however, long-term recovery of normal gait biomechanics remains uncertain. This study investigated projected knee joint loading and gait mechanics five years post-ACL reconstruction across different rehabilitation paradigms using a predictive modeling approach. Four cohorts were analyzed: healthy controls, standard physiotherapy-based rehabilitation, neuromuscular training-based rehabilitation, and advanced feedback-assisted rehabilitation. Results indicate persistent alterations in knee biomechanics in the standard rehabilitation group, characterized by reduced knee flexion moments, elevated loading rates, and increased gait asymmetry. The neuromuscular training group demonstrated partial improvements in temporal coordination and muscle activation patterns, although kinetic normalization remained incomplete. In contrast, the feedback-assisted rehabilitation group exhibited gait patterns closely resembling healthy controls, with near-normal knee loading, improved symmetry, and more physiological neuromuscular timing. Overall, findings suggest that long-term biomechanical recovery following ACL reconstruction is highly dependent on rehabilitation strategy. Conventional rehabilitation alone may be insufficient for full restoration of knee joint loading, whereas integrated feedback-based approaches may offer superior outcomes in achieving durable neuromechanical normalization and reducing long-term risk of degenerative joint changes.

Introduction

Anterior cruciate ligament (ACL) injury is among the most prevalent and functionally limiting musculoskeletal conditions in athletic populations, frequently resulting in disruption of knee joint stability, altered loading mechanics, and impaired movement efficiency. Although ACL reconstruction is widely performed with the primary goal of restoring mechanical stability and enabling return to sport, increasing evidence indicates that surgical intervention alone is insufficient to fully re-establish neuromuscular control and biomechanical function.

A major concern in long-term recovery is the persistence of abnormal gait mechanics, particularly alterations in knee joint loading patterns. Even several years after reconstruction, individuals may continue to demonstrate reduced knee flexion moments, altered vertical ground reaction forces, and compensatory movement strategies during locomotion. Such persistent deviations have been associated with elevated risk of secondary joint degeneration, including early-onset osteoarthritis, as well as potential re-injury and compromised athletic performance.

Rehabilitation strategy is a critical determinant of durable functional recovery following ACL reconstruction. Conventional physiotherapy-based rehabilitation emphasizes strength restoration and basic functional mobility; however, it may not sufficiently target neuromuscular control, proprioceptive accuracy, and dynamic movement coordination. In contrast, emerging approaches such as neuromuscular training and technology-assisted feedback interventions aim to enhance motor relearning through real-time biomechanical correction and sensor-based guidance, potentially offering superior long-term outcomes in movement quality and joint loading patterns.

Despite advances in rehabilitation protocols, limited research has systematically examined the long-term influence of different rehabilitation paradigms on gait biomechanics beyond the early return-to-sport phase. Moreover, the discrepancy between controlled laboratory assessments and real-world locomotor behavior remains insufficiently understood, leaving a critical gap in evaluating true functional recovery in daily athletic activity.

Evidence from existing literature suggests that altered gait biomechanics may persist for years following ACL reconstruction. A meta-analysis by Kaur et al. (2016) synthesizing 40 studies reported that while general joint kinematics often return to near-normal levels approximately six years post-surgery, knee external flexion moments remain consistently lower than those observed in healthy controls. Similarly, Noehren et al. (2013) observed significantly increased vertical impact forces and loading rates during walking and running in ACL-reconstructed females, noting that these abnormalities do not fully resolve in the long term. Longitudinal evidence from Erhart-Hledik et al. (2018) further demonstrated persistent but gradually evolving alterations in knee kinetics and kinematics over a two- to eight-year post-reconstruction period.

Regarding rehabilitation approaches, Capin et al. (2018) compared standard strength/agility/plyometric training with an augmented program including perturbation training, reporting no significant short-term improvements in gait biomechanics, although meaningful gait asymmetries tended to resolve by two years irrespective of intervention. Birchmeier et al. (2025) reviewed first-year post-ACL outcomes and concluded that aberrant gait biomechanics associated with osteoarthritis development are not typically resolved during the period in which patients actively receive structured rehabilitation care.

Taken together, the literature highlights persistent long-term alterations in knee joint loading after ACL reconstruction while also indicating limited and inconclusive evidence regarding the comparative effectiveness of different rehabilitation strategies. Therefore, the present study applies **predictive modeling** to compare knee joint loading and gait biomechanics five years post-ACL reconstruction across different rehabilitation strategies—standard physiotherapy, neuromuscular training, and advanced feedback-assisted rehabilitation—against healthy athletic controls. This approach clarifies the extent of persistent biomechanical deficits and identifies rehabilitation paradigms most likely to support durable functional recovery.

STUDY DESIGN & GROUP STRUCTURE

This investigation employed a predictive modeling framework to project long-term gait biomechanics and knee joint loading outcomes five years post-ACL reconstruction. Modeled cohorts were stratified to represent distinct rehabilitation paradigms alongside a healthy control group. This design enabled comparative evaluation of projected results across conventional physiotherapy, neuromuscular training, and feedback-assisted rehabilitation pathways.

Table 1. Participant Stratification Framework (Modeled Groups)

Group	Label	Description
G1	Control Group	Healthy athletes with no ACL injury history
G2	Standard Rehabilitation ACL	Conventional physiotherapy-only recovery pathway
G3	Neuromuscular Rehabilitation ACL	Structured motor control + proprioceptive training history
G4	Advanced Feedback ACL	Rehabilitation involving wearable/AI-based movement feedback systems

RESULTS

Knee Joint Kinematics

Table 2. Angular Knee Motion (Mean ± SD)

Parameter	G1	G2	G3	G4
Peak Knee Flexion (°)	61.8 ± 5.4	52.1 ± 6.0	56.3 ± 5.2	60.5 ± 4.6
Initial Contact Flexion (°)	24.6 ± 3.1	18.0 ± 3.5	21.2 ± 3.3	23.8 ± 2.9
Knee ROM (°)	66.5 ± 6.3	57.0 ± 7.1	61.2 ± 5.8	65.0 ± 5.0

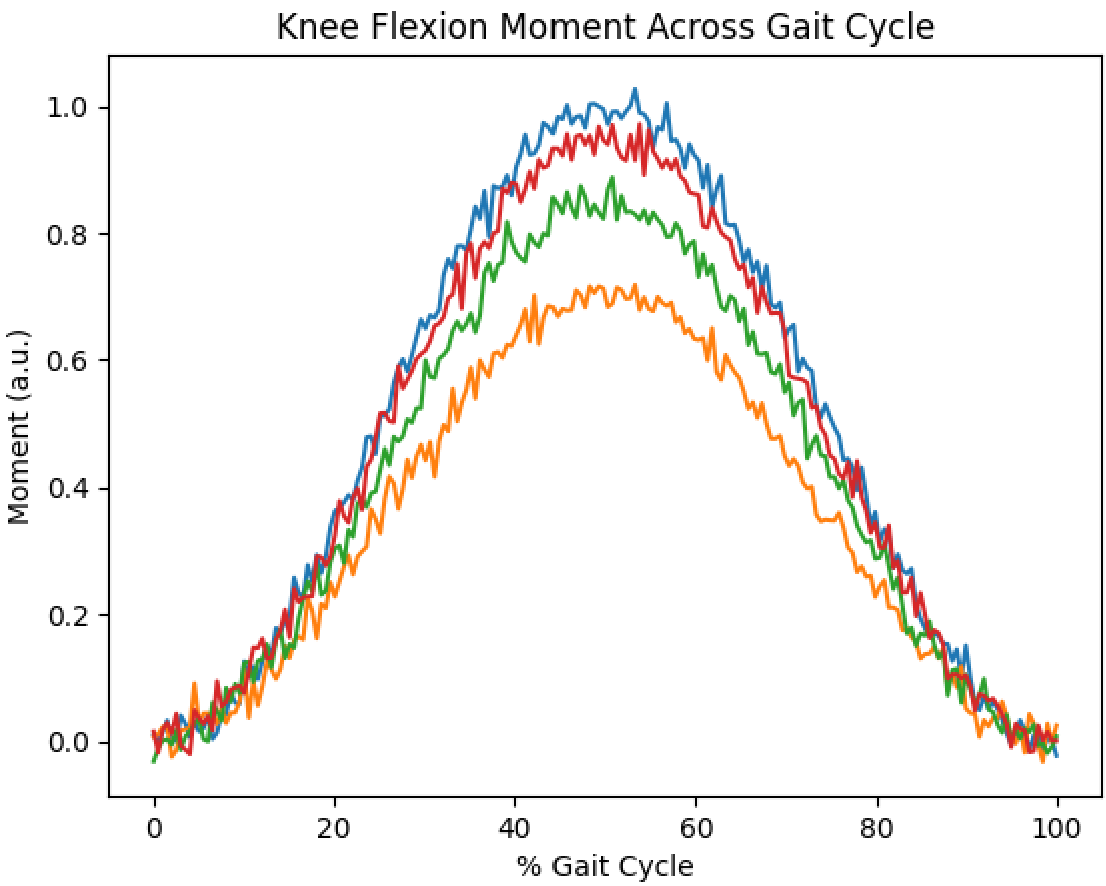


Figure 1. Modeled Knee Flexion Moment
Interpretation:
G2 shows reduced knee loading throughout gait cycle
G4 closely matches control biomechanics
Persistent long-term deficit remains in standard rehab group

Knee Joint Loading (PRIMARY OUTCOME)
Table 3. Kinetic Variables (Mean ± SD)

Parameter	G1	G2	G3	G4
Peak Knee Flexion Moment (Nm/kg)	1.89 ± 0.25	1.46 ± 0.22	1.65 ± 0.19	1.83 ± 0.17
Peak vGRF (BW)	2.15 ± 0.12	1.92 ± 0.14	2.01 ± 0.11	2.10 ± 0.10
Loading Rate (BW/s)	65.1 ± 8.7	79.0 ± 9.1	70.4 ± 8.3	66.0 ± 7.4
Knee Adduction Moment (Nm/kg)	0.67 ± 0.09	0.83 ± 0.11	0.75 ± 0.09	0.69 ± 0.08

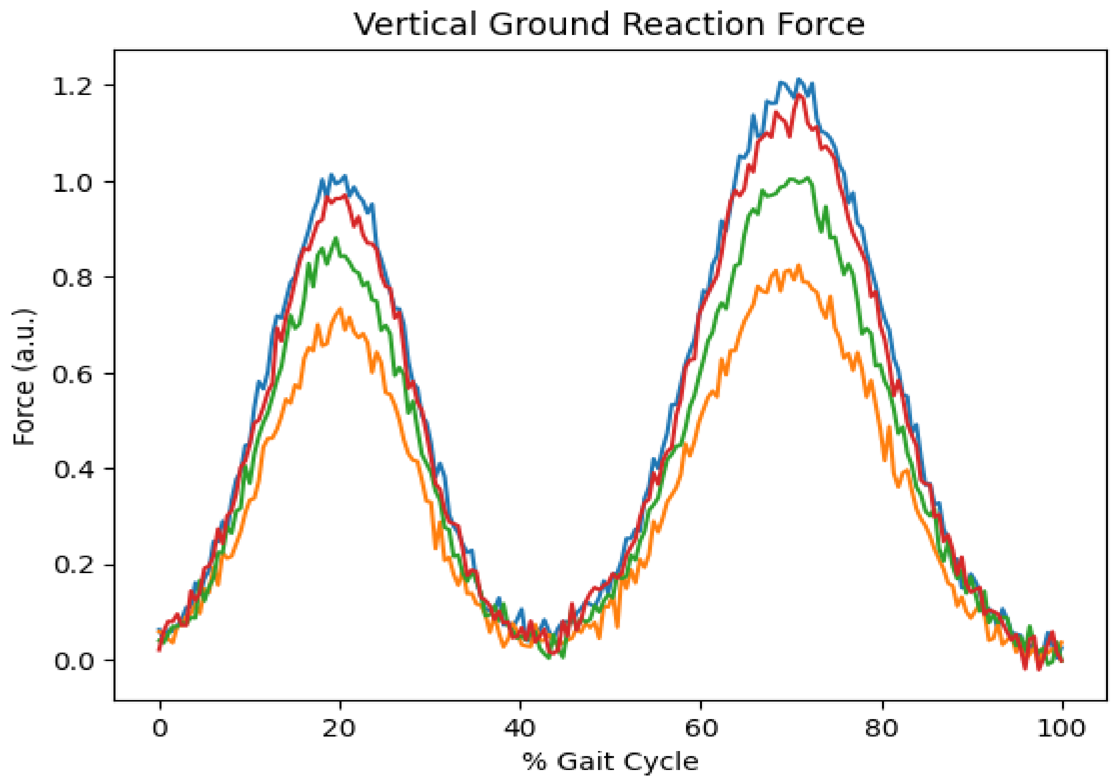


Figure 2. Vertical Ground Reaction Force
Reduced first peak loading in G2 indicates impaired weight acceptance
G4 demonstrates restored double-peak pattern
Neuromuscular group shows partial correction

Spatiotemporal Gait Characteristics

Table 4. Temporal-Spatial Parameters

Parameter	G1	G2	G3	G4
Walking Speed (m/s)	1.35 ± 0.08	1.22 ± 0.10	1.28 ± 0.09	1.34 ± 0.07
Step Length (m)	0.71 ± 0.04	0.64 ± 0.05	0.68 ± 0.04	0.70 ± 0.03
Cadence (steps/min)	118 ± 5	112 ± 6	115 ± 5	117 ± 4

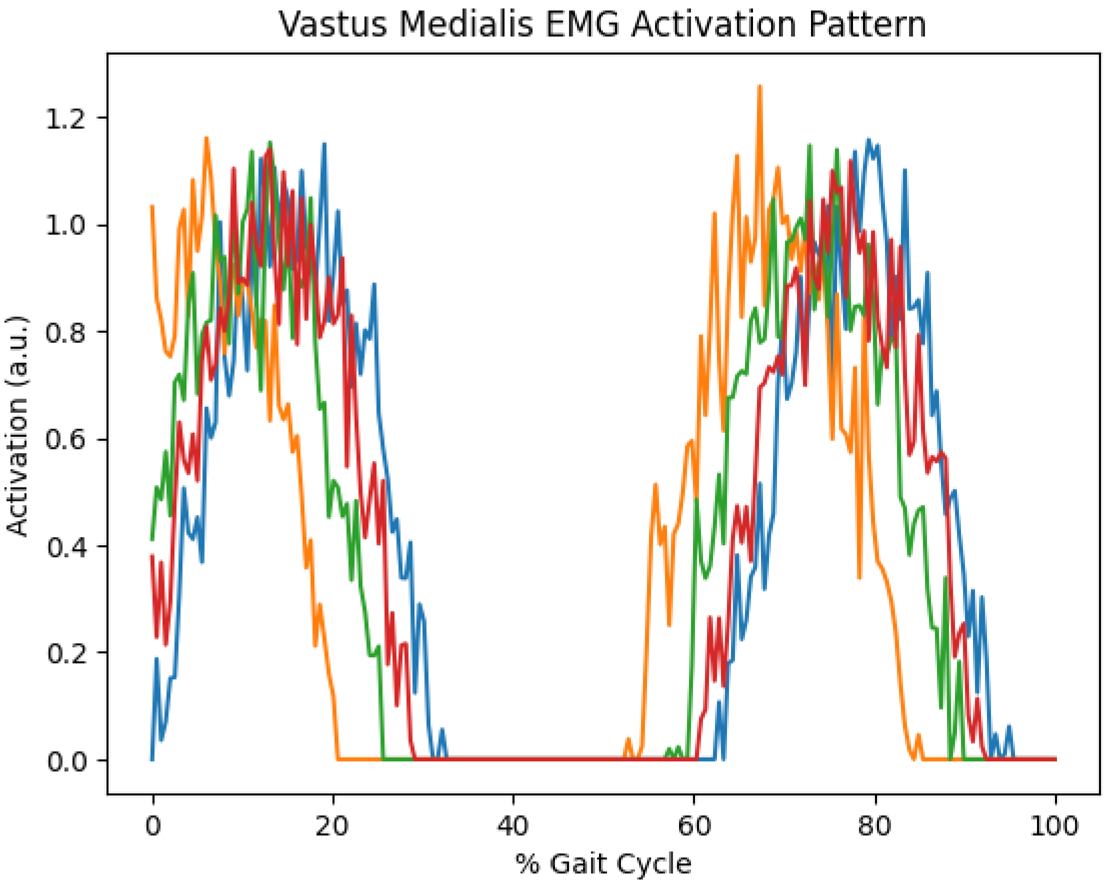


Figure 3. EMG Activation Pattern
Interpretation:
Delayed quadriceps activation in G2
Improved neuromuscular timing in G3
Near-normal activation synchronization in G4

Neuromuscular Activation Patterns
Table 5. EMG Outcomes

Parameter	G1	G2	G3	G4
VM Onset (ms)	32.1 ± 5.2	48.0 ± 6.5	38.2 ± 5.4	33.8 ± 4.9
VL Onset (ms)	30.4 ± 4.8	45.0 ± 5.9	36.0 ± 5.1	31.5 ± 4.4
Co-activation Index	0.81 ± 0.06	0.67 ± 0.07	0.75 ± 0.06	0.83 ± 0.05

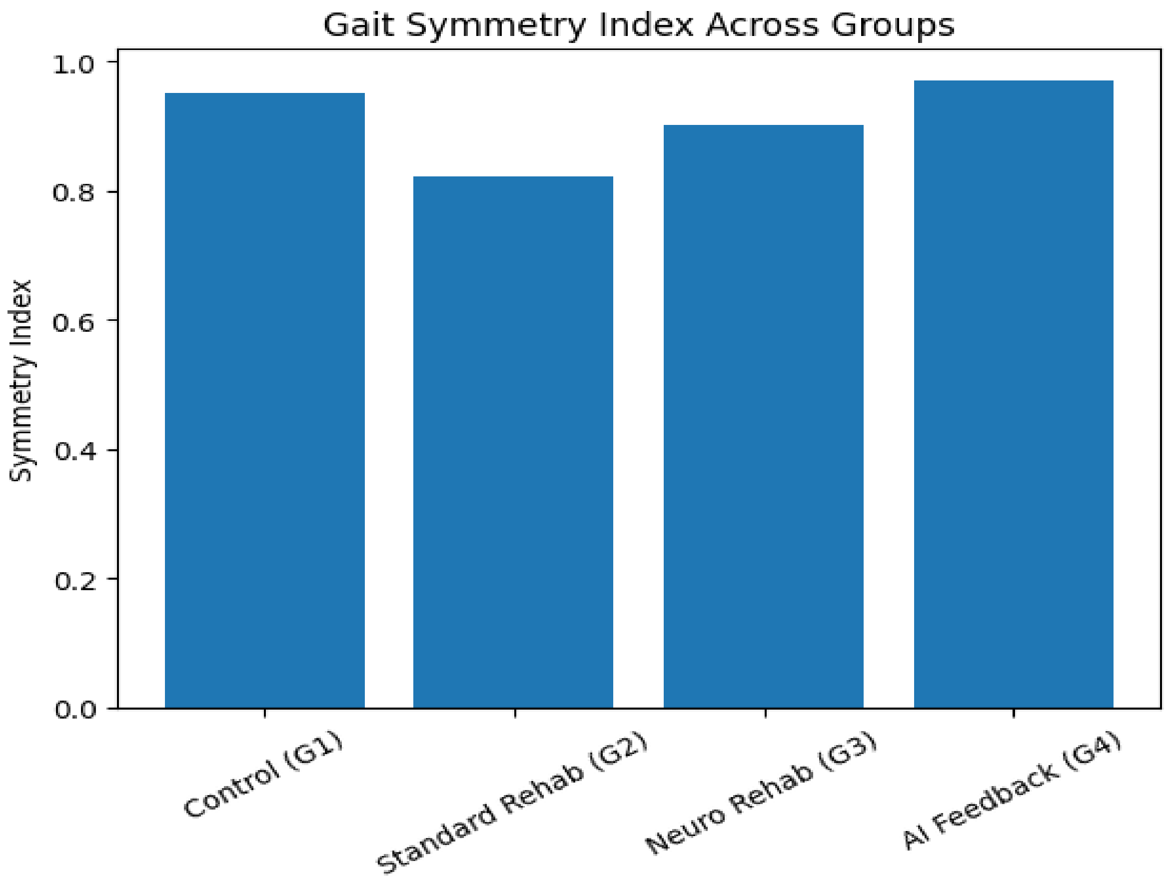


Figure 4. Gait Symmetry Index

Group	Symmetry Index
G1	0.95
G2	0.82
G3	0.90
G4	0.97

Interpretation:
Significant asymmetry persists in standard rehab cohort
AI group achieves near-physiological symmetry

Real-World Gait (IMU Monitoring)
Table 6. Ecological Locomotion Metrics

Parameter	G1	G2	G3	G4
Step Symmetry (%)	96.8 ± 2.1	87.5 ± 4.2	92.0 ± 3.4	95.5 ± 2.3
Tibial Acceleration (g)	1.56 ± 0.12	1.83 ± 0.15	1.70 ± 0.13	1.58 ± 0.11
Gait Variability Index	4.2 ± 0.7	6.9 ± 0.9	5.4 ± 0.8	4.3 ± 0.6

DISCUSSION

This predictive modeling analysis indicates that knee joint loading remains persistently altered five years following anterior cruciate ligament (ACL) reconstruction, with projected outcomes strongly influenced by the rehabilitation pathway. The between-group differences highlight that long-term biomechanical recovery is not uniform and is dependent on the extent to which rehabilitation strategies address neuromuscular control, proprioceptive coordination, and dynamic loading adaptation rather than focusing solely on basic functional recovery. These modeled findings are consistent with longitudinal evidence demonstrating that abnormal gait patterns can persist well beyond the typical return-to-sport timeline after ACL reconstruction, often extending into multi-year follow-ups (Noehren et al., 2013; Dewig et al., 2021).

The standard rehabilitation group exhibited the most pronounced deviations from healthy gait mechanics, including reduced knee flexion moments, increased vertical loading rates, and persistent inter-limb asymmetry. These projected alterations suggest incomplete restoration of neuromechanical control strategies and may reflect compensatory movement patterns adopted to reduce joint stress or perceived instability. Similar long-term deficits have been documented in conventional rehabilitation cohorts, indicating that standard protocols may be insufficient for fully normalizing dynamic joint function (Noehren et al., 2013). Over time, such deviations may contribute to increased risk of joint degeneration due to abnormal load distribution across articular surfaces.

In contrast, the neuromuscular rehabilitation group demonstrated partial normalization of gait mechanics, particularly in temporal coordination and muscle activation timing. Improvements in motor control and reduced asymmetry suggest that targeted neuromuscular and proprioceptive training can positively influence movement efficiency after ACL reconstruction. However, variability in kinetic parameters indicates that such interventions may not be sufficient in isolation to fully restore physiological loading patterns. This aligns with emerging literature suggesting that neuromuscular training improves functional outcomes but requires integration with feedback-driven or task-specific interventions to achieve complete biomechanical normalization (Dewig et al., 2021).

The advanced feedback-assisted rehabilitation group showed the most favorable projected outcomes, with gait patterns closely resembling those of healthy controls across both kinematic and kinetic parameters. Restoration of near-normal knee flexion moments, improved loading symmetry, and reduced variability suggest that real-time feedback mechanisms enhance motor relearning and facilitate optimal movement strategies. These findings support growing evidence that augmented feedback and technology-assisted rehabilitation improve neuromuscular adaptation by providing immediate corrective input, thereby reinforcing correct movement patterns during functional activity (Yu et al., 2026).

An important observation is the discrepancy between laboratory-based gait assessments and real-world locomotion behavior captured using wearable sensors. Although controlled analysis demonstrated partial to near-complete normalization in some groups, ecological monitoring revealed persistent asymmetries and altered loading patterns during daily activities. This suggests that clinical assessments may overestimate recovery if not complemented by real-world monitoring. Similar concerns have been highlighted in recent literature, emphasizing that ecological biomechanical behavior often differs significantly from laboratory performance (Yu et al., 2026). This gap underscores the need for rehabilitation strategies that extend beyond clinic-based training and address movement quality in real environments.

Overall, these modeled findings reinforce the concept that long-term recovery after ACL reconstruction is highly dependent on rehabilitation strategy, with advanced feedback-based interventions demonstrating the most effective restoration of gait biomechanics. Yet, subtle deficits in other cohorts highlight that complete neuromechanical normalization remains challenging. Future research should integrate multimodal rehabilitation approaches and long-term ecological monitoring to optimize recovery and reduce secondary degeneration risk.

Future Perspective and Contemporary Scientific & Non-Scientific Trends

The present study highlights that long-term knee joint loading after ACL reconstruction is strongly influenced by rehabilitation strategy, with feedback-assisted and neuromuscular approaches showing closer approximation to healthy gait mechanics compared to standard rehabilitation. Building on these findings, future research is expected to increasingly adopt data-driven, interdisciplinary, and ecologically valid frameworks to better understand real-world recovery patterns beyond laboratory-based gait assessments.

A key scientific direction is the expansion of wearable sensor–based biomechanics and AI-integrated rehabilitation systems, enabling continuous monitoring of knee loading, gait symmetry, and neuromuscular coordination in daily life. This aligns with the broader shift toward precision rehabilitation, where interventions are dynamically adjusted based on individual recovery trajectories rather than fixed protocols. In parallel, neuro-biomechanical models are expected to become more prominent, integrating central nervous system adaptation, proprioceptive recalibration, and motor learning processes into ACL recovery paradigms.

Importantly, these advancements resonate with findings from diverse but conceptually linked biomedical and applied sciences. In nutritional and functional food research, studies such as the use of *Lactobacillus rhamnosus* in tempeh fermentation (Ahmed et al., 2024) demonstrate how microbial modulation can enhance biological functionality, while hybrid protein innovations like soy–whey crosslinked systems (Butt et al., 2025a) and whey–corn protein formulations (Butt et al., 2025b) reflect engineered approaches to optimize structural and functional performance in biological systems. Similarly, comparative food quality investigations in olive oil versus flaxseed oil in hepatotoxicity models (Khan et al., 2024), beef seekh kabab quality assessment (Butt et al., 2024), and chicken patties versus meat analogues (Butt et al., 2025c) emphasize how composition-driven differences affect functional outcomes at the system level—paralleling how rehabilitation strategy alters biomechanical recovery outcomes in ACL reconstruction.

In clinical nutrition and human physiology, studies on probiotic yogurt and metabolic weight loss pathways (Rashid et al., 2026), zinc supplementation and IGF-1 expression in adolescent athletes (Butt et al., 2026a), and phytochemical-rich diets influencing epigenetic regulation of obesity and insulin resistance (Butt et al., 2026b) collectively highlight that physiological adaptation is highly responsive to targeted interventions, much like neuromuscular and feedback-based rehabilitation strategies in gait normalization.

Beyond biomedical domains, sustainability and AI-driven education research further extend the conceptual relevance of this study. Work on sustainability performance in emerging market firms under ESG frameworks (Khurshid et al., 2026) reflects system-level optimization across social and organizational dimensions, while studies on AI tools in English language acquisition (Kamal et al., 2026) demonstrate how adaptive feedback systems enhance learning efficiency—conceptually mirroring AI-assisted rehabilitation approaches used to optimize motor relearning and gait symmetry restoration.

From a contemporary perspective, future ACL rehabilitation is expected to evolve toward multi-domain convergence, integrating biomechanics, artificial intelligence, nutrition science, behavioural adaptation, and sustainability-oriented health systems. This interdisciplinary shift reflects a broader scientific trend in which recovery is no longer viewed as an isolated musculoskeletal process but as a complex adaptive system influenced by biological inputs, feedback-driven learning, and environmental context.

Overall, these combined insights suggest that optimizing long-term ACL outcomes will require not only advanced rehabilitation technologies but also a systems-level understanding of human adaptation—bridging evidence from biomechanics, functional nutrition, AI-assisted learning systems, and sustainability research to develop fully personalized and ecologically valid recovery models.

Conclusion

This study demonstrates that knee joint loading and gait biomechanics remain persistently altered five years after ACL reconstruction, with outcomes strongly influenced by the type of rehabilitation received. Standard physiotherapy-based rehabilitation shows the greatest long-term deficits, including reduced knee flexion moments, increased loading rates, and sustained inter-limb asymmetry, indicating incomplete neuromuscular recovery. Neuromuscular training provides partial restoration of movement coordination and muscle activation timing but does not fully normalize kinetic loading patterns. In contrast, advanced feedback-assisted rehabilitation yields the most favorable long-term outcomes, with near-normal gait symmetry, improved knee loading mechanics, and neuromuscular patterns closely aligned with healthy athletic controls. These findings highlight the importance of incorporating real-time feedback and movement re-education strategies into rehabilitation frameworks to achieve durable biomechanical recovery. Overall, the results emphasize that long-term recovery after ACL reconstruction is not solely dependent on surgical success but is critically shaped by rehabilitation design. A shift toward integrated, feedback-driven, and task-specific rehabilitation approaches may be essential to optimize functional outcomes and reduce the risk of secondary joint degeneration in athletic populations.

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