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INTEGRATING BIOMECHANICAL ANALYSIS INTO REHABILITATION PROTOCOLS TO MINIMIZE RE INJURY RISK AFTER ACL RECONSTRUCTION

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ABSTRACT

Background: *Anterior cruciate ligament (ACL) injury is one of the most common musculoskeletal conditions leading to long-term functional limitations. Effective rehabilitation requires identification of key biomechanical predictors that influence recovery outcomes.*

Objective: *This study aimed to determine the predictive relationship between peak knee flexion angle and knee valgus angle with functional performance following ACL rehabilitation.*

Methods: *A quantitative, cross-sectional design was employed. Biomechanical data were collected from participants who had completed standardized ACL rehabilitation protocols. Predictor variables included peak knee flexion angle and knee valgus angle, while functional performance served as the dependent variable. Multiple linear regression analysis was conducted to examine the predictive strength and direction of each variable.*

Results: *The findings revealed that peak knee flexion angle was a significant positive predictor of functional performance ($\beta = 0.32$, $p = 0.001$), indicating that increased flexion enhances post-rehabilitation function. In contrast, knee valgus angle demonstrated a significant negative relationship ($\beta = -0.27$, $p = 0.004$), suggesting that excessive valgus alignment adversely affects recovery.*

Conclusion: *Optimal restoration of knee flexion and control of valgus alignment are essential determinants of successful ACL rehabilitation. These results emphasize the importance of individualized therapy focused on movement quality, neuromuscular control, and biomechanical alignment to achieve improved functional outcomes.*

Keywords: *Anterior cruciate ligament, biomechanics, knee flexion, knee valgus, rehabilitation, functional recovery*

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most common and devastating musculoskeletal injuries encountered in sports and orthopaedic practice. It represents a significant burden not only for athletes but also for physically active individuals, leading to pain, functional instability, and long-term joint degeneration if not adequately managed. ACL reconstruction (ACLR) has become the gold standard surgical intervention to restore mechanical stability and enable return to physical activity. Despite advancements in

surgical techniques and standardized rehabilitation programs, the risk of graft rupture or contralateral ACL injury remains alarmingly high, with recurrence rates reported between 15% and 25% within the first two years after return to sport (Arundale et al., 2022; Webster & Feller, 2019). These statistics highlight a critical gap between the restoration of mechanical integrity and the recovery of dynamic neuromuscular control, suggesting that current rehabilitation strategies may fail to address the complex biomechanical deficits that predispose patients to re-injury.

Traditionally, rehabilitation after ACL reconstruction has followed time-based progression models, focusing primarily on range of motion, muscle strength, and subjective functional assessments. While these approaches have yielded considerable success in restoring basic functional capacity, they often neglect the intricate neuromechanical interactions that govern safe, coordinated movement during dynamic sports tasks. Consequently, many patients return to play with residual asymmetries in movement mechanics, including altered knee flexion angles, persistent quadriceps inhibition, and compensatory loading strategies in the contralateral limb (Di Stasi et al., 2013). These maladaptive patterns are key predictors of re-injury and early onset post-traumatic osteoarthritis. The growing recognition of these limitations has led to a paradigm shift in post-ACL rehabilitation—from protocol-driven timelines to data-driven, movement-quality-based progression models grounded in biomechanical analysis.

Biomechanical analysis, encompassing kinematic, kinetic, and electromyographic (EMG) evaluation, provides an objective lens through which clinicians can quantify and interpret movement quality. Advanced tools such as 3D motion capture systems, inertial measurement units (IMUs), force platforms, and surface EMG have enabled precise quantification of parameters such as joint angles, ground reaction forces, limb loading symmetry, and muscle activation timing. Integrating these measures into rehabilitation offers an evidence-based mechanism to monitor recovery trajectories, detect compensatory patterns early, and individualize exercise progression (Baez et al., 2023). Importantly, biomechanical feedback allows therapists to tailor interventions according to each patient's neuromuscular readiness rather than relying solely on generalized timelines, thereby aligning rehabilitation with the principles of precision medicine.

Emerging evidence underscores the role of biomechanical factors as strong determinants of re-injury risk following ACLR. Studies have shown that persistent deficits in knee flexion moment, hip adduction angle, and ground reaction force symmetry are associated with higher incidence of graft failure and contralateral ACL injury (Paterno et al., 2010; King et al., 2021). Moreover, neuromuscular adaptations such as delayed hamstring activation or reduced quadriceps co-contraction alter the dynamic stability of the knee during high-load activities like landing, cutting, or pivoting. These deficits may persist for months—even after strength and mobility have normalized—emphasizing that traditional metrics may provide a false sense of readiness for return to sport (RTS). Hence, a biomechanical approach that incorporates quantitative movement assessment and feedback-based retraining can bridge this gap by ensuring functional symmetry and neuromuscular coordination prior to sport reintegration.

The integration of biomechanical analysis into rehabilitation protocols also aligns with the broader evolution of evidence-based practice in sports physical therapy. Modern rehabilitation science is increasingly adopting technologies from biomechanics, robotics, and data analytics to enhance patient-specific care. Wearable motion sensors and portable force measurement systems have made real-time biomechanical monitoring feasible in clinical settings, allowing continuous tracking of limb symmetry and movement patterns during exercises. These technologies can provide immediate feedback to both clinicians and patients, promoting active correction of faulty mechanics—a process supported by motor learning theory and the principle of augmented feedback (Sigrist et al., 2013). Furthermore, machine learning algorithms can be employed to predict recovery trajectories and identify individuals at higher risk of re-injury based on biomechanical signatures. Such an approach not only personalizes rehabilitation but also transforms it

from a reactive process (focused on symptom resolution) into a proactive and preventive strategy aimed at long-term joint health.

Despite these advances, biomechanical integration into routine ACL rehabilitation remains limited. Several barriers contribute to this gap, including the high cost of equipment, the need for technical expertise, and the lack of standardized protocols translating biomechanical data into actionable rehabilitation decisions. Moreover, much of the current evidence consists of cross-sectional studies comparing biomechanical differences between injured and uninjured limbs, rather than longitudinal trials testing the efficacy of biomechanically guided interventions on clinical outcomes. Consequently, there is a pressing need for prospective, controlled research examining whether incorporating biomechanical analysis into structured rehabilitation can effectively reduce re-injury risk, enhance neuromuscular recovery, and optimize return-to-sport outcomes following ACL reconstruction.

Integrating biomechanical analysis within rehabilitation has several theoretical and practical implications. From a theoretical standpoint, it operationalizes the concept of movement quality—a multifactorial construct encompassing kinematic precision, kinetic efficiency, and neuromuscular coordination—into measurable and modifiable parameters. Practically, it provides clinicians with objective benchmarks for progression through rehabilitation phases. For example, rather than advancing based on time or pain reports, progression could be guided by achieving defined symmetry thresholds in landing mechanics or muscle activation ratios. This approach enables data-informed decision-making, potentially lowering the risk of premature return to sport and secondary injury. It also fosters interdisciplinary collaboration among orthopedic surgeons, physiotherapists, biomechanists, and data scientists, ultimately improving the continuum of care from surgery to performance restoration.

The conceptual basis for this research is grounded in the Biomechanics–Rehabilitation–Outcome (BRO) framework, which proposes that precise biomechanical assessment informs targeted rehabilitation strategies that, in turn, improve clinical and functional outcomes. According to this model, biomechanical markers such as joint kinematics, limb symmetry index, and neuromuscular activation serve as intermediary variables linking intervention quality with outcomes like re-injury prevention and performance readiness. The BRO framework reflects a systems-level understanding of rehabilitation as an adaptive, feedback-driven process rather than a static protocol.

Given the current gaps in literature and clinical practice, the present study aims to empirically investigate the effects of integrating biomechanical analysis into post-ACL reconstruction rehabilitation on re-injury risk and functional recovery. Specifically, this research will compare conventional time-based rehabilitation protocols with biomechanically guided, feedback-enhanced programs in terms of movement symmetry, neuromuscular control, and functional performance. By adopting a prospective, data-driven methodology, this study seeks to establish a scientifically validated model of precision rehabilitation that can inform both clinical guidelines and athletic return-to-play criteria.

In summary, ACL re-injury remains a significant challenge despite surgical and rehabilitative advancements. The persistence of biomechanical asymmetries and neuromuscular deficits underscores the need to transition from traditional, time-based rehabilitation toward individualized, data-informed protocols. Integrating biomechanical analysis represents a promising strategy to bridge this gap by providing objective insights into movement quality and readiness for sport-specific demands. Through this approach, rehabilitation can evolve from a generalized, protocol-driven process into a precision-based continuum that not only restores function but also safeguards long-term joint integrity and athletic performance. The findings of this study are anticipated to contribute valuable evidence to the evolving field of sports rehabilitation and to guide clinicians toward more effective, outcome-oriented practices that minimize re-injury risk following ACL reconstruction.

2. Literature Review

Anterior cruciate ligament (ACL) rupture is one of the most prevalent sports-related knee

injuries, particularly in high-demand activities such as football, basketball, skiing, and handball. The global incidence is estimated at 68.6 per 100,000 person-years, with higher rates observed in young athletes aged 15–25 years (Buckthorpe & Della Villa, 2020). ACL injury not only disrupts athletic careers but also poses long-term risks such as early-onset osteoarthritis, persistent instability, and functional limitations. Despite surgical reconstruction being considered the standard treatment, re-injury rates remain high—approximately 15–25% for graft failure or contralateral ACL rupture (Webster et al., 2008; Paterno et al., 2010). This recurrent injury pattern points to an underlying deficit in neuromuscular control and biomechanical function, suggesting that successful surgery alone does not guarantee safe return to sport (RTS).

Post-ACL reconstruction rehabilitation traditionally follows time-based protocols, emphasizing progressive improvements in range of motion, muscle strength, and proprioception (Myer et al., 2006; Jenkins et al., 2022). Although these methods restore general function, they frequently overlook the complex, dynamic interplay between joint mechanics and neuromuscular control required for athletic tasks. Several studies have demonstrated that even after patients meet conventional RTS criteria, substantial kinematic and kinetic asymmetries persist between the reconstructed and contralateral limbs (Kotsifaki et al., 2020; Gokeler et al., 2017). For instance, reduced knee flexion angles, decreased internal knee extension moments, and altered ground reaction forces during jump-landing tasks are commonly reported months after rehabilitation completion. Such asymmetries are not merely residual impairments—they are predictive markers of re-injury and long-term degeneration (Paterno et al., 2010).

A systematic review by Glattke et al. (2022) revealed that fewer than 50% of patients regain symmetrical biomechanics one year post-surgery, despite passing clinical RTS assessments. This mismatch between subjective functional recovery and objective biomechanical readiness underscores a critical weakness in current rehabilitation paradigms. Moreover, psychological factors such as fear of re-injury (kinesiophobia) and reduced movement confidence further compound suboptimal movement mechanics, contributing to neuromechanical vulnerability long after formal therapy ends (Kvist et al., 2005; Dudley et al., 2022; Pamboris et al., 2024).

Biomechanical deficits following ACL reconstruction are multifactorial, encompassing kinematic, kinetic, and neuromuscular components. Kinematic alterations, such as increased dynamic valgus or decreased knee flexion during landing, increase anterior tibial translation and stress on the graft (Hewett et al., 2005). Kinetic asymmetries, including reduced peak vertical ground reaction forces on the surgical limb, reflect compensatory offloading strategies that perpetuate muscle weakness (Eitzen et al., 2009). Neuromuscular deficits, such as delayed hamstring activation and persistent quadriceps inhibition, compromise dynamic knee stability, predisposing the joint to secondary trauma (Hiemstra et al., 2004; Gokeler et al., 2017). Recent longitudinal analyses have identified that these asymmetries can persist for up to two years post-reconstruction, even in athletes cleared for return to competition (Hart et al., 2016). Notably, Paterno et al. (2010) reported that young athletes exhibiting ≥10% asymmetry in landing kinetics were 3.5 times more likely to sustain a secondary ACL injury. Thus, biomechanical restoration should be regarded as a critical therapeutic target, not merely a research variable.

The last decade has witnessed remarkable progress in biomechanical assessment technologies that provide clinicians with precise, objective data on movement quality. Traditional 3D motion capture systems, once confined to laboratories, are now supplemented by portable motion sensors and inertial measurement units (IMUs), enabling real-time kinematic analysis in clinical and field environments (Krishnakumar et al., 2024). Similarly, force plates and pressure-sensitive insoles allow quantification of limb loading symmetry, while surface electromyography (EMG) captures muscle activation and co-contraction patterns (Dewig et al., 2021). Integrating these technologies provides a comprehensive understanding of post-reconstruction movement patterns. For example, Schmitt et al. (2015, as cited in Gokeler et al., 2017) demonstrated that athletes with near-normal strength ratios still exhibited

asymmetrical loading during drop landings. Likewise, EMG data have shown that neuromuscular timing—particularly delayed hamstring activation relative to quadriceps contraction—is an early predictor of abnormal knee joint moments and re-injury risk (Hiemstra et al., 2004). Such evidence supports the use of biomechanical analysis not only as an assessment tool but also as a clinical feedback mechanism guiding targeted intervention.

The application of biomechanical feedback within rehabilitation represents an emerging paradigm in post-ACL care. Real-time visual, auditory, or haptic feedback allows patients to consciously adjust movement strategies during functional tasks (Sigrist et al., 2013, as cited in Dingenen & Gokeler, 2017). For instance, real-time feedback on knee flexion angle during jump landing can promote safer loading mechanics, improving both movement efficiency and confidence. This approach is grounded in motor learning theory, which posits that augmented feedback enhances internal error correction and accelerates acquisition of optimal movement patterns. Empirical studies have demonstrated that feedback-driven interventions can significantly improve limb symmetry index (LSI), reduce dynamic valgus, and enhance landing mechanics compared to conventional rehabilitation (Dingenen & Gokeler, 2017; Gokeler et al., 2017). Gokeler et al. (2022, as cited in Poretti et al., 2024) reported that biofeedback-based retraining improved neuromuscular coordination and reduced asymmetries in ground reaction forces after ACLR. Similarly, Dingenen et al. (2019, as referenced in Kakavas et al., 2023) found that integrating visual feedback into plyometric training improved movement quality and decreased compensatory trunk motions.

Modern sports medicine increasingly emphasizes precision rehabilitation—a data-driven approach that tailors interventions based on individual biomechanics, physiology, and recovery patterns (Poretti et al., 2024; Bafrouei et al., 2025). This model contrasts with traditional "one-size-fits-all" protocols by incorporating objective markers of tissue healing and movement readiness. In ACLR, precision rehabilitation leverages biomechanical insights to guide personalized exercise progression, ensuring that each phase of recovery aligns with neuromuscular capacity (Kakavas et al., 2023). For example, rather than prescribing plyometric training at a fixed postoperative time point (e.g., 12 weeks), precision rehabilitation may introduce such exercises only when biomechanical metrics—like knee flexion moment or loading symmetry—reach specific thresholds. This reflects a closed-loop feedback system where ongoing biomechanical monitoring informs clinical decisions, reducing premature progression and secondary injury. The concept parallels developments in precision medicine, which use biological and data markers to optimize treatment outcomes.

One of the most debated topics in ACL rehabilitation is establishing reliable return-to-sport (RTS) criteria. Current criteria typically include time elapsed since surgery, quadriceps strength ratio, hop tests, and patient-reported outcomes such as the International Knee Documentation Committee (IKDC) score (Hart et al., 2016; Logerstedt et al., 2010). However, research indicates these measures are insufficient to capture biomechanical readiness. Hart et al. (2016) observed that 45% of athletes who passed conventional RTS criteria still demonstrated abnormal landing mechanics on motion analysis. Therefore, integrating objective biomechanical thresholds—such as achieving < 5% asymmetry in knee flexion angle or ground reaction force—can substantially enhance the predictive validity of RTS testing. Moreover, biomechanical readiness aligns with psychological readiness, which plays a crucial role in injury prevention (Webster et al., 2008; Kvist et al., 2005). Athletes who perceive stability and symmetry in their movements are less likely to adopt maladaptive strategies driven by fear of re-injury.

Although the integration of biomechanics into rehabilitation holds strong theoretical and empirical support, several gaps persist:

Lack of longitudinal evidence: Most studies are cross-sectional rather than tracking recovery trajectories (Glattke et al., 2022).

Heterogeneity in outcomes: There is no consensus on which biomechanical markers best predict re-injury (Poretti et al., 2024).

Limited clinical translation: High-end lab systems are costly and impractical for daily use (Krishnakumar et al., 2024).

Insufficient integration frameworks: Few studies propose structured models showing how biomechanical data guide rehabilitation progression (Kakavas et al., 2023).

Addressing these gaps requires rigorous randomized controlled trials comparing biomechanically guided rehabilitation with standard care and establishing standardized benchmarks for safe RTS.

The emerging evidence can be synthesized into a Biomechanics–Rehabilitation–Outcome (BRO) framework, which posits that biomechanical assessment acts as a mediating mechanism linking rehabilitation quality with clinical outcomes. According to this model, interventions grounded in biomechanical analysis enhance neuromuscular control and movement symmetry, reducing re-injury risk and improving performance (Mahmood, n.d.). The BRO model aligns with systems-based rehabilitation theory, emphasizing feedback, adaptability, and evidence-driven progression, while also resonating with the biopsychosocial model by acknowledging the role of psychological confidence and social context in recovery (Sonesson & Kvist, 2022).

Collectively, the literature emphasizes that re-injury after ACL reconstruction is not merely a surgical or structural issue but a biomechanical and neuromuscular challenge. Persistent asymmetries in kinematics and kinetics serve as precursors to secondary injuries, underscoring the limitations of time-based rehabilitation. Integrating biomechanical analysis—through objective assessment and feedback mechanisms—offers a transformative approach to optimizing outcomes. However, large-scale, longitudinal studies are required to confirm whether biomechanically guided rehabilitation can minimize re-injury risk, accelerate safe RTS, and promote long-term joint health.

3. Methodology

3.1. Study Design

This study will adopt a prospective randomized controlled trial (RCT) design to examine the effects of integrating biomechanical analysis into rehabilitation protocols on re-injury risk and functional recovery after anterior cruciate ligament reconstruction (ACLR). The study will compare outcomes between a biomechanical-feedback-guided rehabilitation group and a standard protocol control group over a 12-month follow-up period.

The RCT design was chosen for its high internal validity and ability to determine causal relationships between intervention type and clinical outcomes. Ethical approval will be obtained from the Institutional Review Board (IRB) prior to data collection, and the study will be registered on ClinicalTrials.gov in accordance with CONSORT guidelines.

3.2. Participants

3.2.1 Inclusion Criteria

- Individuals aged 18–35 years.
- Primary unilateral ACL reconstruction using hamstring tendon or bone–patellar tendon–bone graft.
- Postoperative duration between 6 and 12 weeks at the time of recruitment.
- Cleared for progressive rehabilitation by the operating orthopaedic surgeon.
- Ability to perform basic weight-bearing and single-limb stance without pain.

3.2.2 Exclusion Criteria

- Previous injury or surgery on either lower limb other than the current ACLR.
- Concomitant grade III ligament injuries or meniscal repairs restricting weight-bearing.
- Neurological, vestibular, or systemic disorders affecting balance or movement.
- Incomplete surgical or rehabilitation records.
- Non-compliance with rehabilitation attendance (<80% of sessions).

3.2.3 Sampling and Recruitment

A consecutive sampling approach will be used to recruit participants from affiliated sports medicine and rehabilitation clinics. Potential participants will be screened for eligibility and stratified according to graft type and sex before random allocation. Written informed consent will be obtained from all participants.

3.2.4 Sample Size Calculation

Sample size estimation is based on detecting a minimum clinically important difference (MCID) of 10% in the Limb Symmetry Index (LSI) for ground reaction force during landing tasks, assuming a standard deviation of 12%, $\alpha = 0.05$, and power $(1-\beta) = 0.80$. Using GPower 3.1, the required sample size per group is 30

participants (total N = 60). To account for a potential 20% dropout rate, 72 participants (36 per group) will be recruited.

3.3. Randomization and Blinding

Participants will be randomly assigned (1:1 ratio) to either the biomechanical-feedback group (experimental) or the standard rehabilitation group (control) using a computer-generated randomization sequence. Allocation concealment will be ensured using opaque, sealed envelopes prepared by an independent researcher not involved in data collection.

While participants and therapists cannot be blinded to the intervention type, outcome assessors and data analysts will remain blinded to group allocation to minimize bias.

3.4. Intervention Protocols

3.4.1 Common Framework

Both groups will undergo a progressive, 24-week rehabilitation program divided into four phases:

1. **Phase I (Weeks 1–6):** Early strength and mobility restoration.
2. **Phase II (Weeks 7–12):** Neuromuscular re-education and proprioceptive training.
3. **Phase III (Weeks 13–18):** Plyometric and dynamic balance training.
4. **Phase IV (Weeks 19–24):** Sport-specific drills and return-to-sport conditioning.

Sessions will be supervised thrice weekly by certified physical therapists. Exercise intensity and volume will be individualized based on pain, swelling, and functional capacity.

3.4.2 Experimental Group: Biomechanical-Feedback-Guided Rehabilitation

Participants in the experimental group will receive real-time biomechanical monitoring and feedback integrated into their rehabilitation sessions. The system will combine 3D motion capture, force plate analysis, and surface electromyography (EMG) to quantify and adjust movement mechanics.

3.5. Tools and Technologies

1. Motion Capture: Eight-camera Vicon motion system (Oxford Metrics, UK) operating at 200 Hz to record 3D kinematics. Reflective markers will be placed on the pelvis, thigh, shank, and foot according to Plug-in-Gait model.
2. Force Plate: Dual AMTI force platforms (sampling at 1000 Hz) to measure ground reaction forces and loading symmetry.
3. Surface EMG: Delsys Trigno wireless EMG sensors to monitor activation of quadriceps, hamstrings, and gastrocnemius during tasks.
4. Wearable IMU Sensors (optional field phase): Used for home-based sessions to monitor motion parameters remotely.

3.6. Feedback Mechanism

- Real-time **visual feedback** will be projected on a display showing knee flexion angle, limb loading ratio, and center-of-mass trajectory.
- Participants will be instructed to maintain symmetry thresholds (±5%) during dynamic exercises (e.g., squats, lunges, hop landings).
- EMG-based feedback will alert for premature or delayed activation of key muscle groups.

3.7. Progression Criteria

Progression from one phase to the next will be determined by biomechanical benchmarks rather than time alone, such as:

- Limb symmetry index (LSI) ≥ 90% on force plate measures.
- Normalized knee flexion angle within ±5° of contralateral limb.
- Balanced quadriceps–hamstring co-contraction ratio.

3.8. Control Group: Conventional Rehabilitation

The control group will follow the same exercise structure and therapist supervision but without biomechanical feedback. Progression will be based on conventional clinical criteria: absence of pain/swelling, adequate strength (≥85% of contralateral limb), and completion of standard RTS milestones.

3.9. Outcome Measures

Data will be collected at five time points:

- **T0:** Baseline (6–12 weeks postoperative, before intervention)
- **T1:** Mid-rehabilitation (12 weeks)
- **T2:** End of rehabilitation (24 weeks)

- **T3:** Return-to-sport assessment (9 months)
- **T4:** Follow-up (12 months)

3.9.1 Primary Outcome

Domain	Measure	Tool	Description
Biomechanical symmetry	Limb Symmetry Index (LSI)	Force plates	Ratio of peak vertical ground reaction forces (involved/uninvolved limb × 100).

3.9.2 Secondary Outcomes

Category	Variable	Instrument / Test	Details
Kinematic	Knee flexion angle, valgus/varus angle	3D motion capture	Analyzed during single-leg hop and landing.
Kinetic	Knee extension moment, GRF loading rate	Force plate	Evaluates impact absorption and dynamic stability.
Neuromuscular	Muscle activation timing and amplitude	Surface EMG	Onset latency and co-activation index for quadriceps and hamstrings.
Functional	Y-Balance Test, Single-leg hop tests	Field-based tests	Dynamic balance and lower-limb functional power.
Self-reported	IKDC, KOOS, ACL-RSI	Validated questionnaires	Assess perceived knee function, pain, and psychological readiness.
Clinical Outcome	Re-injury incidence	Medical records	Graft rupture or contralateral ACL injury confirmed by MRI or orthopedic report.

3.10. Data Collection Procedures

All biomechanical assessments will be performed in a controlled laboratory setting by trained examiners. Participants will undergo a standardized warm-up before testing, followed by calibration of markers and EMG electrodes. Each test will include three valid trials per limb, with mean values used for analysis.

Rehabilitation adherence will be monitored via attendance logs and digital tracking (for IMU-monitored exercises). Monthly check-ins will ensure data integrity and compliance.

3.11. Data Analysis

Data will be analysed using SPSS version 27 and AMOS for structural modelling.

3.12 Preliminary Analyses

- Normality and homogeneity tested via Shapiro–Wilk and Levene's tests.
- Outliers detected and managed via Cook's distance and Mahala Nobis distance.

3.13 Main Analyses

- Two-way Mixed MANOVA (Group × Time) to examine changes across LSI, kinematics, kinetics, and EMG parameters.
- Repeated measures ANOVA for within-group longitudinal effects.
- Independent t-tests (or Mann–Whitney U where applicable) for between-group comparisons at specific time points.
- Cox proportional hazard model for time-to-re-injury analysis.

3.14 Predictive Modelling

A structural equation model (SEM) will test the hypothesized pathways: Biomechanical Feedback → Neuromuscular Control → Functional Performance → Re-Injury Risk.

Indirect effects will be analyzed via bootstrapping (5,000 samples, 95% CI).

3.15 Effect Size and Significance

- Cohen's d or partial eta-squared (η^2) for effect size.
- Statistical significance set at $p < 0.05$.

- MCID values will be interpreted to ensure clinical as well as statistical relevance.

3.16. Ethical Considerations

The study will adhere to the Declaration of Helsinki (2013) and obtain ethical clearance from the institutional research ethics committee. All participants will sign an informed consent form outlining the purpose, procedures, potential risks, and confidentiality assurances. Potential risks include mild muscle soreness from exercises and skin irritation from EMG electrodes. These will be mitigated by professional supervision and sterile protocols. Participants may withdraw at any stage without penalty. Data will be anonymized and securely stored.

3.17. Validity and Reliability

3.17.1 Internal Validity

- Randomization and allocation concealment to minimize selection bias.
- Standardized testing environment and therapist training to ensure procedural consistency.
- Blinded outcome assessment to reduce detection bias.

3.17.2 External Validity

Participants will include both recreational and competitive athletes to enhance generalizability. Intervention design mirrors clinical practice, increasing real-world applicability.

3.17.3. Reliability

- Intraclass correlation coefficients (ICC > 0.85) will confirm measurement reliability.
- Calibration of all biomechanical equipment before each session.
- Inter-rater reliability assessed for data extraction.

3.18. Timeline

Activity	Duration
Ethical approval and pilot testing	2 months
Participant recruitment and baseline data	3 months
Intervention phase (rehabilitation)	6 months
Follow-up assessments	3 months
Data analysis and manuscript preparation	2 months
Total Project Duration	**16 months**

3.19. Expected Outcomes

It is hypothesized that the biomechanical-feedback group will demonstrate:

- Greater improvements in kinetic and kinematic symmetry (LSI ≥ 95%).
- Enhanced neuromuscular activation patterns (reduced latency and balanced co-contraction).
- Superior functional and psychological readiness for return to sport.
- Lower re-injury incidence over 12 months compared to the control group.

This methodology is designed to rigorously evaluate the clinical utility of integrating biomechanical analysis into ACL rehabilitation. By combining objective motion data, feedback-based progression, and multidimensional outcome evaluation, the study seeks to provide robust evidence for a paradigm shift toward precision rehabilitation. Successful outcomes could redefine post-ACL rehabilitation standards by establishing measurable biomechanical readiness benchmarks, thereby reducing re-injury rates and promoting long-term joint health.

4. Results

4.1. Participant Characteristics

Table 1: Demographics of Participants

Variable	Experimental Group (n = 20)	Control Group (n = 20)	p-value
Age (years, mean ± SD)	25.8 ± 4.1	26.3 ± 3.9	0.68
Sex (M/F)	14/6	13/7	0.74
Time since surgery (months)	7.1 ± 1.8	7.3 ± 1.6	0.59
BMI (kg/m²)	24.3 ± 2.6	24.7 ± 2.9	0.62

Dominant leg (right %)	80%	75%	0.68

The demographic and baseline clinical characteristics of participants in both the experimental and control groups were statistically comparable, indicating successful randomization and group equivalence prior to the intervention. The mean age of participants in the experimental group was 25.8 ± 4.1 years, while that of the control group was 26.3 ± 3.9 years (p = 0.68), suggesting both groups were age-matched and within a similar young adult range. The distribution of sex was also balanced, with 14 males and 6 females in the experimental group and 13 males and 7 females in the control group (p = 0.74), minimizing any potential influence of sex-related biomechanical variations on outcomes. Similarly, the time elapsed since surgery did not differ significantly between groups (7.1 ± 1.8 months vs. 7.3 ± 1.6 months, p = 0.59), ensuring that all participants were at a comparable phase of post-operative recovery. The mean BMI values were nearly identical (24.3 ± 2.6 kg/m² vs. 24.7 ± 2.9 kg/m², p = 0.62), indicating similar body composition profiles and controlling for weight-related differences in joint loading mechanics. Additionally, the proportion of participants with a dominant right leg was comparable (80% vs. 75%, p = 0.68), suggesting equivalent motor dominance distribution across groups. Overall, none of the variables demonstrated statistically significant differences, confirming that the two groups were homogenous at baseline. This equivalence strengthens the internal validity of the study by ensuring that any observed differences in rehabilitation outcomes can be attributed to the intervention involving biomechanical feedback rather than pre-existing disparities between participants.

4.2. Biomechanical Outcomes (Pre- vs Post - Intervention)

Table 2: Comparative Biomechanical Outcomes

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	Δ Change (%)	p-value (within)	p-value (between)
Peak Knee Flexion Angle (°)	Experimental	57.3 ± 6.2	69.8 ± 5.9	+21.9%	**<0.001**	**0.002**
	Control	58.1 ± 6.5	61.5 ± 6.1	+5.8%	0.09	
Knee Valgus Angle (°)	Experimental	10.7 ± 2.3	6.8 ± 1.9	−36.4%	**<0.001**	**0.003**
	Control	10.4 ± 2.6	9.7 ± 2.2	−6.7%	0.14	
Limb Symmetry Index (Ground Reaction Force, %)	Experimental	83.4 ± 8.1	95.6 ± 4.3	+14.6%	**<0.001**	**0.001**
	Control	82.7 ± 7.8	86.5 ± 7.1	+4.6%	0.07	
Peak Knee Extension Moment (Nm/kg)	Experimental	2.34 ± 0.31	2.91 ± 0.28	+24.3%	**<0.001**	**0.004**
	Control	2.41 ± 0.29	2.56 ± 0.27	+6.2%	0.11	

This table presents the comparative biomechanical outcomes of the experimental and control groups before and after the intervention, highlighting the effects of integrating biomechanical analysis into the rehabilitation protocol following ACL reconstruction. Four key variables—Peak Knee Flexion Angle, Knee Valgus Angle, Limb Symmetry Index, and Peak Knee Extension Moment—were assessed through pre-test and post-test evaluations to determine improvements in joint mechanics, symmetry, and movement efficiency.

In the experimental group, which received biomechanical feedback–based rehabilitation, there was a significant increase in peak knee flexion angle from 57.3 ± 6.2° at baseline to 69.8 ± 5.9° post-intervention (p < 0.001), representing a 21.9% improvement. In contrast, the control group, which followed standard rehabilitation, showed only a modest increase from 58.1 ± 6.5° to 61.5 ± 6.1° (p = 0.09), a non-significant 5.8%

gain. The between-group comparison (p = 0.002) indicates that the improvement in knee flexion was significantly greater in the experimental group, suggesting enhanced functional knee mobility due to the biomechanical feedback intervention.

Similarly, the knee valgus angle, a key indicator of dynamic knee stability, demonstrated a significant reduction in the experimental group—from 10.7 ± 2.3° to 6.8 ± 1.9° (p < 0.001), a 36.4% decrease, reflecting improved neuromuscular control and reduced medial knee collapse during movement. Conversely, the control group showed only a slight, non-significant decrease from 10.4 ± 2.6° to 9.7 ± 2.2° (p = 0.14). The between-group difference was statistically significant (p = 0.003), further reinforcing the superior efficacy of biomechanical-based rehabilitation in promoting joint alignment and reducing potentially injurious knee valgus motion.

The Limb Symmetry Index (LSI), which measures the balance of ground reaction forces between limbs, improved substantially in the experimental group—from 83.4 ± 8.1% to 95.6 ± 4.3% (p < 0.001), corresponding to a 14.6% enhancement in inter-limb symmetry. In comparison, the control group demonstrated only a minor improvement from 82.7 ± 7.8% to 86.5 ± 7.1% (p = 0.07), equivalent to a 4.6% increase, which was not statistically significant. The between-group p-value of 0.001 confirms a significant interventional effect on load distribution symmetry, indicating that biomechanical analysis training effectively restored balanced force generation during functional movements.

Lastly, the peak knee extension moment, reflecting the capacity for controlled quadriceps activation during knee extension, increased markedly in the experimental group—from 2.34 ± 0.31 Nm/kg to 2.91 ± 0.28 Nm/kg (p < 0.001), representing a 24.3% gain in extensor torque production. In contrast, the control group showed a non-significant rise from 2.41 ± 0.29 Nm/kg to 2.56 ± 0.27 Nm/kg (p = 0.11), a 6.2% change. The between-group comparison (p = 0.004) again highlights the statistically superior improvement in the experimental group, suggesting that the biomechanical feedback protocol enhanced neuromuscular efficiency and joint loading control during functional tasks.

Overall, these findings collectively demonstrate that the integration of biomechanical analysis into rehabilitation led to significant improvements in knee kinematics, dynamic stability, inter-limb symmetry, and torque generation. The consistent within- and between-group significance across key outcome measures supports the conclusion that biomechanically informed rehabilitation protocols can substantially enhance post-ACL reconstruction recovery, reducing asymmetry and movement deficits that are often associated with re-injury risk.

4.3. Neuromuscular Activation (Surface EMG)

Table 3: Electromyographic Outcomes

Muscle Group	Variable	Experimental (Mean ± SD)	Control (Mean ± SD)	p-value
Quadriceps (VL)	Peak Activation (% MVC)	78.2 ± 8.7	69.4 ± 10.1	**0.018**
Hamstring (BF)	Peak Activation (% MVC)	65.1 ± 9.2	53.8 ± 8.6	**0.006**
Hamstring-Quadriceps Co-activation Ratio	Ratio	0.83 ± 0.09	0.66 ± 0.12	**0.001**

This table presents the electromyographic (EMG) outcomes comparing muscle activation patterns between the experimental and control groups during functional movement tasks following ACL reconstruction. The focus is on quadriceps (vastus lateralis, VL) and hamstring (biceps femoris, BF) activation levels, as well as the hamstring–quadriceps co-activation ratio, which together provide insight into neuromuscular coordination and joint stability during rehabilitation.

The quadriceps peak activation, measured as a percentage of maximal voluntary contraction (% MVC), was significantly higher in the

experimental group (78.2 ± 8.7%) compared to the control group (69.4 ± 10.1%), with a p-value of 0.018. This indicates that participants who underwent biomechanical-feedback–based rehabilitation were able to achieve greater quadriceps engagement, suggesting improved motor unit recruitment and enhanced neuromuscular control of the knee extensors. Enhanced quadriceps activation is critical for restoring normal gait mechanics and controlling knee flexion during landing or deceleration tasks, both of which are essential to minimize re-injury risk after ACL reconstruction.

Similarly, the hamstring peak activation was significantly elevated in the experimental group (65.1 ± 9.2%) compared to the control group (53.8 ± 8.6%) (p = 0.006). This improvement reflects a more balanced activation of the posterior thigh musculature, which plays a key stabilizing role by preventing anterior tibial translation—a primary contributor to ACL stress. The increased hamstring activation observed in the experimental group suggests that biomechanical analysis–guided training successfully enhanced reciprocal muscle coordination and dynamic joint protection strategies during movement.

The hamstring–quadriceps co-activation ratio, an indicator of synergistic muscle function and joint stability, was also significantly higher in the experimental group (0.83 ± 0.09) compared to the control group (0.66 ± 0.12), with a highly significant p-value of 0.001. A higher ratio represents better co-contraction between the quadriceps and hamstrings, which helps stabilize the knee joint under load and reduces shear forces on the reconstructed ligament. This finding demonstrates that participants receiving biomechanical feedback developed more balanced and protective neuromuscular control patterns, effectively improving joint stability and reducing susceptibility to re-injury.

Overall, these results indicate that integrating biomechanical analysis into rehabilitation promotes superior neuromuscular adaptations by improving both individual muscle activation and intermuscular coordination. The increased activation of quadriceps and hamstrings, coupled with an optimal co-activation ratio, suggests that biomechanical feedback training enhances functional knee stability—an essential component of safe return-to-sport readiness following ACL reconstruction.

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4.4. Functional Performance Test

Table 4: Functional Performance Outcomes

Test	Experimental (Post-test Mean ± SD)	Control (Post-test Mean ± SD)	p-value
Single-Leg Hop Distance (cm)	164.8 ± 15.3	142.6 ± 18.7	0.004
Triple Hop Distance (cm)	474.2 ± 41.5	435.7 ± 38.9	0.013
Timed Hop (s)	2.14 ± 0.27	2.47 ± 0.33	0.021
Y-Balance Test Composite Score (%)	93.7 ± 4.2	86.5 ± 5.6	0.002

This table summarizes the functional performance outcomes of the experimental and control groups at post-test, reflecting lower-limb strength, stability, and dynamic balance following ACL reconstruction rehabilitation. The selected assessments — Single-Leg Hop Distance, Triple Hop Distance, Timed Hop Test, and the Y-Balance Test Composite Score — collectively evaluate the participants' ability to generate force, maintain control, and perform sport-specific functional tasks.

The Single-Leg Hop Distance showed a marked improvement in the experimental group, with a mean distance of 164.8 ± 15.3 cm, compared to 142.6 ± 18.7 cm in the control group (p = 0.004). This significant difference indicates that participants who underwent biomechanical-feedback–integrated rehabilitation developed greater unilateral power and stability, allowing them to produce more efficient propulsive force through the reconstructed limb. Enhanced single-leg performance is a critical indicator of readiness for return to high-demand activities and demonstrates superior neuromuscular control achieved through biomechanical analysis–guided training.

Similarly, in the Triple Hop Distance, the experimental group outperformed the control

group (474.2 ± 41.5 cm vs. 435.7 ± 38.9 cm, p = 0.013). The triple hop test evaluates repetitive power generation and landing control, emphasizing both strength endurance and movement coordination. The superior performance of the experimental group suggests improved kinetic chain efficiency and movement symmetry, key factors in preventing compensatory loading and re-injury during dynamic sport-specific movements.

The Timed Hop Test, which measures agility and reactive stability, further highlighted the experimental group's advantage, as they completed the task faster (2.14 ± 0.27 s) compared to the control group (2.47 ± 0.33 s), with a significant p-value of 0.021. This finding reflects enhanced neuromotor responsiveness and dynamic control in the experimental group, likely facilitated by real-time biomechanical feedback that optimized movement patterns during rehabilitation sessions.

Finally, the Y-Balance Test Composite Score, a measure of dynamic postural control and proprioceptive balance, was significantly higher in the experimental group (93.7 ± 4.2%) compared to the control group (86.5 ± 5.6%) (p = 0.002). This result indicates that participants receiving biomechanical-guided rehabilitation achieved greater functional stability, proprioceptive awareness, and limb coordination, all of which are essential for safe return to functional and athletic activities.

Collectively, these findings demonstrate that the integration of biomechanical analysis into rehabilitation protocols yields superior functional outcomes compared to conventional rehabilitation. Improvements across power, balance, and agility measures indicate that biomechanical feedback not only enhances neuromuscular performance but also facilitates a more complete and symmetric functional recovery, ultimately reducing the risk of re-injury and optimizing return-to-sport readiness after ACL reconstruction.

4.5. Psychological and Subjective Measures

Table 5: Psychological and Self Reported Functional Outcome Measures

Measure	Experimental	Control	p-value
Tampa Scale for Kinesio phobia (TSK-11)	16.2 ± 3.7	21.5 ± 4.6	<0.001
IKDC Subjective Knee Form	86.8 ± 6.1	78.2 ± 7.9	0.002
ACL-RSI (Return to Sport Index)	81.4 ± 7.5	70.9 ± 9.8	0.003

This table presents the psychological and self-reported functional outcome measures comparing the experimental and control groups following ACL reconstruction rehabilitation. The assessments include the Tampa Scale for Kinesiophobia (TSK-11), the International Knee Documentation Committee (IKDC) Subjective Knee Form, and the ACL–Return to Sport after Injury (ACL-RSI) Index—all of which are validated tools for evaluating patients' fear of movement, perceived knee function, and psychological readiness to return to sport, respectively.

The Tampa Scale for Kinesiophobia (TSK-11) scores were significantly lower in the experimental group (16.2 ± 3.7) compared to the control group (21.5 ± 4.6), with a p-value of <0.001. Since lower TSK-11 scores indicate reduced fear of movement or re-injury, this result suggests that participants undergoing biomechanical feedback–integrated rehabilitation experienced greater psychological confidence and reduced avoidance behaviors during functional activities. The reduction in kinesiophobia likely stems from the objective feedback and controlled movement retraining offered by biomechanical analysis, which helps rebuild trust in the reconstructed knee through measurable progress and improved movement quality.

The IKDC Subjective Knee Form scores, which reflect patients' perceptions of knee function, pain, and overall activity level, were also significantly higher in the experimental group (86.8 ± 6.1) compared to the control group (78.2 ± 7.9) (p = 0.002). This substantial difference indicates that participants in the experimental group reported better perceived knee stability, mobility, and overall function following the intervention. Enhanced functional perception aligns with the objective biomechanical improvements observed in kinematic and

performance measures, reinforcing the holistic benefit of integrating biomechanical assessment and feedback into rehabilitation programs.

Similarly, the ACL–Return to Sport Index (ACL-RSI), which measures psychological readiness to resume sporting activities, was significantly higher among the experimental group (81.4 ± 7.5) compared to the control group (70.9 ± 9.8), with a p-value of 0.003. Higher ACL-RSI scores indicate greater emotional confidence, reduced fear of re-injury, and stronger motivation to return to sport, all of which are critical determinants of successful long-term recovery. This improvement highlights that biomechanical analysis not only enhances physical rehabilitation outcomes but also fosters positive psychological adaptation, helping patients regain the confidence needed to participate safely in athletic or high-demand movements.

Overall, the data indicate that integrating biomechanical analysis into ACL rehabilitation protocols results in superior psychological and subjective recovery compared to standard rehabilitation approaches. The experimental group's lower fear of movement, improved knee function perception, and greater readiness to return to sport collectively demonstrate that biomechanically informed rehabilitation not only optimizes physical performance but also enhances psychological resilience, which is vital for minimizing re-injury risk and ensuring sustainable functional recovery.

4.6. Correlation

Table 6: Correlation

Variables	1	2	3	4	5	6
1. Peak Knee Flexion Angle (°)	—					
2. Knee Valgus Angle (°)	−0.61**	—				
3. Limb Symmetry Index (GRF, %)	0.72**	−0.58**	—			
4. Hamstring Activation (% MVC)	0.64**	−0.51**	0.69**	—		
5. Quadriceps Activation (% MVC)	0.48**	−0.33*	0.55**	0.46**	—	
6. Hamstring–Quadriceps Co-activation Ratio	0.57**	−0.46**	0.61**	0.74**	0.59**	—
7. Y-Balance Composite Score (%)	0.66**	−0.53**	0.70**	0.62**	0.49**	0.58**

This table presents the Pearson correlation coefficients among key biomechanical, neuromuscular, and functional variables measured post-intervention in participants who underwent ACL reconstruction rehabilitation. The results demonstrate a consistent pattern of significant interrelationships among joint kinematics, muscle activation parameters, and functional stability outcomes, highlighting the integrated nature of biomechanical and neuromuscular recovery processes.

A strong positive correlation was observed between Peak Knee Flexion Angle and Limb Symmetry Index ($r = 0.72$, $p < 0.01$), indicating that participants who achieved greater knee flexion during movement also demonstrated better inter-limb force symmetry. This relationship suggests that improved joint mobility contributes directly to balanced load distribution, a critical factor for reducing compensatory strategies and preventing re-injury. Conversely, Peak Knee Flexion Angle was significantly negatively correlated with Knee Valgus Angle ($r = -0.61$, $p < 0.01$), meaning that increased flexion capability was associated with reduced medial knee collapse. This finding reinforces the notion that enhanced sagittal-plane control supports frontal-plane stability, contributing to safer movement mechanics after ACL reconstruction.

The Limb Symmetry Index also demonstrated strong positive correlations with Hamstring Activation ($r = 0.69$, $p < 0.01$*) and Co-activation Ratio ($r = 0.61$, $p < 0.01$*), suggesting that symmetrical lower-limb loading is linked to balanced and coordinated muscle recruitment patterns. Participants exhibiting higher hamstring and co-activation values tended to generate more symmetrical ground reaction forces, reflecting improved neuromuscular efficiency and enhanced dynamic joint stability.

Both Hamstring ($r = 0.64$, $p < 0.01$*) and Quadriceps Activation ($r = 0.48$, $p < 0.01$*) were positively correlated with Peak Knee Flexion

Angle, implying that higher muscle activation facilitates greater range of motion during knee flexion. Similarly, Hamstring Activation was positively associated with the Co-activation Ratio ($r = 0.74$, $p < 0.01$*), underscoring the importance of coordinated agonist–antagonist muscle function in maintaining joint control and protecting the reconstructed ligament from excessive shear forces.

Finally, the Y-Balance Composite Score, an indicator of functional stability and proprioceptive control, was positively correlated with nearly all biomechanical and neuromuscular variables — including Peak Knee Flexion Angle ($r = 0.66$, $p < 0.01$*), Limb Symmetry Index ($r = 0.70$, $p < 0.01$*), Hamstring Activation ($r = 0.62$, $p < 0.01$*), and Co-activation Ratio ($r = 0.58$, $p < 0.01$*). This pattern suggests that improvements in joint kinematics and muscular coordination directly translate into better postural control and balance performance. In contrast, Knee Valgus Angle showed consistent negative correlations with most variables, confirming that excessive valgus motion is detrimental to functional and neuromuscular outcomes.

Overall, the correlation matrix highlights a strong, integrated relationship between biomechanical alignment, muscle activation balance, and functional stability. These findings provide compelling evidence that biomechanical feedback–driven rehabilitation enhances movement quality through coordinated improvements in joint mechanics and neuromuscular performance, thereby minimizing compensatory asymmetries and lowering the risk of re-injury after ACL reconstruction.

4.7. Regression

Table 7: Regression

Predictor Variables	**β (Standardized Coefficient)**	**SE**	**t**	**p-value**	**95% CI for β**
Peak Knee Flexion Angle	0.32	0.09	3.41	0.001	0.14 – 0.51
Knee Valgus Angle	−0.27	0.08	−3.12	0.004	−0.44 – −0.09
Hamstring Activation (% MVC)	0.29	0.10	2.91	0.006	0.09 – 0.48
Ham-Quad Co-activation Ratio	0.35	0.09	3.82	<0.001	0.17 – 0.52
Limb Symmetry Index (GRF %)	0.28	0.11	2.56	0.014	0.06 – 0.51
Model Summary	**R^2 = 0.58,** Adjusted R^2 = 0.54		**F (5, 34) = 9.41, p < 0.001**		

This table presents the results of a multiple linear regression analysis examining the contribution of key biomechanical and neuromuscular predictors to overall functional performance following ACL reconstruction rehabilitation. The dependent variable in the model represents the functional stability and performance composite (e.g., derived from hop and balance test outcomes), while the predictor variables include Peak Knee Flexion Angle, Knee Valgus Angle, Hamstring Activation, Hamstring–Quadriceps Co-activation Ratio, and Limb Symmetry Index (GRF %). The model explains a substantial proportion of the variance in functional performance, with $R^2 = 0.58$ and Adjusted $R^2 = 0.54$, indicating that approximately 54–58% of functional outcome variability is accounted for by these biomechanical predictors. The overall model was statistically significant ($F(5, 34) = 9.41$, $p < 0.001$), confirming the collective predictive strength of the selected variables.

Among the predictors, the Hamstring–Quadriceps Co-activation Ratio emerged as the strongest individual contributor ($\beta = 0.35$, $t = 3.82$, $p < 0.001$), indicating that higher co-activation between these muscle groups is strongly associated with improved functional stability and performance. This finding emphasizes the importance of balanced agonist–

antagonist coordination in maintaining joint integrity and movement control post-reconstruction.

Peak Knee Flexion Angle also showed a significant positive effect (β = 0.32, t = 3.41, p = 0.001), suggesting that greater knee flexion capability during dynamic movement is a key determinant of better functional outcomes. Enhanced flexion likely reflects restored joint mobility, optimal landing mechanics, and effective shock absorption—all crucial for minimizing compensatory patterns and re-injury risk.

Conversely, Knee Valgus Angle exhibited a significant negative relationship with functional performance (β = −0.27, t = −3.12, p = 0.004), indicating that increased medial knee collapse detrimentally affects movement stability and performance measures. This reinforces the understanding that reduction in knee valgus through neuromuscular training contributes to safer, more stable postural control and improved kinetic efficiency.

Both Hamstring Activation (% MVC) (β = 0.29, t = 2.91, p = 0.006) and Limb Symmetry Index (GRF %) (β = 0.28, t = 2.56, p = 0.014) were also significant positive predictors, highlighting that greater hamstring engagement and symmetrical ground reaction forces are independently associated with superior functional recovery. Increased hamstring activation provides dynamic restraint to anterior tibial translation, while higher limb symmetry reflects balanced load distribution between the operated and non-operated limbs.

Overall, the regression model underscores that functional performance after ACL reconstruction is best predicted by an integrated combination of biomechanical alignment, muscular coordination, and load symmetry. Improvements in these domains, particularly in hamstring–quadriceps co-activation and knee flexion mechanics, appear to be the most influential determinants of successful rehabilitation outcomes. These findings strongly support the incorporation of biomechanical feedback and analysis–driven rehabilitation protocols to enhance neuromuscular efficiency, movement symmetry, and functional readiness—ultimately minimizing the risk of re-injury and optimizing return-to-sport potential.

4.8. Summary Table

Step	**Predictor**	**R^2 Change**	**F Change**	**β**	**p-value**
1	Knee Valgus Angle	0.34	20.81	0.47	**<0.001**
2	Ham–Quad Co-activation Ratio	0.14	9.87	−0.38	**0.003**
3	Limb Symmetry Index	0.10	7.24	−0.31	**0.009**
Final Model (3 predictors)	**R^2 = 0.58**, Adj. R^2 = 0.55	**F (3, 36) = 14.23, p < 0.001**			

Table 8: Summary Table

The overall findings indicate that the regression model significantly predicts functional performance after ACL reconstruction, explaining 58% of the variance (Adjusted R^2 = 0.54, p < 0.001). Among the predictors, the Ham–Quad Co-activation Ratio and Peak Knee Flexion Angle showed the strongest positive effects, highlighting the importance of muscular coordination and joint mobility in recovery. Hamstring Activation and Limb Symmetry Index also contributed positively, suggesting that balanced muscle engagement and load distribution enhance performance outcomes. In contrast, Knee Valgus Angle had a negative impact, emphasizing the need to reduce medial knee collapse for better stability. Overall, the results demonstrate that optimal neuromuscular control, biomechanical alignment, and movement symmetry are key factors influencing successful functional rehabilitation post-ACL reconstruction.

5. Discussion

The present study examined biomechanical predictors of functional recovery following anterior cruciate ligament (ACL) rehabilitation, focusing on two primary kinematic variables—peak knee flexion angle and knee valgus angle. The findings revealed that peak knee flexion angle had a significant positive relationship with

functional performance (β = 0.32, p = 0.001), while knee valgus angle demonstrated a significant negative relationship (β = −0.27, p = 0.004). These results suggest that greater knee flexion during movement contributes to better knee function, whereas excessive valgus alignment compromises post-rehabilitation outcomes.

The positive influence of peak knee flexion angle aligns with previous findings by Hart et al. (2019) and Sigward & Powers (2018), who reported that enhanced knee flexion facilitates joint stability, optimal load distribution, and improved shock absorption during gait and landing tasks. Greater flexion has also been associated with increased quadriceps engagement, leading to superior neuromuscular control and reduced re-injury risk. This reinforces the notion that functional knee flexion is a critical biomechanical target in ACL rehabilitation protocols. Conversely, limited flexion has been linked to compensatory hip or ankle strategies that may hinder full recovery.

In contrast, the negative association between knee valgus angle and functional outcome is consistent with prior evidence indicating that excessive dynamic valgus is a primary risk factor for ACL injury and delayed rehabilitation progress. Studies by Hewett et al. (2005) and Schmitt et al. (2012) emphasized that valgus collapse during dynamic tasks increases medial knee stress and compromises joint alignment, thereby reducing post-operative stability. The current findings confirm these patterns, highlighting that reducing valgus loading through targeted neuromuscular and proprioceptive training should remain a key rehabilitation goal.

Interestingly, the magnitude of the β coefficients indicates that knee flexion exerts a slightly stronger predictive effect on functional performance compared to knee valgus control. This observation may reflect the progressive nature of rehabilitation programs, where restoration of sagittal-plane motion (flexion/extension) precedes refinement of frontal-plane control. However, persistent valgus deviations, even at lower magnitudes, can still impede return-to-sport readiness and should not be overlooked.

Overall, the study supports previous biomechanical evidence that optimal joint kinematics—particularly adequate knee flexion and controlled valgus—are crucial determinants of successful ACL rehabilitation outcomes. These results underscore the importance of individualized therapy programs emphasizing dynamic alignment retraining, quadriceps strengthening, and movement pattern correction. Future studies may further explore how integrating real-time motion feedback and neuromuscular training technologies could enhance these biomechanical predictors to promote faster and safer recovery.

6. Recommendations

Based on the findings of this study, several recommendations can be made to improve clinical rehabilitation outcomes following anterior cruciate ligament (ACL) reconstruction:

1. **Emphasize Functional Knee Flexion Training:**

Rehabilitation programs should prioritize exercises that promote optimal knee flexion during dynamic movements such as squatting, stepping, and landing. Progressive resistance and closed-kinetic-chain exercises can enhance quadriceps activation and joint stability, facilitating better functional recovery.

2. **Target Valgus Control Through Neuromuscular Training:**

Given the negative influence of excessive knee valgus, therapists should integrate specific neuromuscular and proprioceptive training strategies aimed at improving frontal-plane stability (Sultan & Hasan, 2020). Techniques such as single-leg balance drills, perturbation training, and real-time motion feedback can effectively reduce valgus loading.

3. **Implement Movement Pattern Re-education:**

Early identification and correction of faulty movement patterns are essential. Video or sensor-based movement analysis can be incorporated into routine sessions to ensure proper knee alignment during sport-specific and functional activities.

4. **Adopt Individualized Rehabilitation Protocols:**

Since biomechanical predictors vary among patients, therapy should be personalized according to each individual's kinematic deficits and recovery stage. Continuous assessment of

flexion and valgus angles can guide the progression of exercise intensity and complexity.

5. **Integrate Technological Tools for Monitoring:**
Motion-capture systems, wearable sensors, and virtual feedback platforms may be used to track kinematic improvements objectively. Such technology can enhance patient engagement and provide quantitative data for clinicians to adjust interventions.

6. **Future Research Directions:**
Further studies are recommended to examine additional biomechanical and neuromuscular factors that influence ACL rehabilitation outcomes. Longitudinal research exploring gender differences, sport-specific adaptations, and integration of digital rehabilitation technologies would also strengthen the evidence base.

7. Conclusion

This study investigated the biomechanical predictors of functional recovery following anterior cruciate ligament (ACL) rehabilitation, focusing on the roles of peak knee flexion angle and knee valgus angle. The results revealed that increased knee flexion is a significant positive predictor of post-rehabilitation function, while excessive knee valgus serves as a negative predictor. These findings emphasize the critical importance of restoring optimal knee kinematics for successful recovery and long-term joint stability.

Comparison with previous research confirms that greater flexion facilitates effective load absorption and neuromuscular control, whereas valgus malalignment compromises knee integrity and increases the risk of re-injury. The consistency of these outcomes with earlier biomechanical and clinical studies underscores the universal relevance of movement quality and alignment correction in ACL rehabilitation programs.

Overall, the study highlights that precise control of sagittal and frontal plane movements should remain central to physiotherapeutic practice. Enhancing functional flexion, minimizing dynamic valgus, and employing individualized rehabilitation strategies can collectively improve performance outcomes and reduce recurrence of injury. Future investigations integrating real-time motion analysis and advanced sensor technologies are warranted to further refine these biomechanical predictors and translate them into evidence-based rehabilitation protocols.

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