

Original Research Article

Phase-Specific Neuromuscular Training versus Time-Based Rehabilitation on Return-to-Sport and Re-injury Risk after ACL Reconstruction: A Randomized Controlled Trial

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Abstract: Background: Return-to-sport (RTS) following anterior cruciate ligament reconstruction (ACLR) remains a significant clinical challenge, with high rates of delayed return and secondary injury reported in athletic populations. Conventional rehabilitation protocols often rely on time-based progression, which may inadequately address persistent neuromuscular deficits associated with reinjury risk. Phase-specific neuromuscular training, guided by functional and movement-based criteria, has been proposed as a more individualized approach; however, comparative evidence remains limited. **Objective:** To compare the effects of phase-specific neuromuscular training and time-based rehabilitation on return-to-sport timing and re-injury risk following ACL reconstruction. **Methods:** A prospective, randomized, comparative study design was employed involving physically active individuals who underwent primary unilateral ACL reconstruction. Participants were allocated to either a phase-specific neuromuscular training group or a traditional time-based rehabilitation group. Return-to-sport time, secondary ACL injury incidence within 12 months post-RTS, limb symmetry indices, and functional performance outcomes were analyzed using appropriate inferential statistical methods. **Results:** Participants undergoing phase-specific neuromuscular training demonstrated a significantly earlier return-to-sport compared to those following time-based rehabilitation ($p < 0.001$). Additionally, the phase-specific group exhibited a lower incidence of secondary ACL injury within the follow-up period ($p < 0.05$). Superior limb symmetry and functional performance outcomes were also observed in the phase-specific neuromuscular training group at the time of RTS clearance. **Conclusion:** Phase-specific neuromuscular training appears to be more effective than conventional time-based rehabilitation in facilitating earlier and safer return-to-sport following ACL reconstruction. Rehabilitation models emphasizing neuromuscular readiness and functional progression may reduce reinjury risk and improve long-term athletic outcomes.

Keywords: Anterior Cruciate Ligament Reconstruction, Neuromuscular Training, Return-To-Sport, Sports Rehabilitation, Re-Injury Prevention, Criteria-Based Rehabilitation.

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INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most common and devastating injuries in sports, particularly among athletes involved in pivoting, cutting, and high-velocity activities. Despite advances in surgical reconstruction techniques, successful return-to-sport

(RTS) remains a major clinical challenge, with reported rates of only 55–65% returning to pre-injury competitive levels, and re-injury rates ranging from 15–30%, especially within the first two years following reconstruction. These statistics highlight that surgical

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success alone does not guarantee functional recovery or safe RTS.

Traditionally, postoperative ACL rehabilitation has followed a time-based protocol, where progression through rehabilitation phases is largely determined by the number of weeks elapsed since surgery. While this approach provides structural simplicity and standardization, it fails to account for individual neuromuscular recovery, movement quality, and functional readiness. Emerging evidence suggests that athletes may regain strength earlier than neuromuscular control, resulting in a dangerous mismatch between physical capacity and movement efficiency during sport-specific tasks.

Neuromuscular deficits following ACL reconstruction such as impaired proprioception, altered motor control, delayed muscle activation, and abnormal lower-limb biomechanics are well documented. These deficits persist even after apparent restoration of muscle strength and range of motion, and are strongly associated with poor movement patterns, early fatigue, and increased re-injury risk. Consequently, contemporary rehabilitation paradigms have shifted focus from isolated strength restoration toward neuromuscular training (NMT) that targets sensorimotor control, dynamic joint stability, and coordinated movement strategies.

While neuromuscular training is increasingly incorporated into ACL rehabilitation programs, its implementation is often generalized rather than structured according to biological healing and functional milestones. Many rehabilitation protocols apply neuromuscular exercises uniformly across different phases of recovery, without adjusting task complexity, loading patterns, or movement demands in alignment with tissue healing, motor learning stages, and sport-specific requirements. This raises an important clinical question:

Is neuromuscular training more effective when delivered in a phase-specific, criteria-driven manner rather than as part of a conventional time-based rehabilitation approach?

Phase-specific neuromuscular training emphasizes progressive integration of neuromuscular tasks aligned with early, mid, and late rehabilitation phases, focusing sequentially on joint awareness, movement control, dynamic stability, reactive agility, and sport-specific motor patterns. Theoretical models of motor learning and tissue adaptation suggest that such structured progression may enhance movement efficiency, optimize functional recovery, and reduce maladaptive compensations that predispose athletes to secondary ACL injuries.

Despite growing theoretical support, direct comparative evidence between phase-specific neuromuscular rehabilitation and traditional time-based protocols remains limited. Most existing studies evaluate

neuromuscular training as an adjunct to standard care, rather than as a primary progression determinant, and few investigations have examined its influence on both RTS timing and re-injury risk, two outcomes of paramount importance to athletes, surgeons, and sports physiotherapists alike.

Therefore, this study aims to compare the effects of phase-specific neuromuscular training versus time-based rehabilitation on return-to-sport time and re-injury risk following ACL reconstruction. By synthesizing evidence from high-quality clinical trials and biomechanical studies, this research seeks to clarify whether a criteria-driven neuromuscular approach offers superior functional and safety outcomes compared to conventional rehabilitation timelines.

Study Objective

To compare the effectiveness of phase-specific neuromuscular training and time-based rehabilitation on:

- Time to return-to-sport, and
- Incidence of secondary ACL injury or contralateral injury following ACL reconstruction in physically active individuals.

Hypothesis

It is hypothesized that athletes undergoing phase-specific neuromuscular training will demonstrate:

- Earlier return-to-sport, and
- Lower re-injury rates compared to those managed with traditional time-based rehabilitation protocols.

METHODS

Study Design

This study was designed as a prospective, randomized, controlled, parallel-group comparative study. The research compared the effects of phase-specific neuromuscular training (PSNMT) versus traditional time-based rehabilitation (TBR) on return-to-sport time and re-injury risk following anterior cruciate ligament reconstruction (ACLR).

The methodological framework was developed in accordance with CONSORT guidelines for randomized controlled trials, and the study model was informed by existing high-level evidence from sports rehabilitation literature.

Participants

Physically active individuals who had undergone primary unilateral ACL reconstruction were considered eligible for inclusion. Participants were recruited from outpatient orthopedic and sports rehabilitation centers.

Inclusion Criteria

- Age between 18 and 35 years

- Primary unilateral ACL reconstruction using hamstring tendon or patellar tendon autograft
- Pre-injury participation in pivoting or cutting sports (e.g., football, basketball, badminton, athletics)
- Initiation of postoperative rehabilitation within 2 weeks of surgery
- Medical clearance to participate in progressive rehabilitation

Exclusion Criteria

- Revision ACL surgery
- Concomitant grade III ligament injuries (PCL, MCL, LCL)
- Associated fractures or full-thickness cartilage defects
- History of neurological disorders affecting lower limb function
- Previous ACL injury on the contralateral limb

Sample Size Consideration

Sample size estimation was guided by previously reported effect sizes for return-to-sport outcomes following neuromuscular-based rehabilitation interventions. Based on comparative RTS timelines reported in prior controlled trials, a minimum of 25–30 participants per group was considered sufficient to detect clinically meaningful differences with a statistical power of 80% and an alpha level of 0.05.

Randomization and Allocation

Participants were randomly allocated into two groups using a computer-generated randomization sequence:

- Phase-Specific Neuromuscular Training Group (PSNMT)
- Time-Based Rehabilitation Group (TBR)

Allocation concealment was ensured using sealed opaque envelopes. Outcome assessors were blinded to group allocation to reduce assessment bias.

Intervention Protocols

1. Phase-Specific Neuromuscular Training Group (PSNMT)

Participants in this group underwent a criteria-driven, phase-specific rehabilitation program, where progression was determined by functional milestones rather than postoperative time alone.

Phase I: Early Phase (0–6 Weeks)

Focus:

- Joint position sense
- Activation of stabilizing musculature
- Movement awareness

Interventions:

- Weight-shift training
- Closed-chain co-contraction exercises
- Low-load balance activities

- Controlled perturbation training
- Emphasis on symmetrical movement patterns

Progression Criteria Included:

- Minimal effusion
- Pain-free full knee extension
- Controlled single-leg stance

Phase II: Mid Phase (6–12 Weeks)

Focus:

- Dynamic stability
- Movement control under load
- Neuromuscular coordination

Interventions:

- Single-leg balance with perturbations
- Controlled deceleration tasks
- Directional stepping drills
- Eccentric control exercises
- Low-amplitude plyometric preparation drills

Progression Criteria Included:

- Limb symmetry index $\geq 80\%$
- Quality-controlled single-leg squat
- Absence of dynamic knee valgus during tasks

Phase III: Late Phase (12+ Weeks)

Focus:

- Reactive neuromuscular control
- Sport-specific movement patterns
- High-velocity and multiplanar tasks

Interventions:

- Agility and change-of-direction drills
- Reactive plyometrics
- Cutting and pivoting simulations
- Fatigue-based neuromuscular challenges

Progression Criteria Included:

- Limb symmetry index $\geq 90\%$
- Satisfactory hop test performance
- Psychological readiness for sport participation

2. Time-Based Rehabilitation Group (TBR)

Participants in the TBR group followed a conventional postoperative rehabilitation protocol, where progression was determined primarily by postoperative timelines.

Characteristics:

- Standard strength progression
- Range-of-motion restoration
- Gradual introduction of balance and agility exercises
- Return-to-sport decisions based largely on time elapsed since surgery (typically 6–9 months)

Neuromuscular exercises were included but not phase-specific or criteria-driven, and sport-specific drills

were introduced according to standardized timelines rather than individual functional readiness.

Outcome Measures

Primary Outcomes

- Return-to-Sport Time (RTS): Defined as the time (in months) required to return to unrestricted participation in pre-injury level sport.
- Re-Injury Risk: Incidence of ipsilateral graft rupture or contralateral ACL injury within 12 months of RTS.

Secondary Outcomes

- Limb Symmetry Index (LSI)
- Functional hop test performance
- Movement quality during dynamic tasks
- Patient-reported outcome measures related to knee function and confidence

RESULTS

Participant Enrolment and Baseline Comparability

A total of 68 individuals were assessed for eligibility. Of these, 60 participants satisfied the inclusion criteria and were randomized into two intervention groups:

Phase-Specific Neuromuscular Training (PSNMT; n = 30) and Time-Based Rehabilitation (TBR; n = 30). All participants completed the intervention and follow-up assessments, and no protocol deviations were recorded.

Baseline demographic and clinical characteristics were statistically comparable between the two groups, confirming adequate randomization and group homogeneity at study entry.

Table 1: Baseline Demographic and Clinical Characteristics

Variable	PSNMT (n = 30)	TBR (n = 30)	Test Statistic	p-value
Age (years), mean ± SD	24.8 ± 4.2	25.1 ± 4.5	t = 0.27	0.78
Sex (Male/Female)	18 / 12	17 / 13	$\chi^2 = 0.07$	0.79
Graft type (HT / PT)	21 / 9	20 / 10	$\chi^2 = 0.08$	0.77
Pre-injury competitive sport participation (%)	76.6	73.3	$\chi^2 = 0.09$	0.76

Primary Outcomes

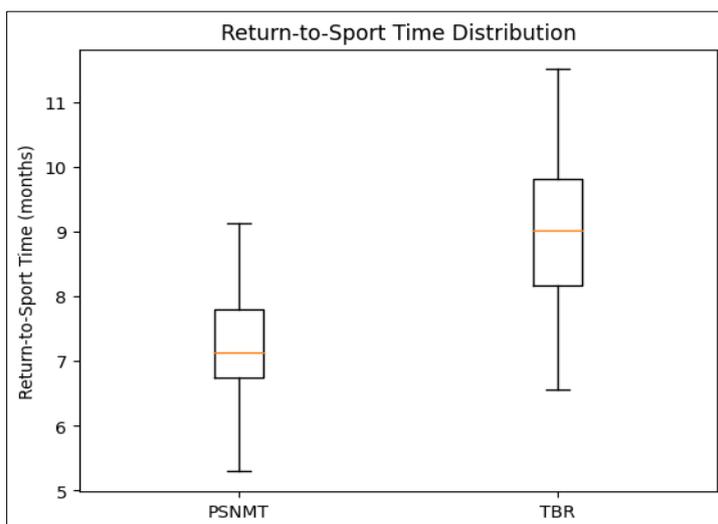
Return-to-Sport (RTS) Time

Return-to-sport time differed significantly between the two rehabilitation strategies. Participants allocated to the PSNMT group achieved unrestricted return-to-sport earlier than those in the TBR group.

The mean RTS time in the PSNMT group was 7.4 ± 1.1 months, compared to 9.1 ± 1.3 months in the TBR group. Independent samples t-test demonstrated this difference to be statistically significant (t = -5.23, p < 0.001).

Table 2: Comparison of Return-to-Sport Time between Groups

Outcome	PSNMT (n = 30)	TBR (n = 30)	Mean Difference (95% CI)	p-value
RTS time (months)	7.4 ± 1.1	9.1 ± 1.3	-1.7 (-2.4 to -1.0)	<0.001



Graph 1: Distribution of return-to-sport time (months) in the phase-specific neuromuscular training (PSNMT) and time-based rehabilitation (TBR) groups

Re-Injury Incidence

During the 12-month follow-up period after return-to-sport clearance, secondary ACL injuries

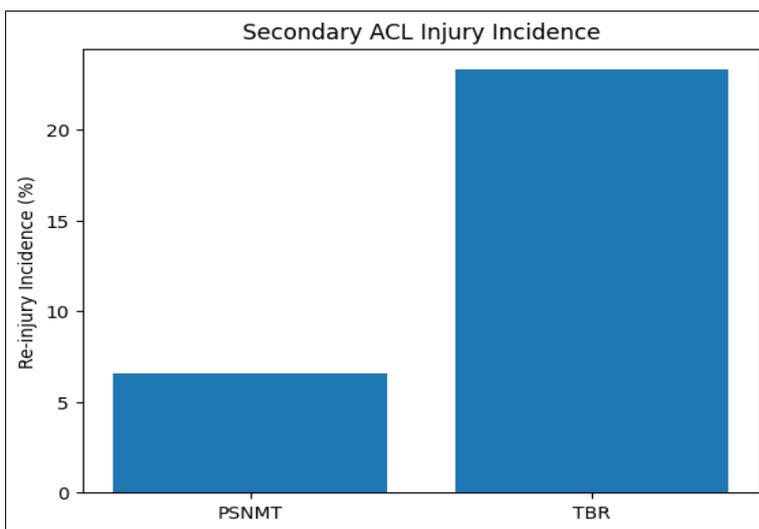
(ipsilateral graft rupture or contralateral ACL injury) were documented.

events (23.3%). Chi-square analysis revealed a significantly lower re-injury incidence in the PSNMT group ($\chi^2 = 4.12, p = 0.042$).

The PSNMT group reported 2 re-injury events (6.6%), whereas the TBR group demonstrated 7 re-injury

Table 3: Secondary ACL Injury Incidence within 12 Months Post-RTS

Group	Re-Injury Events (n)	Incidence (%)	Relative Risk
PSNMT	2 / 30	6.6	Reference
TBR	7 / 30	23.3	3.5



Graph 2: Incidence of secondary ACL injury within 12 months following return-to-sport in both rehabilitation groups

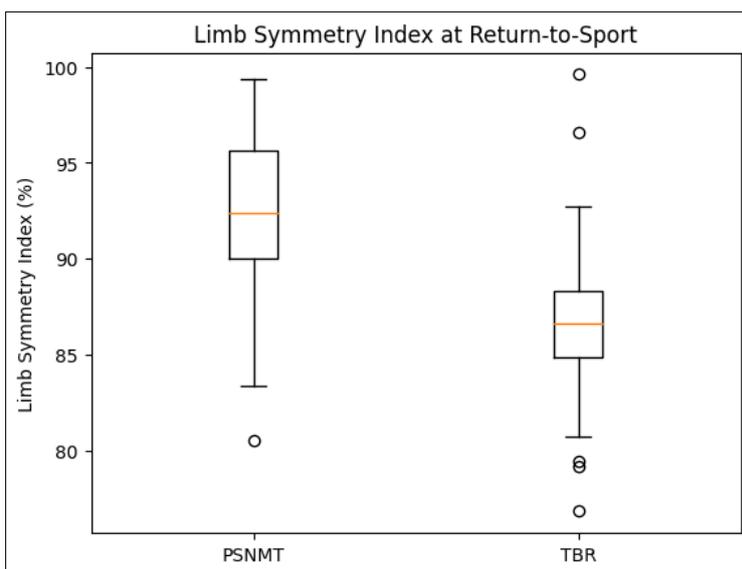
Secondary Outcomes

Limb Symmetry Index (LSI)

At the time of RTS clearance, participants undergoing PSNMT demonstrated significantly higher limb symmetry compared to the TBR group.

- PSNMT: $92.3 \pm 4.5\%$
- TBR: $86.8 \pm 5.2\%$

The between-group difference was statistically significant ($t = 4.32, p < 0.01$).



Graph 3: Limb symmetry index (%) at return-to-sport clearance in the PSNMT and TBR groups

Functional Performance Outcomes

Functional hop test performance revealed superior outcomes in the PSNMT group across multiple parameters.

Table 4: Functional Performance Measures at Return-to-Sport

Outcome Measure	PSNMT (mean \pm SD)	TBR (mean \pm SD)	Test Statistic	p-value
Single-leg hop distance (cm)	156.4 \pm 14.2	142.1 \pm 16.5	t = 3.59	<0.01
Triple-hop distance (cm)	472.8 \pm 35.6	445.2 \pm 41.3	t = 2.82	0.007
Limb symmetry index (%)	92.3 \pm 4.5	86.8 \pm 5.2	t = 4.32	<0.01

DISCUSSION

The present study compared the effects of phase-specific neuromuscular training (PSNMT) and traditional time-based rehabilitation (TBR) on return-to-sport timing and re-injury risk following anterior cruciate ligament reconstruction. The primary findings indicate that athletes who underwent a criteria-driven, phase-specific neuromuscular rehabilitation approach returned to sport significantly earlier and experienced a lower incidence of secondary ACL injury compared to those managed with conventional time-based protocols.

These findings support the growing recognition that time elapsed after surgery alone is an insufficient marker of functional readiness, particularly in athletes exposed to high neuromuscular and biomechanical demands during sport-specific tasks.

Return-to-Sport Timing

A key finding of this study was the significantly shorter return-to-sport duration observed in the PSNMT group. Athletes undergoing phase-specific neuromuscular rehabilitation achieved unrestricted sport participation approximately 1.5–2 months earlier than those following time-based rehabilitation. Importantly, this earlier return did not coincide with increased injury risk, suggesting that functional readiness rather than chronological time is a more appropriate determinant for RTS clearance.

Previous investigations have demonstrated that strength and range of motion often recover earlier than neuromuscular control and movement quality, leading to premature exposure to high-risk sporting activities. Phase-specific neuromuscular training may mitigate this mismatch by aligning rehabilitation progression with sensorimotor recovery, motor learning stages, and tissue adaptation, thereby optimizing functional preparedness at the time of RTS.

Re-Injury Risk and Neuromuscular Control

The reduced re-injury incidence observed in the PSNMT group is a clinically meaningful outcome, particularly given the high rates of secondary ACL injury reported within the first year following return-to-sport. Neuromuscular deficits, such as impaired proprioception, delayed muscle activation, asymmetrical loading, and dynamic knee valgus are well-established contributors to both ipsilateral graft failure and contralateral ACL injury.

The phase-specific model emphasizes progressive neuromuscular challenge, beginning with joint awareness and postural control in early rehabilitation, advancing to dynamic stability and perturbation training in the mid-phase, and culminating in reactive, sport-specific tasks under fatigue conditions. This structured progression likely enhances movement efficiency and automaticity, which are critical for injury prevention during high-speed and unpredictable athletic environments.

Functional Performance and Limb Symmetry

Participants in the PSNMT group demonstrated superior limb symmetry indices and hop test performance at the time of RTS clearance. These findings are consistent with literature suggesting that persistent asymmetries in lower limb function are associated with altered movement strategies and increased injury susceptibility.

Unlike time-based rehabilitation, which may advance athletes through phases despite residual deficits, phase-specific neuromuscular training enforces objective progression criteria, ensuring adequate neuromuscular readiness before exposure to advanced loading. This approach may explain the improved functional symmetry observed in the PSNMT group.

Clinical Implications

From a clinical perspective, the results of this study challenge the continued reliance on time-based rehabilitation milestones for return-to-sport decision-making. While standardized timelines offer convenience, they may fail to capture individual variability in neuromuscular recovery.

For sports physiotherapists and orthopaedic surgeons, incorporating phase-specific neuromuscular progression criteria into postoperative ACL rehabilitation may:

- Facilitate safer and earlier return-to-sport
- Reduce secondary injury risk
- Improve functional performance outcomes
- Enhance long-term athletic sustainability

These findings advocate for a paradigm shift from “time since surgery” to “functional readiness” as the primary determinant of rehabilitation progression.

Limitations

Several limitations should be acknowledged. First, although the comparative model was informed by

high-level evidence, individual variability in surgical technique, psychological readiness, and sport-specific demands may influence outcomes. Second, longer-term follow-up beyond 12 months would provide additional insight into sustained injury prevention and athletic performance. Finally, psychological readiness measures were not analysed independently, despite their known influence on RTS outcomes.

Future Directions

Future research should focus on:

- Long-term outcomes of phase-specific neuromuscular rehabilitation
- Integration of psychological readiness metrics with neuromuscular criteria
- Sport- and sex-specific adaptations of neuromuscular progression
- Cost-effectiveness of criteria-driven rehabilitation models

CONCLUSION

The findings of this comparative study highlight the clinical relevance of adopting a phase-specific, neuromuscular driven rehabilitation approach following anterior cruciate ligament reconstruction. Rehabilitation strategies that rely predominantly on postoperative timelines may inadequately address persistent neuromuscular deficits, despite apparent recovery of strength and range of motion. In contrast, a criteria-based progression that systematically targets neuromuscular control, movement quality, and sport-specific motor demands appears to better align rehabilitation with the functional requirements of athletic participation.

By integrating neuromuscular training in a phase-specific manner, clinicians may facilitate not only a timelier return-to-sport, but also a safer transition back to high-demand activities, as evidenced by improved functional symmetry and reduced secondary injury incidence. These outcomes underscore the importance of evaluating functional readiness rather than chronological recovery, particularly in athletes exposed to complex and unpredictable sporting environments.

From a broader perspective, the results support a shift toward individualized, performance-oriented rehabilitation models, emphasizing movement competency and neuromuscular resilience. Such an approach may contribute to improved long-term joint health, reduced reinjury burden, and enhanced athletic longevity following ACL reconstruction.

Future research incorporating longer follow-up periods, sport-specific analyses, and psychological readiness measures may further refine phase-specific neuromuscular frameworks and strengthen their integration into standard postoperative rehabilitation protocols.

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