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EFFECTIVENESS OF BILATERAL NEUROMUSCULAR TRAINING IN COMBINATION WITH CONVENTIONAL REHABILITATION ON STRENGTH, POWER, BALANCE, AND AGILITY IN YOUNG ADULTS POST-ACL RECONSTRUCTION: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: Knee stability following an ACL injury is usually restored through an anterior cruciate ligament reconstruction (ACLR). However, after conventional rehabilitation, ACLR people still have residual deficits in muscle strength, lower limb power, balance, and agility. Overcoming musculoskeletal dysfunction through effective rehabilitation may result from bilateral neuromuscular training that enhances sensorimotor control, proprioception, and performance.
Objective: This study aimed to compare the effectiveness of Bilateral Neuromuscular Training combined with Conventional Rehabilitation versus Conventional Rehabilitation alone on muscle strength, lower limb power, dynamic balance, and agility in individuals following ACL reconstruction.
Methods: A randomized controlled trial on 48 participants with ACL reconstruction was conducted. Twenty-four patients were chosen for both the conventional rehabilitation and the bilateral neuromuscular training groups. The measures that were observed were muscle strength, lower limb power, Y-Balance Test (dynamic balance), and agility at pre-intervention, post-intervention, and follow-up. To analyze the data, repeated-measures ANOVA, independent-samples t-tests, and paired-samples t-tests were completed at an alpha level of $p < .05$.
Results: Time-related improvements were reported in all evaluation measures in both intervention groups ($p < .001$). Improvements in muscle strength, lower limb power, and agility at follow-up were significantly greater in the Bilateral Neuromuscular Training group than the Conventional Rehabilitation group. A bilateral neuromuscular training approach enhances functionality and recovery compared to all other training modes. Within-group analyses showed improvement in both groups at all assessment periods.
Conclusion: Bilateral neuromuscular training is an effective addition to conventional therapy for ACL reconstruction. Adding bilateral neuromuscular exercise into postoperative rehabilitation increases strength, lower limb power, balance, and agility, thus improving functional recovery and supporting a safer return to sport and activities of daily living.

KEYWORDS: Anterior cruciate ligament reconstruction; Bilateral neuromuscular training; Conventional rehabilitation; Muscle strength; Dynamic balance; Lower limb power; Agility; Randomized controlled trial.

1. INTRODUCTION

1.1 Epidemiology of ACL Injuries and Importance of ACL Reconstruction in Young Adults

Injury to the anterior cruciate ligament (ACL) is one of the most common knee injuries in young adults, especially those playing pivoting and cutting sports. Rupture of the anterior cruciate ligament (ACL) may result in knee instability, muscle weakness, impaired neuromuscular control, and reduced functional performance. Surgery is the common treatment for people who want to return to high-level activity (White et al. 2013). Athletes who participate in sports, either competitively or recreationally, often require ACL reconstruction (ACLR) to restore stability to the joint. Nonetheless, impairments with quadriceps strength, balance, proprioception and agility are common despite usual rehabilitation (Vidmar et al., 2020; Arumugam et al., 2021). Many young adults do not return to their pre-injury functional level, increasing the risk of a secondary ACL injury and delayed return to sport (Bortone et al., 2021; Nelson et al., 2021). Therefore, it is essential to optimize postoperative rehabilitation by the application of specific neuromuscular strategies for improving strength, dynamic stability, functional performance, and long-term clinical outcomes following ACLR.

1.2 Functional Deficits Following ACL Reconstruction

In spite of the improvements in surgical methods and postoperative rehabilitation, many individuals still demonstrate various important clinical deficits after anterior cruciate ligament reconstruction (ACLR). This may be in their strength, lower-limb power, balance, agility, and functional performance. According to White et al. 2013, many months and even years after ACLR, quadriceps weakness, movement pattern alteration, and knee function have been reported to persist, contributing to limb asymmetry and increasing the chance for secondary ACL injury. Ehrlich (2020), on the other hand, noted that ACL injury affects motor control and postural regulation. Also, visuodependence and persistent postural disorders affect return to sport (RTS) and injury risk. Vidmar et al. (2020) showed that quadriceps muscle mass and strength can remain affected after ACLR but that intensive isokinetic eccentric training leads to greater muscle strength compared with conventional rehabilitation. According to a systematic review by Arumugam et al. (2021), there is a high likelihood of the existence of proprioceptive impairments following ACLR. Further, the authors noted that although it seems that NM training can improve proprioception, the evidence is currently heterogeneous and inconclusive regarding the best intervention. According to Bortone et al. (2021), deficits in strength, balance, agility, and movement symmetry are still present in athletes two years after surgery, leading to an inability to meet safe return-to-sport criteria. According to Nelson et al. (2021), postoperative rehabilitation must focus on restoring quadriceps strength, endurance, and neuromuscular control, as functional impairments are usually not removed with conventional protocols. Chaput et al. (2021) showed that quadriceps strength deficits cause greater patient-reported knee function deficits than hop performance. Nearly 90% of patients do not satisfy the recommended RTS criteria due to continuing muscle weakness. Another significant challenge that occurs after ACLR is proprioception deficits (Hajouj et al., 2021). A land-based proprioceptive training was shown to improve joint position sense. Subsequent evidence has supported these observations. According to Li et al. (2022), water-based rehabilitation is more effective than land-based rehabilitation in terms of extensor strength. Conclusion reached by Culvenor et al. (2022), for enhancing quadriceps strength, although many rehabilitation strategies helped, for restoring neuromuscular control, evidence remains limited. According to a report by Kim et al. (2022), dynamic balance measured using the Y-Balance Test was correlated with muscle strength and functional performance post-ACLR. In recent studies, they discovered that multimodal neuromuscular rehabilitation improves strength, power, balance, agility, and perturbation abilities (Kaiyaperumal et al., 2023). Persistent bilateral quadriceps neuromuscular impairments (Qiu et al., 2024) and neurocognitive deficits (Wilk et al., 2024; Thomas et al., 2024) are still increasing the risks of reinjury and delaying the safe return to sport.

1.3 Conventional Rehabilitation Following ACL Reconstruction

The conventional rehabilitation after ACL reconstruction is a phased and structured protocol to promote full range of motion, muscle strength, proprioception, dynamic stability, gait, and performance-related to function and safely return to sport. According to a typical rehabilitation protocol, progressive weight bearing, quadriceps and hamstrings strengthening, open and closed kinetic chain exercises, balance and proprioceptive training, neuromuscular electrical stimulation, agility drills, and functional exercise would be included. According to White et al. (2013), traditional post-operative rehabilitation usually comprises prevention exercises, quadriceps strengthening, and agility training. Nonetheless, a lot of patients continue to present with quadriceps weakness, abnormal movement patterns, limb asymmetry, and poor knee function, which can increase the risk of a secondary ACL injury. Evidence-based therapy methods were incorporated into conventional rehabilitation through subsequent research. Despite conventional eccentric strengthening improving the quadriceps, Vidmar et al. show that isokinetic eccentric training produces superior improvements in muscle strength and hypertrophy. As per the study conducted by Arumugam et al. (2021), regular rehab works, including neuromuscular exercise, balance exercise, whole-body vibration, and sport-specific exercise, yield inconsistent change in proprioception. As per Nelson et al. (2021), when dealing with recent rehabilitation frequently use of vibration therapy, open- and closed-chain strengthening exercises, neuromuscular electrical stimulation, aquatic therapy, accelerated rehabilitation protocols, and postoperative bracing has only a minor clinical benefit. It is further demonstrated by Hajouj et al. (2021) that innovative proprioceptive exercises, which were added to accelerated rehabilitation, enhance joint position sense significantly compared to conventional rehabilitation. The effectiveness of some traditional rehabilitation methods is corroborated by more evidence. However, such evidence also casts doubt on the efficacy of other rehabilitation methods. Water-based treadmill rehabilitation delivers greater enhancements in quadriceps strength, proprioception, and functional performance than traditional land-based treadmill training (Li et al., 2022). An equivalent parallel is drawn to Culvenor et al. (2022), who conclude that quadriceps strength and functional outcomes are improved by neuromuscular electrical stimulation, open- and closed-kinetic chain exercises, and structured home-based rehabilitation. Postoperative bracing, however, provides no additional benefit. Even with these advancements, conventional rehabilitation frequently fails to deliver ideal long-term functional recovery and a safe return to sport owing to persistent neuromuscular deficits, bilateral strength asymmetry, impaired motor control, psychological barriers, and a greater risk of reinjury.

1.4 Bilateral Neuromuscular Training

Bilateral neuromuscular training (BNT) is a rehabilitative method that trains the injured and non-injured limbs together to improve disturbed muscle activation, proprioception, postural control, and motor coordination after anterior cruciate ligament reconstruction (ACLR). At the core of BNT is the incorporation of sensorimotor integration, muscle strengthening (bilateral), perturbation exercises, balance training, movement coordination, as well as progressive loading to benefit lower-limb symmetry and reduce the risk of re-injury. According to White et al. (2013), neuromuscular training is important after an ACLR. They reported that postoperative deficits such as a quadriceps deficiency, an abnormal gait, and limb asymmetries contribute to poor functional outcomes and second ACL injuries. The authors suggested that a perturbation-based neuromuscular training, used in addition to conventional rehabilitation, can improve limb symmetry and return-to-sport outcomes. ACL injury modifies motor control and postural regulation through increased visual reliance (Ehrlich 2020). Neuromotor rehabilitation is recommended to address lasting sensorimotor deficits and optimize safe return to competition. Bilateral neuromuscular training helps restore afferent sensory input, enhances corticospinal excitability, reduces arthrogenic muscle inhibition, and reorganises the central motor pathways, all on a neurophysiological basis. The study by Arumugam et al. (2021) mentioned that balance training, whole-body vibration, sport-specific exercises, and backward walking are all neuromuscular interventions that can improve proprioception. However, no single intervention was established as superior due to methodological heterogeneity. Brown et al. (2021) found that functional resistance training creates hypoxic conditions as a consequence of muscle fatigue and independent of hypoxaemia. According to the work of Hajouj et al., the addition of innovative proprioception training to regular rehabilitation produced a greater improvement in joint position sense and proprioception efficiency. This further supports the neurophysiological effects of neuromuscular rehabilitation. One major mechanism that could explain bilateral neuromuscular training is the cross-education effect, also known as the contralateral effect. Here, it refers to how training one limb can lead to neural adaptations that improve strength and motor performance in the opposite-side limb. Additionally, it is believed that the underlying mechanism is due to shared pathways in the cortex and spinal cord. According to the findings, using bilateral rehabilitation engages central neural mechanisms and reduces bilateral neuromuscular deficits post-ACL injury. Qiu et al. (2024) found that both limbs (injured and uninjured) exhibit reduced quadriceps strength, impaired rate of torque development, and activation failure soon after an ACL injury. As a result, rehabilitation strategies should target both limbs and not just the reconstructed limb. Kim et al. (2024) also mentioned that functional ability is reliant on the strength and balance of the affected and unaffected limbs. On the other hand, Thomas et al. (2024) and Wilk et al. (2024) called for including neurocognitive and neuromuscular training during rehabilitation to facilitate neuroplasticity and improve the safety of return to sport through better bilateral motor control. In sum, these results substantiate the utilization of bilateral neuromuscular training as a complete rehabilitation treatment that targets peripheral impairments and neural adaptations following ACL reconstruction.

1.5 Research Gap

Many studies have analysed conventional rehabilitation, eccentric strengthening, proprioceptive exercises, perturbation training, and neuromuscular rehabilitation following anterior cruciate ligament reconstruction (ACLR). However, little evidence exists to show the effect of bilateral neuromuscular training (BNT) with conventional rehabilitation (CR) in young adults after ACLR. Many earlier studies assessed either isolated rehabilitation interventions or one outcome, such as strength or proprioception, and did not focus on improving muscle strength, lower-limb power, balance, and agility simultaneously. Moreover, randomized controlled trials have yet to investigate the bilateral neuromuscular adaptations and cross-education effect further. This study seeks to fill this gap by assessing whether combining bilateral neuromuscular training with conventional rehabilitation results in better functional outcomes than just conventional rehabilitation alone in young adults following ACL reconstruction.

1.6 Aim of the Study

This randomized controlled trial seeks to assess the effectiveness of bilateral neuromuscular training in addition to conventional rehabilitation on enhancing muscle strength, lower-limb power, balance, and agility in young adults following anterior cruciate ligament reconstruction (ACLR). This study also aims to find out the superior functional recovery from the addition of bilateral neuromuscular training over rehabilitation alone. This intervention aims to enhance neuromuscular control, bilateral limb symmetry and overall physical performance to enable a safer and more efficient return to daily activities and sports, and to reduce the risk of reinjury after ACL reconstruction.

1.8 Objectives

- To evaluate the effectiveness of bilateral neuromuscular training in combination with conventional rehabilitation on muscle strength, lower-limb power, balance, and agility in young adults following anterior cruciate ligament reconstruction.
- To compare the effects of bilateral neuromuscular training combined with conventional rehabilitation versus conventional rehabilitation alone on muscle strength, lower-limb power, balance, and agility in young adults after anterior cruciate ligament reconstruction.

1.9 Hypothesis

- **Null Hypothesis (H_0):** There is **no significant difference** in muscle strength, lower-limb power, balance, and agility between young adults receiving **bilateral neuromuscular training combined with conventional rehabilitation** and those receiving **conventional rehabilitation alone** following anterior cruciate ligament reconstruction.
- **Alternative Hypothesis (H_1):** Young adults receiving **bilateral neuromuscular training combined with conventional rehabilitation** will demonstrate **significantly greater improvements** in muscle strength, lower-limb power, balance, and agility compared with those receiving **conventional rehabilitation alone** following anterior cruciate ligament reconstruction.

2. REVIEW OF LITERATURE

The strengthening protocols for ACLR rehabilitation have evolved progressively from traditional strengthening approaches to neuromuscular rehabilitation focused on functional recovery and prevention of reinjury. The program ACL-SPORTS created by White et al. (2013) highlighted that perturbation training after surgery combined with strengthening and agility exercise can reduce quadriceps weakness, limb asymmetry, and abnormal movement patterns, which are associated with poor functional outcomes after ACLR. According to Ehrlich (2020), with an ACL injury, postural control and visuomotor regulation are altered. Therefore, persisting visual dependence must be addressed in neuromotor rehabilitation to minimize recurrent ACL injuries. According to Vidmar et al. (2020), isokinetic eccentric training of the quadriceps muscle produces greater muscle mass and strength improvements than conventional eccentric training. Multiple randomized studies and systematic reviews solidified the evidence of multimodal rehabilitation. As per the findings of Arumugam et al. (2021), the authors found that the neuromuscular interventions such as balance training, whole-body vibration, sport-specific exercises, and backward walking may improve proprioception. However, the authors rated evidence quality as low. Bortone and colleagues (2021) stated that assessment of strength, balance, and agility is essential for return to sport after injury. Vibration therapy, neuromuscular electrical stimulation, aquatic therapy, and accelerated rehabilitation were suggested, while routine postoperative bracing was discouraged. Functional resistance training enhanced strength symmetry, gait mechanics, and corticospinal adaptation, as observed by Brown et al. (2021). The study by Chaput et al. (2021) shows that quadriceps strength is a stronger predictor of patient function than hop performance. According to Hajouj et al. (2021), combining innovative proprioceptive exercises with conventional rehabilitation significantly improves joint position sense. Evidence released in 2022 has further refined rehab strategies. Li et al. (2022) found greater improvements in extensor strength, proprioception, and knee performance in the water-based treadmill rehabilitation compared to land-based training. Neuromuscular electrical stimulation, structured rehabilitation, and either open-circuit or closed-circuit exercises probably improve quadriceps strength. Post-operative bracing probably does not make a worthwhile difference (Culvenor et al. 2022). Culvenor et al. (2022) synthesized systematic review evidence.

Within the research context, Zumstein et al. (2022) illustrated how limb dominance affects strength symmetry and return-to-sport decision-making. In addition, Kim et al. (2022) reported significant relationships between Y-Balance Test performance, muscle strength, and functional outcomes after ACLR. In summary, successful rehabilitation of ACL injuries requires more than just conventional strengthening. It requires a comprehensive approach focusing on strength, proprioception, balance, functional symmetry, and neuromuscular control. Recent evidence has provided various advanced rehabilitation strategies focusing on neuromuscular, sensorimotor, and neurocognitive functions in order to optimize the functional recovery after ACL reconstruction (ACLR). According to a study by Gholami et al. (2023), both differential learning and visuomotor training improved functional performance, dynamic balance, landing biomechanics, and kinesiophobia significantly. Multimodal exercise programs that included perturbation, agility training, and functional training have been reported to improve physical function, balance, and agility more than standardized rehabilitation. This was reported... The findings of Stojanović et al. (2023) indicated that eccentric-oriented strength training was more effective than traditional strengthening for improving leg strength and hopping performance. Wang et al. (2023) proved that isokinetic strength training significantly improved muscle strength, proprioception and balance, while Lee et al. (2023) confirmed that accelerated rehabilitation improved quadriceps strength, muscular endurance and dynamic balance. Wii-based rehabilitation improved pain, balance, functional performance, and postural stability beyond conventional rehabilitation, according to Kazemnejad et al. (2023). In addition, Patel et al. (2023) mentioned the neuroplastic modifications following the ACLR and advocated for the use of motor imagery and brain–computer interface technologies to enhance corticospinal excitability and quadriceps activation. The periodical evidence here focuses on bilateral rehabilitation, neurocognitive recovery and individualised return-to-sport strategies (2024-2026). Wang et al. (2024) suggested that, in the future, supervised multicomponent telerehabilitation could improve postoperative recovery. Kaliyaperumal et al. (2024) showed that single-leg dynamic balance training significantly improves proprioception and knee stability. Kim and colleagues (2024) revealed that bilateral muscle strength and Y-Balance Test performance were among the main determinants of recovery. Bruder et al. (2024) discussed varied rehabilitation needs by gender, and Qiu et al.(2024) supported bilateral rehabilitation approaches through bilateral quadriceps neuromuscular impairments post-ACL injury. A safe return to sport requires a comprehensive assessment of one's strength, balance, neuromotor and neurocognitive ability (Tsevtkova-Gaberska and Pencheva 2024, Memain et al. 2024, Mo et al. 2024, Thomas et al. 2024, Wilk et al. 2024). According to Discoveries et al. (2025), van der Schoor et al. (2025), Butler et al. (2025), Hasan et al. (2025), Stofberg et al. (2025), Dash and Gakhar (2025), and Çağlayan (2025), the risk of reinjury and functional outcomes can be improved by phase-based rehabilitation, psychological readiness, motor control, sensorimotor training, limb symmetry, and a structured return-to-sport program.

Together, these modern investigations lend credence to the idea that rehabilitation efforts that rely on bilateral neuromuscular, neurocognitive, and multimodal approaches combined with conventional protocols will maximize strength, power, balance, agility, and successful return to sport after ACLR. Numerous recent studies have shown the favourable outcomes of neuromuscular, proprioceptive, multimodal, and neurocognitive rehabilitation following anterior cruciate ligament reconstruction, but most have assessed these solely as independent or isolated outcomes. There are limited randomized controlled trials investigating combined bilateral neuromuscular training with conventional rehabilitation on muscle strength, lower-limb power, balance, and agility among young adults after ACL reconstruction. Based on the above reasons, the current randomized controlled trial aims to study whether the incorporation of bilateral neuromuscular training in conventional rehabilitation gives better functional recovery and postoperative outcome.

3. MATERIALS AND METHODS

3.1 Study Design

This was a prospective, parallel group, single-blinded randomized controlled trial (RCT) to assess the efficacy of bilateral neuromuscular training with conventional rehabilitation versus conventional rehabilitation alone in young adults after anterior cruciate ligament reconstruction (ACLR). The CONSORT 2025 reporting guideline was followed for randomized trials. A design of a randomized controlled trial should be considered when evaluating postoperative rehabilitation interventions in ACLR (Wang et al., 2024; White et al., 2013).

3.2 Study Setting

Research was conducted at a tertiary care rehabilitation centre that rehabilitates patients with orthopedic & sports injuries in the Department of Physiotherapy. Subjects participated in monitored rehabilitation sessions by qualified physiotherapists.

3.3 Study Duration

The study was conducted over **4 months**, including participant recruitment, intervention, follow-up assessment, data analysis, and interpretation.

3.4 Ethical Approval

Before initiation of the study, ethical approval was obtained from the Institutional Ethics Committee (Approval No.:). Informed consent was obtained in writing from all the participants. The study followed the Declaration of Helsinki principles (2013).

3.5 Participants

Young adults who underwent **primary unilateral ACL reconstruction** and were referred for postoperative rehabilitation were screened for eligibility.

3.6 Eligibility Criteria

Inclusion Criteria

- Young adults aged **18–35 years**
- Primary unilateral ACL reconstruction
- Postoperative period of **4–8 weeks**
- Medically cleared for supervised rehabilitation
- Ability to provide informed consent

Exclusion Criteria

- Revision ACL reconstruction
- Multi-ligament knee injuries
- Previous fracture or surgery of either lower limb
- Neurological or vestibular disorders affecting balance
- Severe cardiopulmonary disease
- Inability to complete the rehabilitation protocol

3.7 Sample Size Estimation

The sample size was calculated using G*Power software (Version 3.1.9.7), based on a repeated-measures analysis of variance (ANOVA) using a within-between interaction design. The analysis was based on a medium effect size ($f = 0.25$). Furthermore, a two-sided significance level (α) of 0.05 was used, with 95% statistical power and specification of two intervention groups. In addition to this, three repeated measures were specified, taken at the baseline, post-intervention, and follow-up. A correlation of the repeated measures of 0.50 was assumed, along with a nonsphericity correction (ε) of 1.0. The analysis required a minimum of 44 participants (22 per group). To compensate for a presumed 15% attrition rate, the sample size was inflated to 52 (26 per group), thus ensuring adequate statistical power throughout the research. Four participants withdrew from the study because of a lack of interest and time, and the data from 48 participants were analysed. Group A(n=24) underwent regular rehabilitation, while Group B(n=24) underwent bilateral neuromuscular training and regular rehabilitation.

3.8 Randomization

Participants were randomly allocated into two equal groups using a **computer-generated(SPSS-27) randomization sequence** with a **1:1 allocation ratio**, as recommended by CONSORT.

3.9 Allocation Concealment

Sequentially numbered, opaque, sealed envelopes (SNOSE) were used to conceal allocation and were prepared by an investigator who was not involved in recruiting or outcome assessments.

3.10 Blinding

The study employed a single-blinded design where the outcome assessor and data analyst were blinded to group allocation. Because of the types of rehabilitation interventions, it was not possible to blind participants and therapists.

3.11 Intervention Protocol

Group A: Conventional Rehabilitation

All participants received the standardized ACL rehabilitation program consisting of progressive range-of-motion exercises; quadriceps and hamstring strengthening; closed- and open-kinetic-chain exercises; balance training; gait training; flexibility exercises; and functional rehabilitation in accordance with current rehabilitation guidelines (Nelson et al., 2021; Culvenor et al.,2022).

Group B: Bilateral Neuromuscular Training + Conventional Rehabilitation

Along with the conventional rehabilitation program, participants received bilateral neuromuscular training that consisted of bilateral perturbation exercises, proprioceptive training, dynamic balance exercises, bilateral strength training, coordination drills, plyometric exercises, and agility training. The intervention used was based on previous neuromuscular rehabilitation protocols (White et al., 2013; Arumugam et al., 2021; Kaiyaperumal et al., 2023).

3.12 Outcome Measures

Primary Outcomes

- Muscle Strength
- Lower Limb Power

Secondary Outcomes

- Balance
- Agility

Validated and reliable outcome measures commonly used in ACL rehabilitation research were employed (Kim et al., 2022; Wang et al., 2023).

3.13 Instruments Used

Muscle Strength: To assess the muscle strength of the quadriceps and hamstring muscles, an isokinetic dynamometer was used. The use of an Isokinetic Dynamometer is considered the gold standard to measure lower-limb muscle strength after ACL reconstruction due to its high reliability and validity (Vidmar et al., 2020; Wang et al., 2023).

Lower Limb Power: Lower-limb power was evaluated using the **Single-Leg Hop Test**, a reliable functional performance measure commonly used to assess an athlete's explosive power and readiness to return to sport after ACL reconstruction (Chaput et al., 2021; Kim et al., 2022).

Balance: The Y-Balance Test (YBT) was used to evaluate dynamic balance, which is a valid and reliable postural control and functional balance measurement tool in ACL reconstruction (Kim et al., 2022; Kim et al., 2024).

Agility: The Agility T-Test is a standardized test with high reliability that was used to assess the agility of athletes with ACL reconstruction (Kaiyaperumal et al., 2023).

3.14 Assessment Timeline

Outcome assessments were conducted at **baseline (pre-intervention)** and **post-intervention (after completion of the rehabilitation program)** by a blinded assessor.

3.15 Data Collection Procedure

Screened eligible participants were enrolled after informed consent, randomly assigned to two different intervention groups, and underwent baseline evaluations. Once the intervention period ended, the blinded assessor reassessed all primary and secondary outcomes using standardised protocols.

3.16 Statistical Analysis

Data were analyzed using the IBM SPSS v27. The Shapiro-Wilk Test was used to assess normality. Descriptive statistics for continuous variables were expressed as mean ± standard deviation, and those for categorical variables as frequency (percentage). Unpaired t-test and chi-square methods were used to assess baseline characteristics. To test changes within groups, the paired t-test was used, and to test differences between groups, the independent-samples t-test was used. The analysis utilized a mixed-model repeated-measures ANOVA for Group × Time for the repeated assessment. Cohen's d and 95% confidence intervals were reported for effect sizes. Statistical significance was set at $p < 0.05$ in line with CONSORT.

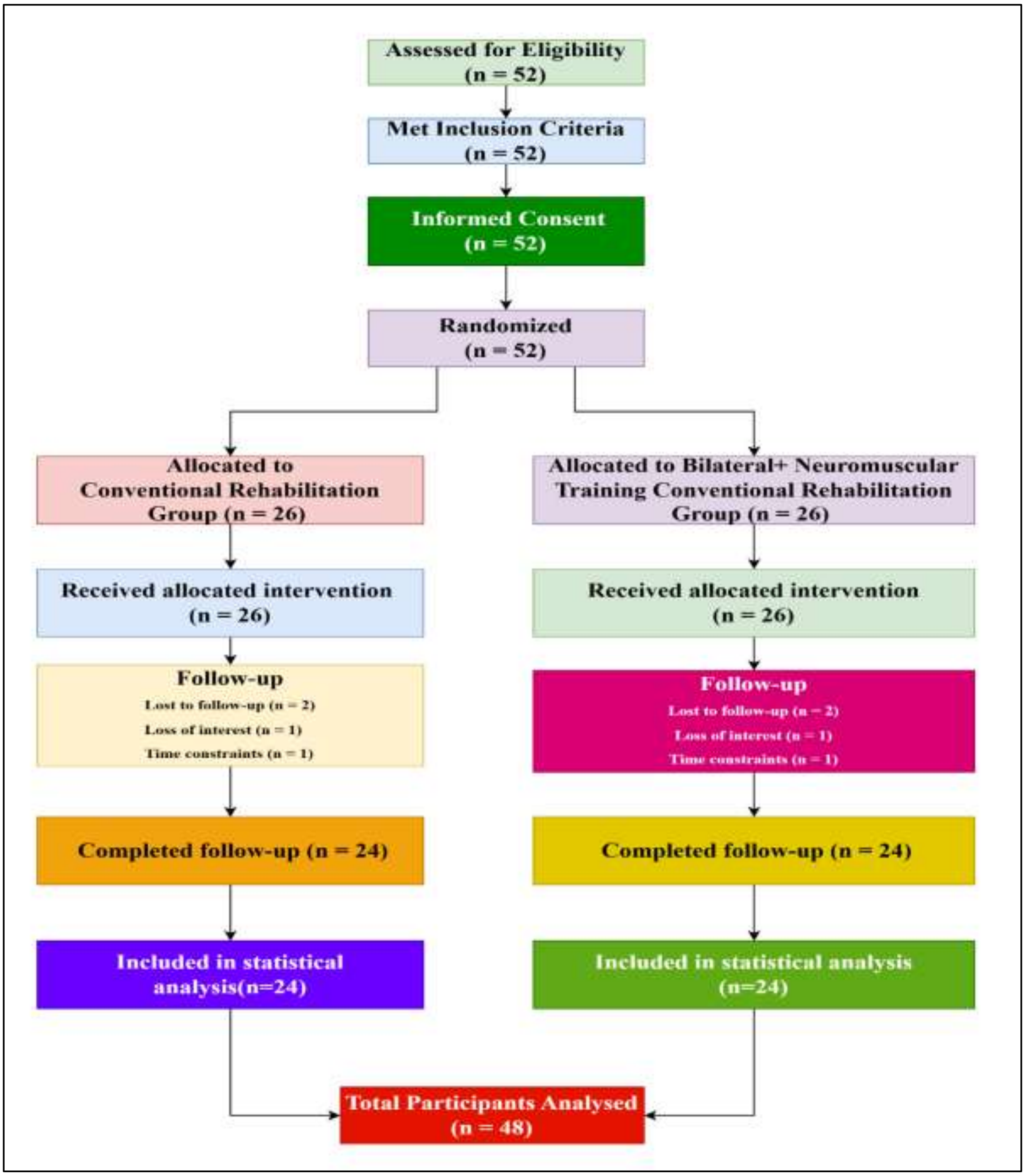

Figure 1. CONSORT 2025 flow diagram of participant recruitment, randomization, allocation, follow-up, and analysis. Fifty-two young adults who underwent anterior cruciate ligament reconstruction (ACLR) met the eligibility criteria, provided written informed consent, and were randomized equally to the Conventional Rehabilitation group (n = 26) or the Bilateral Neuromuscular Training plus Conventional Rehabilitation group (n = 26). During follow-up, two participants from each group withdrew because of loss of interest (n = 2) and time constraints (n = 2). Consequently, data from 48 participants (24 per group) were included in the final statistical analyses.

4. RESULTS

Table 1: Distribution of Participants by Sex Across the Intervention Groups (N = 48)

Sex [n (%)]	**Conventional Rehabilitation (n = 24)**	**Bilateral Neuromuscular Training (n = 24)**	**Total**
Male	11 (45.8%)	12 (50.0%)	23 (47.9%)
Female	13 (54.2%)	12 (50.0%)	25 (52.1%)

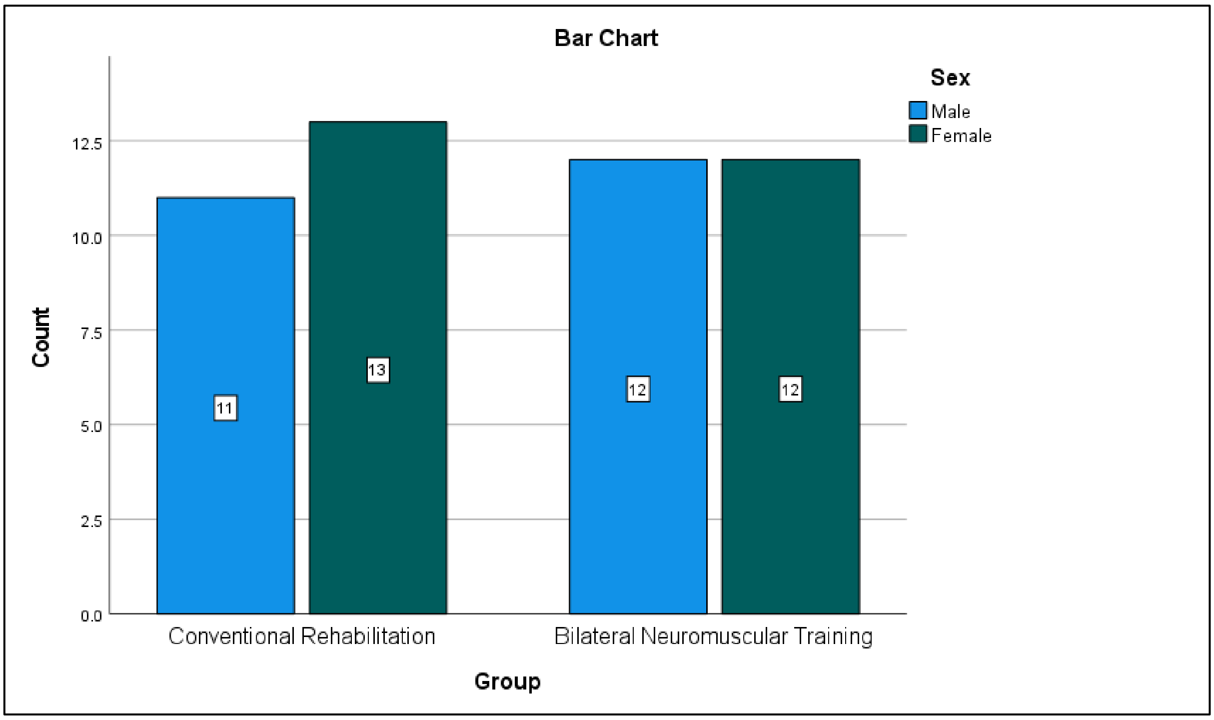

Figure 2 Distribution of Male and Female Participants Across the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups

Table 2: Comparison of Baseline Age and Body Mass Index Between the Intervention Groups (N = 48)

Variable	**Conventional Rehabilitation (n = 24) Mean ± SD**	**Bilateral Neuromuscular Training (n = 24) Mean ± SD**	**t (46)**	**p**	**Cohen's d**
Age (years)	26.29 ± 4.80	24.83 ± 5.00	1.03	.308	0.30
BMI (kg/m²)	24.50 ± 3.09	23.97 ± 2.45	0.67	.508	0.19

$p < .05$.

Table 3: Comparison of Age and Body Mass Index Between Male and Female Participants (N = 48)

Variable	**Male (n = 23) Mean ± SD**	**Female (n = 25) Mean ± SD**	**t (46)**	**p**	**Cohen's d**
Age (years)	27.13 ± 4.53	24.12 ± 4.88	2.21	.032*	0.64
BMI (kg/m²)	24.33 ± 2.44	24.15 ± 3.10	0.22	.831	0.06

$p < .05$.

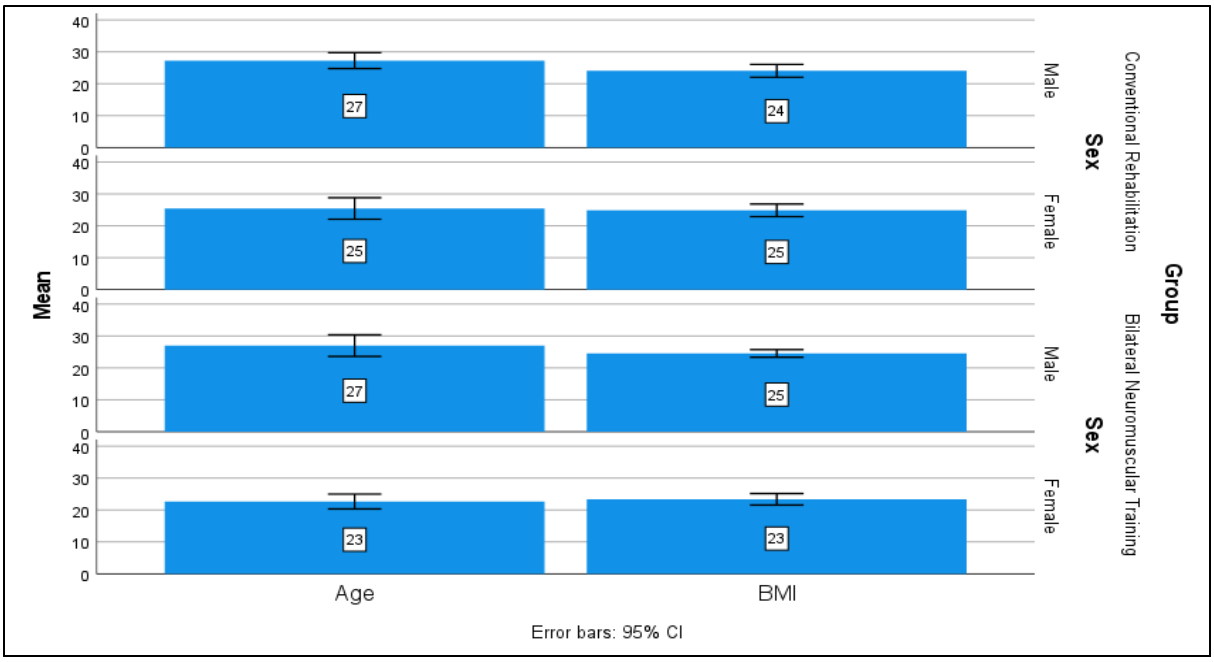

Figure 3: Mean Age and Body Mass Index According to Intervention Group and Sex with 95% Confidence Intervals

Table 4: Repeated-Measures Analysis of Variance for Agility Performance Across Assessment Time Points Between the Intervention Groups (N = 48)

Outcome	Conventional Rehabilitation (n = 24) Mean ± SD	Bilateral Neuromuscular Training (n = 24) Mean ± SD	Time Effect F (p), ηp²	Group Effect F (p), ηp²	Time × Group Effect F (p), ηp²
Pre-intervention	11.61 ± 0.64	11.40 ± 0.77	**1323.64 (< .001), .966**	**9.59 (.003), .173**	**89.18 (< .001), .660**
Post-intervention	10.81 ± 0.67	10.08 ± 0.77			
Follow-up	10.54 ± 0.68	9.56 ± 0.79			

Note. (Mauchly's W = .418, $\chi^2(2) = 39.26$, p < .001); (p < .001).

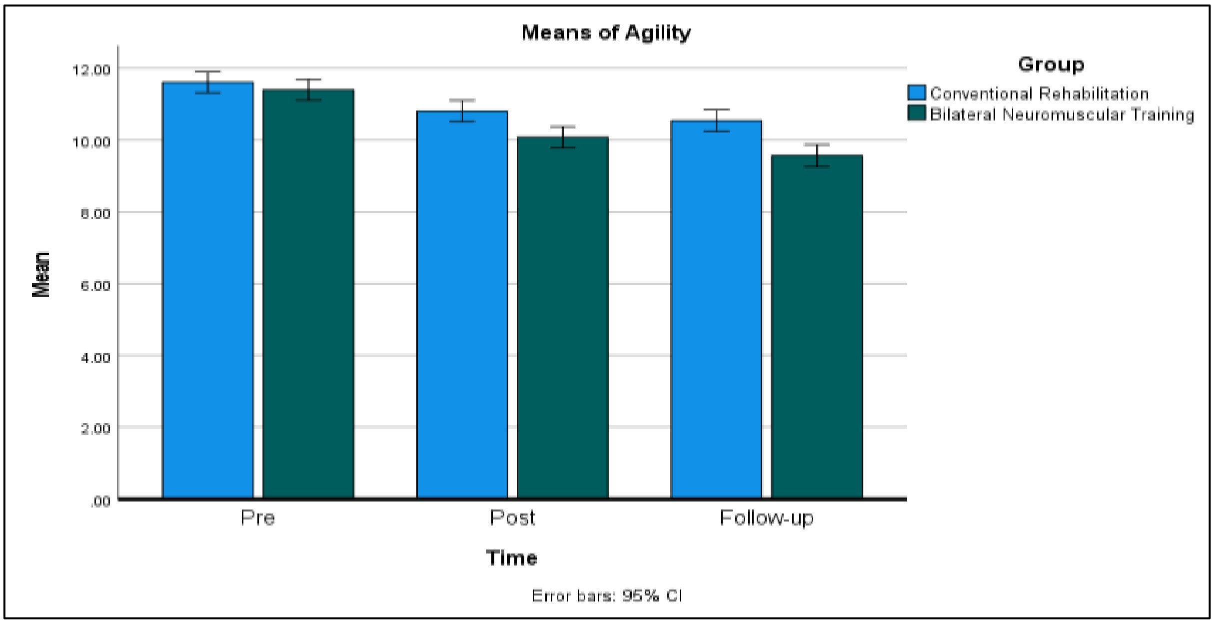

Figure 4: Changes in Mean Agility Scores Across Pre-intervention, Post-intervention, and Follow-up Assessments in the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups

Table 5: Repeated-Measures Analysis of Variance for Balance (Y-Balance Test) Scores Across Assessment Time Points Between the Intervention Groups (N = 48)

Outcome	Conventional Rehabilitation (n = 24) Mean ± SD	Bilateral Neuromuscular Training (n = 24) Mean ± SD	Time Effect F (p), ηp²	Group Effect F (p), ηp²	Time × Group Effect F (p), ηp²
Pre-intervention	82.50 ± 3.88	81.11 ± 3.81	**877.45 (< .001), .950**	**0.33 (.571), .007**	**40.92 (< .001), .471**
Post-intervention	87.37 ± 4.34	88.42 ± 4.22			
Follow-up	89.23 ± 4.66	91.61 ± 4.31			

Note. (Mauchly's W = .738, $\chi^2(2) = 13.65$, p = .001), (all p < .001)

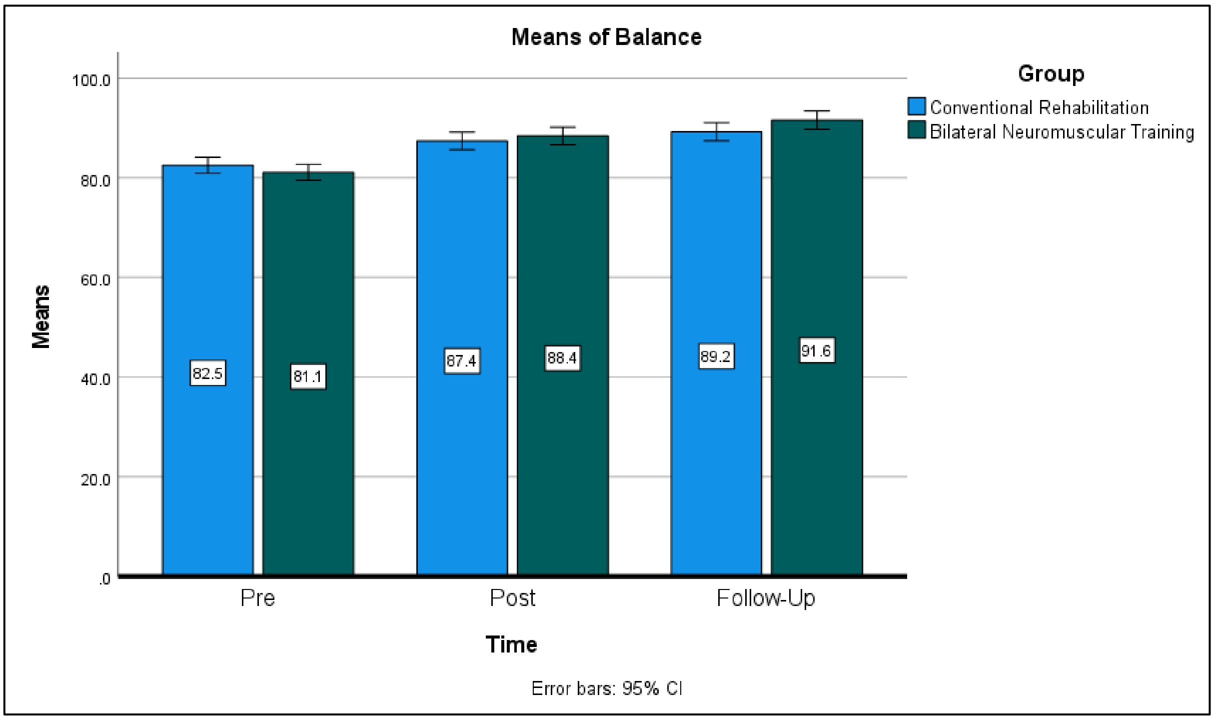

Figure 5: Changes in Mean Balance (Y-Balance Test) Scores Across Pre-intervention, Post-intervention, and Follow-up Assessments in the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups

Table 6: Repeated-Measures Analysis of Variance for Lower Limb Power Across Assessment Time Points Between the Intervention Groups (N = 48)

Outcome	**Conventional Rehabilitation (n = 24) Mean ± SD**	**Bilateral Neuromuscular Training (n = 24) Mean ± SD**	**Time Effect F (p), ηp²**	**Group Effect F (p), ηp²**	**Time × Group Effect F (p), ηp²**
Pre-intervention	142.35 ± 14.33	140.87 ± 15.33	**1201.48 (< .001), .963**	**1.75 (.192), .037**	**41.15 (< .001), .472**
Post-intervention	161.18 ± 14.94	168.88 ± 15.03			
Follow-up	169.13 ± 15.42	179.55 ± 13.58			

Note. (Mauchly's W = .539, $\chi^2(2) = 27.82$, $p < .001$).

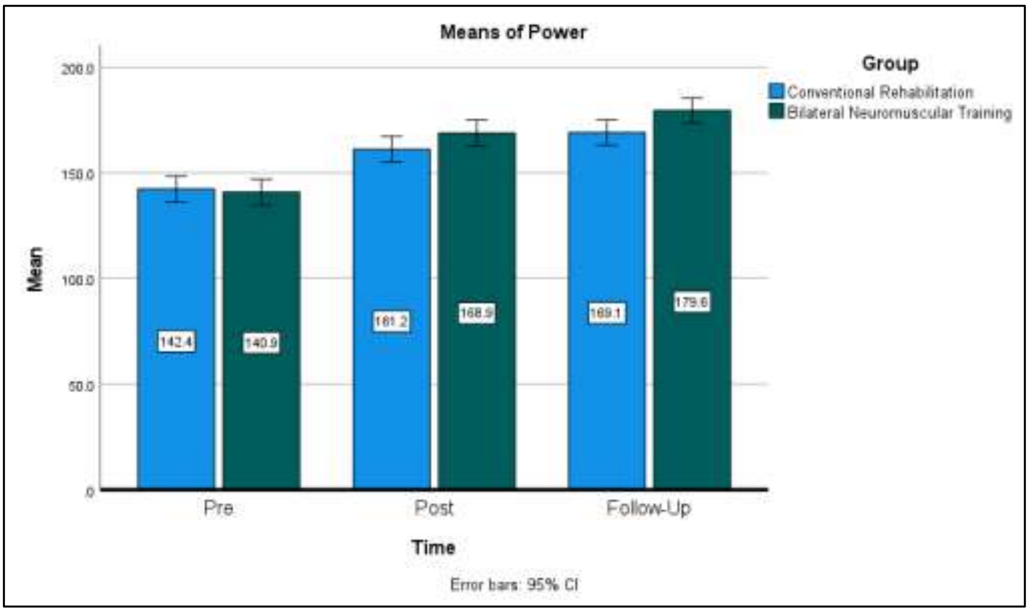

Figure 6: Changes in Mean Lower Limb Power Across Pre-intervention, Post-intervention, and Follow-up Assessments in the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups

Table 7: Repeated-Measures Analysis of Variance for Muscle Strength Across Assessment Time Points Between the Intervention Groups (N = 48)

Outcome	Conventional Rehabilitation (n = 24) Mean ± SD	Bilateral Neuromuscular Training (n = 24) Mean ± SD	Time Effect F (p), ηp^2	Group Effect F (p), ηp^2	Time × Group Effect F (p), ηp^2
Pre-intervention	122.50 ± 8.54	117.60 ± 11.13	1605.19 (< .001), .972	0.66 (.421), .014	55.76 (< .001), .548
Post-intervention	143.42 ± 11.28	147.56 ± 11.10			
Follow-up	151.01 ± 12.31	159.33 ± 11.63			

Note. (Mauchly's W = .620, $\chi^2(2) = 21.53$, p < .001).

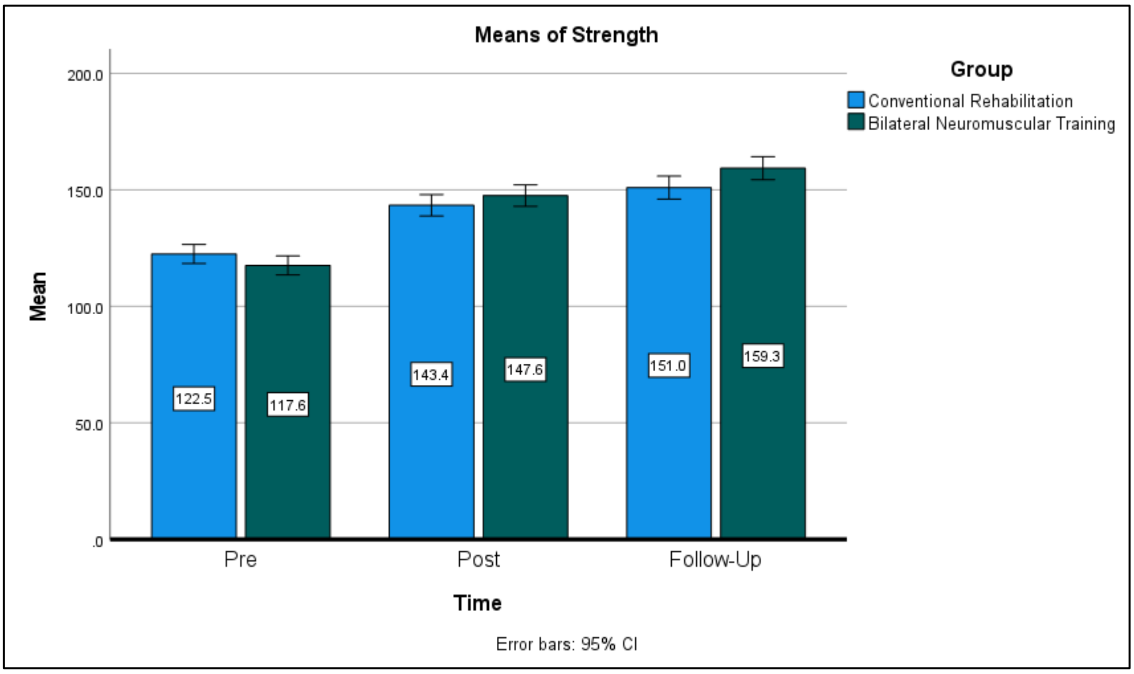

Figure 7: Mean Muscle Strength Across Pre-intervention, Post-intervention, and Follow-up Assessments in the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups

Table 8: Independent-Samples t-Test Comparing Strength, Power, Balance, and Agility Outcomes Between the Conventional Rehabilitation and Bilateral Neuromuscular Training Groups (N = 48)

Outcome Measure	Conventional Rehabilitation (n = 24) Mean ± SD	Bilateral Neuromuscular Training (n = 24) Mean ± SD	t (46)	p	Cohen's d
Strength					
Pre-intervention	122.50 ± 8.54	117.60 ± 11.13	1.71	.093	0.49
Post-intervention	143.42 ± 11.28	147.56 ± 11.10	−1.28	.207	−0.37
Follow-up	151.01 ± 12.31	159.33 ± 11.63	−2.41	.020*	−0.70
Power					
Pre-intervention	142.35 ± 14.33	140.87 ± 15.33	0.35	.730	0.10
Post-intervention	161.18 ± 14.94	168.88 ± 15.03	−1.78	.082	−0.51
Follow-up	169.13 ± 15.42	179.55 ± 13.58	−2.49	.017*	−0.72
Balance (Y-Balance Test)					
Pre-intervention	82.50 ± 3.88	81.11 ± 3.81	1.25	.218	0.36
Post-intervention	87.37 ± 4.34	88.42 ± 4.22	−0.85	.402	−0.24
Follow-up	89.23 ± 4.66	91.61 ± 4.31	−1.84	.072	−0.53
Agility					
Pre-intervention	11.61 ± 0.64	11.40 ± 0.77	1.02	.311	0.30
Post-intervention	10.81 ± 0.67	10.08 ± 0.77	3.50	.001**	1.01
Follow-up	10.54 ± 0.68	9.56 ± 0.79	4.58	< .001***	1.32

Note. p < .05*, p < .01**, p < .001***.

Table 9: Within-Group Comparison of Strength, Power, Balance, and Agility Across Assessment Time Points in the Conventional Rehabilitation Group (n = 24)

Outcome Measure	Comparison	Mean Difference	t (23)	p	Cohen's d
Strength	Pre vs. Post	−20.92	−22.62	< .001***	4.62
	Post vs. Follow-up	−7.59	−15.61	< .001***	3.19
	Pre vs. Follow-up	−28.50	−23.84	< .001***	4.87
Power	Pre vs. Post	−18.83	−17.64	< .001***	3.60
	Post vs. Follow-up	−7.95	−16.14	< .001***	3.30
	Pre vs. Follow-up	−26.78	−22.27	< .001***	4.55
Balance (Y-Balance Test)	Pre vs. Post	−4.87	−16.49	< .001***	3.37
	Post vs. Follow-up	−1.85	−7.27	< .001***	1.49
	Pre vs. Follow-up	−6.73	−16.98	< .001***	3.47
Agility	Pre vs. Post	0.80	19.53	< .001***	3.99
	Post vs. Follow-up	0.27	12.18	< .001***	2.49
	Pre vs. Follow-up	1.07	20.54	< .001***	4.19

Note. p < .001***.

Table 11: Within-Group Comparison of Strength, Power, Balance, and Agility Across Assessment Time Points in the Bilateral Neuromuscular Training Group (n = 24)

Outcome Measure	Comparison	Mean Difference	t (23)	p	Cohen's d
Strength	**Pre vs. Post**	−29.96	−31.39	< .001***	6.41
	Post vs. Follow-up	−11.78	−17.15	< .001***	3.50
	Pre vs. Follow-up	−41.73	−41.40	< .001***	8.45
Power	**Pre vs. Post**	−28.02	−28.16	< .001***	5.75
	Post vs. Follow-up	−10.67	−16.11	< .001***	3.29
	Pre vs. Follow-up	−38.69	−32.41	< .001***	6.62
Balance (Y-Balance Test)	**Pre vs. Post**	−7.30	−25.71	< .001***	5.25
	Post vs. Follow-up	−3.19	−15.89	< .001***	3.24
	Pre vs. Follow-up	−10.50	−32.28	< .001***	6.59
Agility	**Pre vs. Post**	1.32	28.36	< .001***	5.79
	Post vs. Follow-up	0.51	23.17	< .001***	4.73
	Pre vs. Follow-up	1.83	35.32	< .001***	7.21

Note. p < .001***.

Out of 48 participants who joined the study, 24 were allocated to the Conventional Rehabilitation group and another 24 to the Bilateral Neuromuscular Training (BNT) group. The proportion of males (47.9%) and females (52.1%) was similar in both groups, indicating effective randomization. There were no significant differences in baseline demographic characteristics between the intervention groups for age ($p = .308$) or BMI ($p = .508$), indicating no differences at entry in the sample.

When participants were compared by sex, males were significantly older than females ($p = .032$). However, no significant difference was found between sexes in BMI. This suggests that age did vary, but body composition did not vary by sex.

The repeated-measures ANOVA showed a significant improvement in all outcome measures over time, including muscle strength, lower limb power, balance (Y-Balance Test), and agility (all $p < 0.001$). Both rehabilitation protocols were useful in improving the functional performance post-anterior cruciate ligament reconstruction, according to these findings. Nonetheless, a significant Time × Group interaction effect was found for all outcomes, indicating that the magnitude of improvement varied for both interventions. The Bilateral Neuromuscular Training group exhibited more significant improvements in agility, muscle strength, lower limb power, and dynamic balance than the Conventional Rehabilitation group, as demonstrated by large interaction effect sizes (ηp^2) of .660, .548, .472, and .471, respectively. The findings are in agreement with previous randomized controlled trials that have demonstrated that perturbation and balance-oriented rehabilitation programs appear to provide better neuromuscular adaptations after ACL reconstruction (White et al. 2013, Hajouj et al. 2021, Kaiyaperumal et al. 2023).

T-tests on independent samples found no between-group differences at baseline in any of the functional variables, confirming comparable performance before intervention. After the interventions, the Bilateral Neuromuscular Training group was significantly more agile than the Conventional Rehabilitation group ($p = .001$, $d = 1.01$); strength, power, and balance differences were not significantly different. At the follow-up, the participants receiving Bilateral Neuromuscular Training demonstrated a significantly greater muscle strength ($p = .020$; $d = 0.70$), lower limb power ($p = .017$; $d = 0.72$), and agility ($p < .001$; $d = 1.32$). However, the balance difference was not significant, although it neared significance ($p = .072$). The evidence presented supports earlier findings that neuromuscular and balance-focused rehabilitation lead to better outcomes and long-term gains in strength, agility, and functional performance (Vidmar et al., 2020; Wang et al., 2023; Kaliyaperumal et al., 2024) compared with conventional rehabilitation.

The differences between the pre- and post-intervention measures in both groups, and between the post-intervention and follow-up measures in both groups, were statistically significant (all $p < .001$). The Bilateral Neuromuscular Training group demonstrated greater improvement in all metrics. The Cohen's d values for muscle strength (d = 6.41–8.45), lower limb power (d = 3.29–6.62), balance (d = 3.24–6.59), and agility (d = 4.73–7.21) were extremely large and markedly higher than those of Conventional Rehabilitation. Based on the results that we have put forward, bilateral neuromuscular training promotes recovery and persistent increases in neuromuscular control, dynamic balance, and functional performance. As per Arumugam et al. (2021), Gholami et al. (2023), Stojanović et al. (2023), and Thomas et al. (2024), neuromuscular rehabilitation improves one's proprioception, movement quality, strength recovery and readiness for return to sport after ACL reconstruction.

4. DISCUSSION

The present randomized controlled trial showed that recovery from conventional rehabilitation and bilateral neuromuscular training resulted in significant improvement in muscle strength, lower limb power, dynamic balance, and agility after ACLR. Participants who engaged in bilateral neuromuscular training showed significantly superior outcomes, especially at follow-up, suggesting that the inclusion of bilateral neuromuscular exercises optimizes functional recovery beyond standard rehabilitation alone. A range of recent research suggests a successful ACL rehabilitation programme should not only include strengthening but also neuromuscular control, proprioceptive and bilateral coordination training (White et al., 2013; Vidmar et al., 2020; Nelson et al., 2021; Culvenor et al., 2022). The greater muscle strength improvement in the bilateral neuromuscular training group is in accordance with findings that quadriceps strengthening is an essential component of restoring knee function and reducing the risk of reinjury after ACLR (Brown et al., 2021; Chaput et al., 2021; Stojanović et al., 2023; Wang et al., 2023; Lee et al., 2023). Similarly, the greater improvements in lower limb power are in line with those reported by Li et al. (2022), Kaiyaperumal et al. (2023), Gholami et al. (2023), Thomas et al. (2024) and Wilk et al. (2024), who found that neuromuscular rehabilitation enhances explosive force production via greater motor-unit recruitment and intermuscular coordination. According to Arumugam et al. (2021), Hajouj et al. (2021), Kim et al. (2022), Kazemnejad et al. (2023), Kaliyaperumal et al. (2024), and Hasan et al. (2025), proprioceptive and sensorimotor training restores postural stability after ACL injury. As a result, dynamic balance improved significantly. Moreover, the significant enhancement in agility provides evidence in favour of studies by Bortone et al. (2021), Kaiyaperumal et al. (2023), Dash and Gakhar (2025) and van der Schoor et al. (2025), confirming that bilateral neuromuscular exercises enhance movement efficiency, change-of-direction ability and sports performance. The changes observed might be explained by an improvement in corticospinal excitability, cross-education, proprioceptive feedback, motor learning, and reduction of arthrogenic muscle inhibition that result in better neuromuscular coordination and movement symmetry (Patel et al., 2023; Qiu et al., 2024; Kim et al., 2024). The results collectively demonstrate that bilateral neuromuscular training is a clinically useful adjunct to common rehabilitation. It is suggested that bilateral neuromuscular training is regarded as an essential part of postoperative ACL rehabilitation programmes.

5. CONCLUSION

The presently enrolled randomized controlled trial has demonstrated that both Conventional Rehabilitation and Bilateral Neuromuscular Training exhibit a significant increase in muscle strength, lower limb power, dynamic balance, and agility following anterior cruciate ligament reconstruction. Yet, following the completion of training, those subjected to bilateral neuromuscular training experienced significantly greater improvements in muscle strength, lower limb power, and agility at follow-up than those in conventional rehabilitation. These findings underline the significance of including bilateral neuromuscular exercises in post-operative rehabilitation to enable proper neuromuscular control, proprioception, movement symmetry and dynamic stability. The research also shows that there are great improvements over time in all functional outcomes that come with large effect sizes, which offer support to clinical effectiveness. Improved lower-limb functional performance and safer return to physical and sporting activities may result from bilateral training with concomitant improvement in neuromuscular coordination and sensorimotor integration. The findings align with the current literature recommending integrated rehabilitation strategies combining strength training with proprioception and neuromuscular exercises. Ultimately, bilateral non-functional training represents a good complementary method to standard rehabilitation after ACL reconstruction. Incorporating it into standard rehabilitation protocols may speed up recovery, enhance performance, lessen lasting neuromuscular injuries, and perhaps lower reinjury risk. Larger multicenter studies with more samples and longer follow-up are warranted to affirm these findings and develop evidence-based clinical guidelines for the postoperative ACL rehabilitation.

Declarations

Ethical Approval and Consent to Participate

The study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the Institutional Ethics Committee before the commencement of the study (Approval No.: **[Insert Approval Number]**). Written informed consent was obtained from all participants before enrolment in the study.

Consent for Publication

Written informed consent for publication of anonymized research data was obtained from all participants. No personally identifiable information is included in this manuscript.

Availability of Data and Materials
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflict of Interest
The authors declare that they have no competing interests or conflicts of interest related to this study.

Author Contributions
All authors contributed substantially to the conception and design of the study. Data collection, statistical analysis, interpretation of findings, manuscript drafting, critical revision, and approval of the final version were performed collaboratively by all authors. All authors have read and approved the final manuscript.

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