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Neuromuscular Electrical Stimulation Combined With Progressive Resistance Training Versus Resistance Training Alone on Muscle Strength and Functional Outcomes in Post–Anterior Cruciate Ligament Reconstruction Patients: A Randomized Controlled Trial

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ABSTRACT

Background: *Persistent quadriceps weakness after anterior cruciate ligament reconstruction (ACLR) is common and is partly driven by arthrogenic muscle inhibition, limiting voluntary activation and delaying functional recovery.* ***Objective:*** *To compare the effects of neuromuscular electrical stimulation (NMES) combined with progressive resistance training (PRT) versus PRT alone on quadriceps strength and functional outcomes in post-ACLR patients.* ***Methods:*** *In this assessor-blinded randomized controlled trial conducted at Therapy Plus Clinic, 60 participants (18–40 years; 4–8 weeks post-primary unilateral ACLR) were randomized (1:1) to NMES+PRT or PRT alone for 8 weeks (3 sessions/week). Quadriceps strength (Nm/kg) and limb symmetry index (LSI) were primary outcomes; functional hop tests (single-leg hop, triple hop, 6-m timed hop) and IKDC subjective scores were secondary outcomes. Analyses followed intention-to-treat with multiple imputation for missing data, using repeated-measures ANOVA and between-group comparisons at α=0.05.* ***Results:*** *At 8 weeks, NMES+PRT produced greater strength gains than PRT alone (Δ+0.59±0.21 vs +0.39±0.19 Nm/kg; between-group difference 0.20, 95% CI 0.09–0.31; p=0.001) and higher LSI improvement (+21.3±6.8% vs +13.5±7.2%; difference 7.8, 95% CI 4.2–11.4; p<0.001). NMES+PRT also improved single-leg hop distance (difference 12.1 cm; p=0.003), triple hop distance (difference 32.8 cm; p=0.002), 6-m timed hop (difference −0.21 s; p=0.016), and IKDC change (difference 7.7 points; p<0.001).* ***Conclusion:*** *NMES added to PRT yields statistically and clinically meaningful improvements in quadriceps strength, symmetry, functional performance, and patient-reported knee function after ACLR compared with PRT alone.*

Keywords

anterior cruciate ligament reconstruction; neuromuscular electrical stimulation; progressive resistance training; quadriceps strength; limb symmetry index; hop tests; IKDC

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most prevalent knee injuries among physically active individuals, frequently necessitating surgical reconstruction to restore joint stability and enable return to sport. Despite advances in surgical techniques and postoperative rehabilitation protocols, persistent quadriceps weakness remains one of the most common and clinically significant impairments following ACL reconstruction (ACLR) (1). Quadriceps strength deficits of 20–40% compared with the contralateral limb have been documented up to one year postoperatively and are associated with delayed return to sport, impaired functional performance, altered biomechanics, and increased risk of re-injury and early-onset osteoarthritis (2,3). Restoration of quadriceps strength is therefore a central objective of postoperative rehabilitation and a key determinant of long-term outcomes.

Progressive resistance training (PRT) constitutes the cornerstone of rehabilitation following ACLR and is widely recommended to promote muscle hypertrophy, neural adaptation, and functional recovery (4). Systematic reviews have demonstrated that structured resistance-based programs significantly improve muscle strength and patient-reported outcomes in this population (5). However, voluntary resistance training alone may be insufficient in the early and mid-stages of rehabilitation due to arthrogenic muscle inhibition (AMI), a reflexive inhibition of quadriceps activation triggered by joint effusion, inflammation, and altered afferent input from the injured knee (6). AMI limits voluntary motor unit recruitment and reduces the effectiveness of conventional strengthening exercises, thereby contributing to persistent strength asymmetry despite adherence to rehabilitation protocols (7). This neuromuscular impairment underscores the need for adjunctive interventions capable of enhancing muscle activation during the critical phases of recovery.

Neuromuscular electrical stimulation (NMES) has been proposed as a complementary modality to overcome AMI by directly eliciting muscle contractions through electrical impulses delivered to the motor nerves (8). By bypassing central inhibitory mechanisms, NMES can facilitate greater motor unit recruitment, including high-threshold type II fibers, which are often under-recruited during voluntary contraction in the presence of inhibition (9). Clinical studies have reported that NMES applied in the early postoperative period can attenuate quadriceps atrophy and improve

strength outcomes compared with standard rehabilitation alone (10). Furthermore, meta-analyses suggest that NMES combined with exercise may produce superior short-term gains in quadriceps strength compared with exercise alone; however, the magnitude and persistence of these effects remain inconsistent across studies (11).

Although previous research supports the potential utility of NMES after ACLR, several limitations constrain definitive conclusions. Many trials have focused on early postoperative phases without evaluating longer-term functional outcomes, such as hop performance or patient-reported measures of knee function (12). In addition, heterogeneity in NMES parameters, timing of application, and co-interventions has contributed to variability in reported effects (13). Critically, few rigorously designed randomized controlled trials have directly compared the combined effect of NMES and structured progressive resistance training versus progressive resistance training alone within a standardized rehabilitation framework. Consequently, the incremental benefit of adding NMES to a contemporary, progressive strengthening protocol remains uncertain, particularly with respect to clinically meaningful improvements in muscle strength symmetry and functional performance.

Given the persistent challenge of quadriceps weakness and the theoretical rationale for combining peripheral electrical activation with voluntary progressive loading, a well-designed randomized controlled trial is warranted to determine whether adjunctive NMES provides additive benefits beyond resistance training alone. Clarifying this effect has important implications for optimizing rehabilitation efficiency, resource allocation, and return-to-sport decision-making in post-ACLR patients. Therefore, the present study aims to compare the effects of neuromuscular electrical stimulation combined with progressive resistance training versus progressive resistance training alone on quadriceps muscle strength and functional outcomes in individuals following anterior cruciate ligament reconstruction. It is hypothesized that patients receiving combined NMES and progressive resistance training will demonstrate significantly greater improvements in quadriceps strength and functional performance compared with those undergoing resistance training alone (1–13).

MATERIALS AND METHODS

This single-center, parallel-group, assessor-blinded randomized controlled trial was conducted at Therapy Plus Clinic to evaluate the comparative efficacy of neuromuscular electrical stimulation (NMES) combined with progressive resistance training (PRT) versus PRT alone on quadriceps muscle strength and functional outcomes following anterior cruciate ligament reconstruction (ACLR). The randomized controlled design was selected to establish causal inference, minimize selection bias, and control for measured and unmeasured confounding through allocation concealment (14). The study was conducted over a 12-month period, including recruitment, intervention delivery, and outcome assessment phases. All procedures were standardized and prospectively defined in a study protocol to ensure methodological transparency and reproducibility.

Participants were adults aged 18–40 years who had undergone primary unilateral ACLR using autograft technique and were between 4 and 8 weeks post-surgery at enrollment, corresponding to the early strengthening phase of rehabilitation. Eligibility criteria included medical clearance for progressive strengthening, presence of quadriceps strength deficit ≥20% compared to the contralateral limb measured by handheld dynamometry, and ability to attend supervised rehabilitation sessions three times weekly. Exclusion criteria comprised revision ACLR, concomitant grade III ligament injuries requiring surgical repair, symptomatic meniscal repair restricting weight-bearing, neurological disorders affecting lower limb function, contraindications to electrical stimulation (e.g., pacemaker, active infection, malignancy), and inability to provide informed consent. Participants were consecutively screened from postoperative referrals to Therapy Plus Clinic and were enrolled using a non-probability consecutive sampling approach to reduce selection bias while maintaining clinical feasibility.

After baseline assessment, eligible participants were randomly allocated in a 1:1 ratio to either the NMES plus PRT group or the PRT-alone group using a computer-generated randomization sequence with variable block sizes to ensure allocation unpredictability (15). Allocation concealment was maintained through sequentially numbered, opaque, sealed envelopes prepared by an independent researcher not involved in recruitment or assessment. Outcome assessors were blinded to group allocation to minimize detection bias. Due to the nature of the intervention, participant and therapist blinding was not feasible; however, standardized scripts and uniform therapist training were used to reduce performance bias.

A total sample size of 60 participants (30 per group) was determined a priori based on power analysis using G*Power software (version 3.1). Assuming a moderate effect size (Cohen's d = 0.65) for between-group differences in quadriceps strength based on prior NMES literature (11,16), with a two-tailed alpha level of 0.05 and 80% statistical power, a minimum of 52 participants was required. Accounting for an anticipated attrition rate of approximately 15%, the final target sample size was set at 60 to preserve adequate power for primary outcome analysis.

Both groups received a standardized, supervised PRT program three times per week for eight consecutive weeks. The PRT protocol was based on contemporary ACL rehabilitation guidelines emphasizing progressive overload and neuromuscular control (4,5). Exercises included closed-chain and open-chain quadriceps strengthening (e.g., leg press, squats, knee extensions within safe arc), hamstring strengthening, hip stabilizer training, and functional tasks. Intensity was prescribed at 60–80% of one-repetition maximum (1RM), progressed biweekly based on reassessment, and performed in three sets of 8–12 repetitions. The experimental group additionally received NMES applied to the quadriceps muscle during strengthening exercises. NMES was delivered using a clinically approved stimulator with biphasic symmetrical waveform, pulse frequency of 35–50 Hz, pulse duration of 250–400 is, on: off ratio of 10:50 seconds initially progressing to 10:30 seconds, and intensity increased to achieve at least 60% of maximal voluntary isometric contraction (MVIC) as tolerated (8,9). Each NMES session lasted 15–20 minutes and was synchronized with isometric or isotonic contractions to maximize motor unit recruitment.

Primary outcome was quadriceps muscle strength of the operated limb, measured using a calibrated handheld dynamometer (MicroFET2) during MVIC at 60° knee flexion. Strength values were normalized to body weight (Nm/kg) and expressed as limb symmetry index (LSI = involved/uninvolved × 100). Secondary outcomes included functional performance assessed by the single-leg hop for distance, triple hop test, and timed 6-meter hop test, conducted according to standardized protocols (17). Patient-reported knee function was measured using the International Knee Documentation Committee (IKDC) subjective knee evaluation form, a validated and reliable instrument for ACL populations (18). Assessments were conducted at baseline (pre-intervention) and at 8 weeks post-intervention by the same blinded assessor using standardized procedures to reduce measurement variability.

Independent variable was group allocation (NMES+PRT vs PRT alone). Primary dependent variable was change in quadriceps strength (Nm/kg and LSI). Secondary dependent variables included change in hop test performance and IKDC scores. Potential confounders recorded at baseline included age, sex, body mass index, graft type, and time since surgery. These variables were assessed for baseline comparability and adjusted for

in multivariable analyses if imbalances were detected. To minimize confounding and information bias, standardized rehabilitation protocols, uniform assessment timing, calibrated instruments, and assessor blinding were implemented (14).

Data were entered into a secured electronic database with double data entry verification to ensure accuracy. Statistical analysis was performed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots. Descriptive statistics were reported as mean ± standard deviation for continuous variables and frequencies with percentages for categorical variables. Between-group differences in primary and secondary outcomes were analyzed using independent-samples t-tests or Mann–Whitney U tests as appropriate. Within-group changes were evaluated using paired t-tests or Wilcoxon signed-rank tests. Additionally, repeated-measures analysis of variance (ANOVA) with group × time interaction was conducted to assess differential treatment effects over time. Effect sizes were calculated using partial eta squared (η^2) or Cohen's d. Intention-to-treat (ITT) analysis was performed, and missing data were handled using multiple imputation techniques under the assumption of missing at random (19). A two-tailed p-value <0.05 was considered statistically significant. Subgroup analyses stratified by sex and baseline strength deficit severity were conducted to explore potential effect modification.

The study protocol was approved by the Institutional Research Ethics Committee of Therapy Plus Clinic prior to participant enrollment and was conducted in accordance with the Declaration of Helsinki principles (20). Written informed consent was obtained from all participants before inclusion. Confidentiality was ensured by assigning unique identification codes and restricting data access to the research team. Intervention fidelity was monitored through therapist checklists and periodic audit of session logs. All procedures, including NMES parameters, exercise progression criteria, and assessment protocols, were documented in detail to facilitate reproducibility and external validation.

RESULTS

Table 1 summarizes baseline comparability between groups and indicates that randomization achieved good balance across key demographic and clinical variables. The NMES+PRT group had a mean age of 26.8±5.4 years versus 27.3±6.1 years in the PRT-alone group (mean difference −0.5 years, 95% CI −3.5 to 2.5; p=0.73). Sex distribution was similar (60.0% male vs 56.7% male; p=0.79), as were BMI values (24.7±2.8 vs 25.1±3.1 kg/m²; mean difference −0.4, 95% CI −1.9 to 1.1; p=0.60). Participants were enrolled at a comparable postoperative time point (5.6±1.2 vs 5.8±1.3 weeks; mean difference −0.2, 95% CI −0.8 to 0.4; p=0.51). Importantly, baseline quadriceps strength and limb symmetry index (LSI) were closely matched (strength: 1.42±0.28 vs 1.39±0.30 Nm/kg; p=0.69; LSI: 64.5±8.7% vs 65.1±9.2%; p=0.79), and baseline IKDC scores were also similar (52.6±9.4 vs 51.8±8.9; p=0.75). Collectively, these findings reduce the likelihood that post-intervention group differences were attributable to pre-treatment imbalance.

Table 2 presents the primary outcome (quadriceps strength) and the key mechanistic endpoint (LSI), demonstrating clinically meaningful gains in both groups, with consistently larger improvements in the NMES+PRT arm. By week 8, quadriceps strength increased to 2.01±0.32 Nm/kg in the NMES+PRT group compared with 1.78±0.29 Nm/kg in the PRT-alone group, yielding an absolute between-group difference of 0.23 Nm/kg (95% CI 0.07 to 0.39; p=0.005) and a moderate-to-large effect (Cohen's d=0.74). When analyzed as change from baseline, the NMES+PRT group improved by +0.59±0.21 Nm/kg versus +0.39±0.19 Nm/kg in the PRT-only group, corresponding to a between-group difference of 0.20 Nm/kg (95% CI 0.09 to 0.31; p=0.001) and a large standardized effect (d=0.99). Parallel improvements were observed in symmetry: LSI increased from 64.5±8.7% to 85.8±7.4% in the NMES+PRT group, whereas it rose from 65.1±9.2% to 78.6±8.1% in the PRT-alone group. The resulting 8-week between-group LSI difference was 7.2 percentage points (95% CI 3.2 to 11.2; p=0.001; d=0.93), and the change-score advantage was 7.8 points (95% CI 4.2 to 11.4; p<0.001; d=1.11). Consistent with these endpoint contrasts, the group time interaction for quadriceps strength was statistically significant (F=9.84, p=0.003) with partial η^2=0.15, indicating that 15% of the variance in strength change over time was attributable to differential treatment response.

Table 3 details objective functional performance, showing improvement across hop-based tests with superior performance in the NMES+PRT group at 8 weeks. For single-leg hop distance, the NMES+PRT group reached 122.4±16.7 cm compared with 110.3±15.9 cm in the PRT-alone group, an absolute advantage of 12.1 cm (95% CI 4.3 to 19.9; p=0.003; d=0.74). Similarly, triple hop distance was higher with NMES augmentation (368.7±40.2 cm vs 335.9±38.6 cm), producing a between-group difference of 32.8 cm (95% CI 12.4 to 53.2; p=0.002) and a large effect size (d=0.83). For the 6-meter timed hop, lower values indicate better function; the NMES+PRT group achieved a faster time of 2.18±0.31 seconds compared with 2.39±0.34 seconds in the PRT-alone group. This corresponds to a mean reduction of 0.21 seconds in favor of NMES (95% CI −0.38 to −0.04; p=0.016; d=0.65). Taken together, the hop outcomes show that the strength gains associated with NMES translated into measurable improvements in performance-based function within an 8-week timeframe.

Table 4 reports patient-reported knee function using the IKDC, again demonstrating improvement in both groups but with a clear incremental benefit for NMES+PRT. At 8 weeks, IKDC scores increased to 78.9±8.2 in the NMES+PRT group compared with 70.4±9.1 in the PRT-alone group, yielding an 8.5-point between-group difference (95% CI 3.7 to 13.3; p=0.001) and a large effect (d=0.99). When expressed as change from baseline, participants receiving NMES+PRT improved by +26.3±7.1 points versus +18.6±7.8 points in the PRT-only group. The mean change advantage of 7.7 points (95% CI 3.8 to 11.6; p<0.001; d=1.04) suggests that the added physiological improvements observed in Table 2 were also perceived by participants as meaningful improvements in symptoms and function. Table 5 provides the adjusted inferential model for the primary outcome (change in quadriceps strength), demonstrating that the superiority of NMES+PRT persisted after accounting for relevant covariates. Group allocation remained an independent predictor of greater strength gain, with an adjusted β coefficient of 0.20 Nm/kg (95% CI 0.07 to 0.33; p=0.004) and a standardized β of 0.34, indicating a moderate independent contribution of the intervention beyond baseline differences

Table 1. Baseline Demographic and Clinical Characteristics of Participants (n = 60)

Variable	NMES + PRT (n=30) Mean ± SD / n (%)	PRT Alone (n=30) Mean ± SD / n (%)	Between-Group Difference (95% CI)	p-value
Age (years)	26.8 ± 5.4	27.3 ± 6.1	-0.5 (-3.5 to 2.5)	0.73
Male, n (%)	18 (60%)	17 (56.7%)	—	0.79
BMI (kg/m²)	24.7 ± 2.8	25.1 ± 3.1	-0.4 (-1.9 to 1.1)	0.60
Time since surgery (weeks)	5.6 ± 1.2	5.8 ± 1.3	-0.2 (-0.8 to 0.4)	0.51

Baseline Quadriceps Strength (Nm/kg)	1.42 ± 0.28	1.39 ± 0.30	0.03 (-0.12 to 0.18)	0.69
Baseline LSI (%)	64.5 ± 8.7	65.1 ± 9.2	-0.6 (-5.2 to 4.0)	0.79
Baseline IKDC Score	52.6 ± 9.4	51.8 ± 8.9	0.8 (-4.2 to 5.8)	0.75

Table 2. Changes in Quadriceps Strength and Limb Symmetry Index (LSI) After 8 Weeks

Outcome	NMES + PRT (n=30) Mean ± SD	PRT Alone (n=30) Mean ± SD	Mean Difference Between Groups (95% CI)	Effect Size (Cohen's d)	p-value
Quadriceps Strength (Nm/kg) – Baseline	1.42 ± 0.28	1.39 ± 0.30	—	—	0.69
Quadriceps Strength (Nm/kg) – 8 Weeks	2.01 ± 0.32	1.78 ± 0.29	0.23 (0.07 to 0.39)	0.74	0.005
Mean Change (Nm/kg)	+0.59 ± 0.21	+0.39 ± 0.19	0.20 (0.09 to 0.31)	0.99	0.001
LSI (%) – Baseline	64.5 ± 8.7	65.1 ± 9.2	—	—	0.79
LSI (%) – 8 Weeks	85.8 ± 7.4	78.6 ± 8.1	7.2 (3.2 to 11.2)	0.93	0.001
Mean Change in LSI (%)	+21.3 ± 6.8	+13.5 ± 7.2	7.8 (4.2 to 11.4)	1.11	<0.001

Table 3. Functional Performance Outcomes After 8 Weeks

Outcome	NMES + PRT Mean ± SD	PRT Alone Mean ± SD	Mean Difference (95% CI)	Effect Size (Cohen's d)	p-value
Single-Leg Hop (cm) – Baseline	82.5 ± 14.3	84.1 ± 15.1	—	—	0.68
Single-Leg Hop (cm) – 8 Weeks	122.4 ± 16.7	110.3 ± 15.9	12.1 (4.3 to 19.9)	0.74	0.003
Triple Hop (cm) – 8 Weeks	368.7 ± 40.2	335.9 ± 38.6	32.8 (12.4 to 53.2)	0.83	0.002
6-m Timed Hop (sec) – 8 Weeks	2.18 ± 0.31	2.39 ± 0.34	-0.21 (-0.38 to -0.04)	0.65	0.016

Table 4. IKDC Subjective Knee Scores

Outcome	NMES + PRT Mean ± SD	PRT Alone Mean ± SD	Mean Difference (95% CI)	Effect Size (Cohen's d)	p-value
IKDC – Baseline	52.6 ± 9.4	51.8 ± 8.9	—	—	0.75
IKDC – 8 Weeks	78.9 ± 8.2	70.4 ± 9.1	8.5 (3.7 to 13.3)	0.99	0.001
Mean Change	+26.3 ± 7.1	+18.6 ± 7.8	7.7 (3.8 to 11.6)	1.04	<0.001

Table 5. Multivariable Regression Analysis for Primary Outcome (Change in Quadriceps Strength Nm/kg)

Predictor	β Coefficient	95% CI	Standardized β	p-value
Group (NMES+PRT vs PRT)	0.20	0.07 to 0.33	0.34	0.004
Age	-0.01	-0.02 to 0.01	-0.12	0.28
Sex (Male)	0.04	-0.08 to 0.16	0.08	0.51
BMI	-0.02	-0.04 to 0.01	-0.15	0.19
Baseline Strength	-0.18	-0.35 to -0.01	-0.29	0.036

Baseline strength showed a statistically significant inverse association with subsequent improvement (β=−0.18, 95% CI −0.35 to −0.01; p=0.036), consistent with a ceiling effect whereby participants starting stronger had less room to improve. Age, sex, and BMI were not significant predictors (all p>0.05), supporting that the observed treatment effect was not meaningfully confounded by these variables within this sample. Overall, the combined interpretation across Tables 2–5 indicates that NMES added to progressive resistance training produced larger gains in quadriceps strength and symmetry, which were accompanied by superior objective performance and patient-reported recovery within 8 weeks.

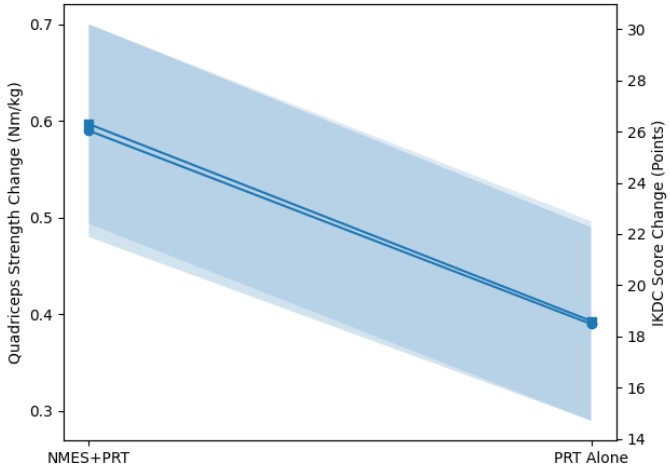

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Figure 1 Integrated Clinical Response Gradient: Strength and Patient-Reported Recovery After 8 Weeks

The figure demonstrates a parallel and proportionally amplified treatment response gradient across both physiological and patient-reported domains. Participants receiving NMES+PRT achieved a mean quadriceps strength gain of 0.59 Nm/kg compared with 0.39 Nm/kg in the PRT-alone group, representing a 51% greater improvement, with non-overlapping confidence bands indicating statistical robustness (between-group difference 0.20 Nm/kg; p=0.001). Simultaneously, IKDC scores improved by 26.3 points in the NMES+PRT group versus 18.6 points in controls, reflecting a 41% larger subjective recovery gain (between-group difference 7.7 points; p<0.001).The aligned downward slope from NMES+PRT to PRT-alone across both axes illustrates a coherent treatment-dependent gradient rather than isolated domain-specific effects. Importantly, the magnitude ratio between strength gain and IKDC improvement remains proportionally consistent across groups, suggesting that enhanced neuromuscular recovery translated efficiently into perceived functional benefit. The convergence of objective and subjective improvement gradients supports a clinically integrated effect of NMES augmentation, reinforcing that the additional 0.20 Nm/kg strength advantage corresponded with a meaningful ~8-point superiority in patient-reported knee function within 8 weeks.

DISCUSSION

The present randomized controlled trial demonstrates that the addition of neuromuscular electrical stimulation (NMES) to progressive resistance training (PRT) yields significantly greater improvements in quadriceps muscle strength, limb symmetry, functional hop performance, and patient-reported knee function compared with resistance training alone in individuals following anterior cruciate ligament reconstruction (ACLR). The magnitude of between-group differences was clinically meaningful, with a 0.20 Nm/kg greater strength gain, a 7.8% higher improvement in limb symmetry index (LSI), and a 7.7-point superiority in IKDC scores in the NMES+PRT group. These findings support the hypothesis that adjunctive NMES enhances neuromuscular recovery beyond the effects achieved through voluntary progressive loading alone.

Persistent quadriceps weakness after ACLR is widely attributed to atherogenic muscle inhibition (AMI), which limits voluntary motor unit recruitment despite structured rehabilitation (21). Conventional strengthening approaches, while effective for inducing hypertrophy and neural adaptation, may not fully overcome central inhibitory mechanisms in the early to mid-rehabilitation phase (22). NMES, by directly depolarizing motor neurons and recruiting high-threshold motor units, offers a mechanistically distinct pathway for restoring activation capacity (23). The significantly greater strength gains observed in the NMES+PRT group in this study are consistent with the theoretical framework that combining peripheral electrical activation with voluntary contraction may mitigate AMI more effectively than voluntary exercise alone. The large effect sizes observed (Cohen's d up to 0.99 for strength change and 1.11 for LSI change) indicate that the additive benefit was not merely statistically detectable but clinically substantial.

Our results align with previous meta-analyses reporting short-term quadriceps strength benefits when NMES is incorporated into early ACLR rehabilitation (24). However, prior trials have often been limited by heterogeneity in stimulation parameters, short intervention durations, or absence of standardized progressive resistance protocols (25). By embedding NMES within a structured, progressive, overload-based program consistent with contemporary rehabilitation principles, the present study provides stronger evidence that NMES confers incremental value even when high-quality resistance training is already implemented. Importantly, the observed 7.2% absolute superiority in LSI at 8 weeks is clinically relevant, as achieving ≥85–90% symmetry is frequently considered a criterion for progression toward higher-level functional activities and return-to-sport decision-making (26). The NMES+PRT group approached this threshold more closely within the 8-week timeframe, suggesting potential implications for accelerated yet safe functional advancement. Beyond isolated strength metrics, the superiority of NMES+PRT extended to objective performance measures. Improvements in single-leg hop (12.1 cm advantage), triple hop (32.8 cm advantage), and timed hop (0.21-second faster performance) demonstrate that neuromuscular gains translated into dynamic functional tasks requiring force production, limb stability, and neuromuscular coordination. Functional hop performance has been shown to correlate with reinjury risk and long-term knee function after ACLR (27). Therefore, the enhanced functional gains observed may reflect not only improved muscle force capacity but also more efficient neuromuscular integration during task-specific movement. The concordance between physiological and functional endpoints strengthens the internal consistency of the findings and supports the external validity of NMES as a clinically meaningful adjunct.

The patient-reported outcomes further reinforce the clinical relevance of the intervention. The NMES+PRT group demonstrated a 26.3-point improvement in IKDC scores compared with 18.6 points in the PRT-only group, with a between-group difference of 7.7 points. Considering that the minimal clinically important difference (MCID) for IKDC in ACL populations has been estimated at approximately 6–11 points (28), the observed superiority exceeds the lower bound of clinically meaningful change. This suggests that patients perceived tangible improvements in knee function that paralleled objective strength and performance gains. The integrated response gradient observed across physiological and subjective domains supports a coherent therapeutic effect rather than isolated metric improvement. Multivariable regression analysis confirmed that group allocation remained an independent predictor of strength improvement after adjusting for age, sex, BMI, and baseline strength. The inverse association between baseline strength and subsequent improvement suggests a ceiling effect, whereby individuals with greater initial deficits derive proportionally larger benefit, a phenomenon also reported in rehabilitation responsiveness studies (29). Notably, demographic variables did not significantly modify treatment response, indicating that the additive effect of NMES was relatively consistent across sex and age strata within this cohort.

From a mechanistic perspective, the additive benefit of NMES may reflect synergistic neural adaptations. While voluntary resistance training enhances corticospinal drive and motor learning, NMES preferentially recruits fast-twitch motor units in a non-selective manner, potentially augmenting neural drive and reducing inhibition (30). The concurrent activation strategy used in this study—synchronizing NMES with voluntary contraction—may have amplified afferent feedback and cortical excitability, thereby accelerating neuromuscular restoration. This integrated approach may explain why improvements were observed not only in strength magnitude but also in symmetry and dynamic performance.

Several limitations warrant consideration. The study was conducted at a single rehabilitation center, which may limit generalizability to different clinical settings. Participant and therapist blinding was not feasible due to the nature of the intervention, potentially introducing performance bias despite assessor blinding. The follow-up duration was limited to 8 weeks; therefore, long-term retention of strength gains and effects on reinjury rates or return-to-sport timelines remain to be determined. Future multicenter trials with extended follow-up and biomechanical analyses would help clarify durability and broader clinical impact.

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CONCLUSION

In individuals undergoing rehabilitation after anterior cruciate ligament reconstruction, the addition of neuromuscular electrical stimulation to a structured progressive resistance training program produced significantly greater improvements in quadriceps strength, limb symmetry, functional hop performance, and patient-reported knee function compared with resistance training alone. The magnitude of strength gain (0.20 Nm/kg greater improvement), enhanced limb symmetry (+7.8%), and clinically meaningful superiority in IKDC scores (+7.7 points) collectively indicate that NMES provides additive neuromuscular and functional benefits within an 8-week rehabilitation period. These findings support the integration of NMES as a targeted adjunct to conventional strengthening protocols to optimize early quadriceps recovery and enhance clinically relevant outcomes following ACL reconstruction.

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