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Comparative Effects of NMES and Resistance Training on Lower Limb Strength

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Abstract

This review systematically compares the effects of neuromuscular electrical stimulation (NMES) and conventional resistance training on lower limb strength development, and evaluates the transfer of strength gains to functional motor performance as well as parameter optimisation strategies. The main findings are as follows: (1) Under training volume-matched conditions, NMES-induced maximal lower-limb strength gains are equivalent to those of conventional resistance training (effect size difference 0.023, p= 0.836); whole-body electrical muscle stimulation (WB-EMS) can achieve equivalent strength improvements within extremely short training durations, demonstrating marked time efficiency. (2) The effects of NMES on speed strength and explosive power are divergent; evidence for independent application on jumping, sprinting and agility is weak, and transfer effects may emerge only when combined with sport-specific dynamic training (e.g., plyometric training). (3) Superimposed NMES training shows a small-to-moderate independent advantage in muscle hypertrophy (SMD = 0.26), but direct comparative data between standalone NMES and conventional resistance training are limited. (4) Optimisation strategies for stimulation parameters: high frequencies (50–100 Hz) favour immediate strength gains, while low frequencies (20–50 Hz) are more suitable for rehabilitation or endurance-oriented purposes; intensity must reach the maximally tolerated level with gradual progression; contraction-rest cycles, electrode placement, joint angle and training frequency (1–2 sessions per week) all significantly influence therapeutic efficacy.

Keywords

NEMS; Resistance Training; Lower Limb Strength.

1. Introduction

Neuromuscular Electrical Stimulation (NMES) is a non-invasive training modality that delivers electrical currents at specific frequencies and intensities to the neuromuscular system, inducing passive muscle contraction. The earliest applications of NMES date back to rehabilitative medicine, where it was primarily used to prevent muscle atrophy resulting from prolonged immobilization and to facilitate the recovery of neuromuscular function. With advancing research, its scope has gradually expanded into competitive sports training. In recent years, multiple studies have confirmed the potential value of NMES in enhancing muscle strength. Furthermore, research on young football players has shown that combining NMES with proprioceptive neuromuscular facilitation (PNF) stretching techniques can effectively improve hamstring flexibility and potentially reduce the risk of injury.

In the practical context of competitive sports conditioning, lower-limb strength constitutes the physiological foundation for male athletes to perform key technical movements such as jumping, sprinting, changing direction, and physical confrontations. Although traditional resistance training (e.g., squats, leg presses, deadlifts) is widely recognized as the primary

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method for developing lower-limb strength, its high-intensity nature entails substantial loading on the spine and lower-limb joints, accumulation of central nervous system fatigue, and difficulties in implementation during the in-season period—issues that have long challenged coaches and athletes. Particularly for athletes in sports such as basketball and football during the competitive season, how to effectively maintain or even improve lower-limb strength while avoiding excessive fatigue and injury risk has become an urgent practical problem.

From a practical standpoint, male athletes, as the backbone of competitive sports, have their lower-limb strength levels directly influencing athletic performance and competition outcomes. Localized NMES, owing to its portability, low joint load, and precise targeting of specific muscle groups, holds unique application value during training transition periods, injury rehabilitation phases, and congested match schedules. While traditional resistance training is undoubtedly effective, it is accompanied by prolonged post-training recovery periods and high joint loading. A systematic comparative study of these two modalities is therefore not only conducive to revealing the differences in their effects on strength development but also capable of providing scientific evidence for the design of individualized training programs for athletes.

Given the above practical challenges, this study selects "localized electrical muscle stimulation" and "traditional resistance training" as two lower-limb strength training methods. With male athletes as participants and under strictly dose-matched experimental conditions, we systematically compare the effects of the two interventions on maximal lower-limb strength, explosive power, and speed performance.

2. Comparative Analysis of NMES and Conventional Resistance Training on Lower Limb Strength Development.

2.1. Maximal Strength Gains Under Volume-Matched Conditions

Maximal strength is the most direct indicator for evaluating training effects and represents the dimension with the most accumulated evidence in comparative studies between NMES and conventional resistance training. Gabriel's systematic review and meta-analysis included 19 randomised controlled trials, all of which ensured equal total training volume between the electrical stimulation and voluntary contraction groups. The meta-analytic results showed that the effect size difference in strength gains between the two groups was only 0.023, with a 95% confidence interval of [−0.198, 0.246] and $p = 0.836$, failing to reach statistical significance. This indicates that, under volume-matched conditions, the maximal strength gains produced by NMES training are nearly identical to those of conventional strength training. Further subgroup analyses based on stimulation frequency and whether voluntary contraction was superimposed also revealed no significant intergroup differences, confirming from an evidence-based perspective the independent effectiveness of NMES in improving lower-limb maximal strength.

In terms of training efficiency, a randomised controlled trial published in 2025 compared two training regimens: the whole-body electrical muscle stimulation (WB-EMS) group underwent only 20 minutes of training per week, whereas the conventional resistance training group performed two 60-minute sessions per week for 10 weeks. Results showed that in squat 1-RM improvement, the WB-EMS group reached +36% ($p = 0.0001$) and the conventional resistance training group +34% ($p = 0.0001$), with comparable improvements and no significant interaction effect This study demonstrates that WB-EMS can achieve maximal strength gains equivalent to conventional resistance training under substantially shortened training durations, highlighting its unique advantage in time efficiency. Another 20-week direct comparative study further enriched this conclusion: conventional resistance training was superior to EMS in maximal strength improvement across multiple exercises (bench press, leg press, shoulder press), yet both modalities effectively enhanced strength performance. Overall, under

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volume-matched conditions, standalone NMES is essentially equivalent to conventional resistance training in lower-limb maximal strength gains; when volumes are not matched, conventional resistance training yields more comprehensive overall strength development.

2.2. Evidence Divergence in Speed Strength and Explosive Power Development

Compared with maximal strength, the effects of NMES on speed strength and explosive power show a divergent pattern. A systematic review published in 2026 analysed the effects of WB-EMS on jumping, sprinting and agility performance in athletes, including 12 studies with 293 participants. Meta-analytic results showed that WB-EMS superimposed protocols did not produce significant positive effects on maximal jump height (SMD = 0.34, 95% CI: −0.35 to 1.03), sprint performance (SMD = 0.07, 95% CI: −0.66 to 0.80), or agility (SMD = −0.11, 95% CI: −1.28 to 1.06). Another review published in 2011 analysed the effects of EMS on athletic performance, incorporating 12 studies, and showed that EMS could effectively improve athletes' anaerobic power (vertical jump and sprint capacity). Narvaez's meta-regression analysis also found a trend-based association between stimulation frequency and study effect sizes, suggesting that high-frequency electrical stimulation may favour preferential recruitment of fast-twitch motor units, thereby playing a role in explosive power development.

Notably, a 2024 randomised controlled trial that integrated whole-body electrical stimulation into running training reported negative results: after 8 weeks of intervention, neither the experimental group (running + WB-EMS) nor the control group (running alone) showed significant improvements in countermovement jump height, and knee extensor strength even slightly decreased. This finding supports the principle of training specificity for strength adaptations—embedding NMES in endurance-type training does not effectively translate into explosive power gains. In summary, the effect of standalone NMES on explosive power remains highly uncertain, largely depending on stimulation parameter selection, the manner of superimposed exercise, and participants' training background; evidence for purely passive NMES in enhancing explosive power is weak.

2.3. Comparative Effects on Muscle Hypertrophy

Muscle hypertrophy is another core indicator for evaluating strength training outcomes. At the direct comparison level, Narvaez's 2025 meta-analysis including 13 randomised controlled trials showed that superimposed NMES training had a significant advantage in muscle mass gains (SMD = 0.26, 95% CI: 0.04–0.49, p= 0.02, I^2 = 21.45%), with a small-to-moderate effect size and low heterogeneity[2]. This provides robust evidence for the independent contribution of superimposed NMES in promoting muscle hypertrophy

However, in direct comparisons between standalone EMS and conventional resistance training, the evidence is not entirely consistent. A 20-week intervention study found that conventional resistance training was more effective in reducing body fat percentage, whereas the EMS group showed greater advantages in reducing body weight and BMI, yet direct comparative data on muscle hypertrophy between the two modalities remain limited. Another study reported, over a 16-week intervention, that superimposed EMS increased leg extension strength by 7%–9%, an improvement partly attributable to increased muscle cross-sectional area. Taken together, the potential of NMES to induce muscle hypertrophy has been preliminarily validated, but the number of studies directly comparing its standalone effects with conventional resistance training is insufficient and their quality is heterogeneous.

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3. Transfer of NMES-Induced Strength Gains to Functional Motor Performance

3.1. Limited Overall Transfer Effects

Neuromuscular electrical stimulation has been demonstrated in numerous studies to effectively enhance lower-limb maximal strength. However, the core principle in strength training—the principle of training specificity—dictates that strength gains do not necessarily translate into improved functional motor performance. Specifically, whether NMES-induced strength gains can effectively transfer to sport-specific performances such as jumping, sprinting and change-of-direction manoeuvres is a key issue in evaluating its value in athletic training. Existing evidence indicates that, although NMES can produce significant strength gains, its transfer to functional motor performance remains highly controversial, with research conclusions showing clear divergence.

The highest-quality recent evidence tends not to support independent transfer effects of NMES on functional motor performance. A 2026 systematic review and meta-analysis by Püttner et al. specifically examined the effects of WB-EMS on jumping, sprinting and agility performance, including 12 studies with 293 participants, of which 10 jumping studies and all sprint and agility studies adopted superimposed WB-EMS protocols compared with the voluntary exercise onto which it was superimposed. Results showed that WB-EMS did not produce significant positive effects on maximal jump height (SMD = 0.34, 95% CI: −0.35 to 1.03), sprint performance (8 studies, SMD = 0.07, 95% CI: −0.66 to 0.80), or agility (5 studies, SMD = −0.11, 95% CI: −1.28 to 1.06), with substantial heterogeneity across studies ($I^2 > 80\%$). The study clearly stated that superimposed WB-EMS yielded only limited additional effects on jumping, sprinting and agility performance compared with the high-intensity voluntary exercise onto which it was superimposed.

3.2. Effects Depend on Precise Training Protocol Design

In contrast to the above evidence, another group of high-quality studies reveals positive possibilities for transfer effects under specific conditions. Micke et al. (2023) published in the European Journal of Sport Science a systematic review and network meta-analysis including 36 studies with 1,092 participants, establishing four evidence networks for strength, jumping, sprinting and aerobic capacity. The most important finding was that the transfer effects of EMS are highly dependent on stimulation protocol design. The highest effect size for jumping performance came from the combined protocol of "resistance training superimposed with EMS plus additional jumping training" (SMD = 3.14, 95% CI: 1.80 to 4.49), while the highest effect size for sprint performance came from "jumping training superimposed with WB-EMS" (SMD = 1.65, 95% CI: 0.67 to 2.63). The study thus concluded that the effectiveness of EMS training is highly dependent on the chosen EMS method, with training volume, intensity, movement pattern and movement specificity playing key roles; superimposed EMS is most likely to produce positive adaptations in athletes when delivered with relatively low EMS volume, high-intensity stimulation, and movement forms matched to sport-specific movement patterns.

Gondin et al.'s review also expressed a similar position: the effects of NMES on dynamic strength, motor skills and explosive actions (e.g., jumping and sprinting ability) remain unclear, and "only when NMES is combined with voluntary dynamic training (e.g., plyometric training) can such effects be obtained." In other words, standalone NMES is unlikely to produce significant transfer to functional performance, but when used as an adjunct to plyometric or dynamic resistance training, transfer effects may emerge.

A randomised controlled trial by Dörmann et al. (2019) provided direct empirical evidence for the above viewpoint. The study randomly assigned 22 active females to a strength-training-only group and a strength-training-plus-WB-EMS group for 4 weeks. Results showed that both

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groups achieved comparable improvements in linear sprint speed, change-of-direction speed and jump performance, with WB-EMS showing no superiority over strength training alone; the study therefore concluded that WB-EMS could serve as a "reasonable but not superior alternative" to classical training protocols. This finding further suggests that when NMES is applied merely as a superimposition onto conventional strength training, its additional contribution to functional performance may be marginal.

4. Training Protocol Optimisation and Stimulation Parameter Setting Strategies

4.1. Stimulation Frequency: Core Regulator of Strength Development

The systematic review and meta-analysis by Happ and Behringe included 19 randomised controlled trials that directly compared NMES with conventional strength training under volume-matched conditions. Meta-regression analysis revealed an important trend between stimulation frequency and study effect size: higher frequencies tended to correspond to larger effect size differences (predicted effect size = −0.599 + 0.008 × Hz, p= 0.176). Although not statistically significant, this trend provides an important reference for frequency selection optimisation. From a neurophysiological perspective, high-frequency stimulation (>80 Hz) promotes temporal summation of postsynaptic excitatory potentials and reflexively activates spinal motor neurons via Ia afferent fibres, thereby enhancing force output.

In rehabilitation and clinical settings, Arhos et al., based on evidence-based practice for post-arthroplasty rehabilitation, recommended NMES frequencies of 50–75 Hz. A 2025 original study published in the *Journal of Exercise Rehabilitation* directly compared the effects of high-frequency (100 Hz) and low-frequency (50 Hz) NMES on neuromuscular function and muscle mass. Results indicated that high frequency significantly increased maximal voluntary isometric contraction (MVIC) during the intervention period, suggesting immediate neuromuscular improvement, whereas the significant effects of low frequency (particularly muscle quality improvement assessed by ultrasound echo intensity) emerged only after the intervention ended. Statistical analysis revealed a significant time-by-intervention interaction, confirming that NMES adaptations are frequency-dependent. This study indicates that frequency selection is key to designing effective NMES protocols: high frequencies promote immediate strength gains, while low frequencies yield delayed muscle quality improvements.

Taken together, frequency selection optimisation should follow a tiered strategy: strength- and power-oriented training preferentially uses high-frequency stimulation of 50–100 Hz to maximise motor unit recruitment efficiency; endurance-oriented or early-rehabilitation settings may adopt low-to-medium frequencies of 20–50 Hz.

4.2. Stimulation Intensity: Core Dose Determinant of Training Efficacy

Stimulation intensity is the most critical and challenging parameter in NMES training, as its setting directly determines the magnitude of evoked torque and the effectiveness of the training stimulus. The general consensus in the field is that intensity should reach the individual's maximally tolerated current to ensure adequate motor unit recruitment. Early studies showed that NMES training at maximally tolerated current could increase maximal voluntary isometric contraction strength by approximately 15.6%. However, a systematic review also noted that, although all 10 included studies reported significant strength gains after EMS treatment, methodological heterogeneity and inconsistent EMS application protocols across studies precluded determination of optimal thresholds for treatment duration, EMS intensity, pulse and frequency.

In practice, progressive increases in stimulation intensity are crucial. Because NMES-evoked contractions exhibit non-physiological motor unit recruitment order (preferential activation of

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superficial fast-twitch fibres) and synchronised discharge patterns, subjects typically experience considerable discomfort in the initial training phase. Therefore, a gradual incremental strategy is recommended to allow subjects to adapt to the electrical stimulation sensation and eventually reach therapeutic dose levels. From the perspective of wide-pulse protocols, wide-pulse high-frequency NMES can produce greater maximal evoked torque at lower stimulation intensities while reducing the maximally tolerated current intensity, thereby alleviating discomfort and improving training tolerance.

4.3. Contraction-Rest Cycles and Single-Session Duration

The contraction-rest cycle determines the temporal ratio between stimulation and recovery in NMES training, directly influencing fatigue accumulation and training tolerance. The NSCA Spanish Chapter position statement indicates that conventional WB-EMS protocols use cycle settings of 4-s contraction-4-s rest or 6-s contraction-4-s rest. Studies have shown that even WB-EMS training once per week can produce significant improvements in maximal oxygen uptake, running economy and vertical jump performance within 6 weeks. For local NMES training targeting specific muscle groups, a single session typically includes 15–30 evoked contractions, each lasting 5–10 s. Training volume should follow a progressive principle, starting from lower volumes and gradually increasing contraction number and duration.

4.4. Electrode Placement and Joint Angle Optimisation

Electrode placement directly affects current pathways and activation of target muscles. No standardised electrode placement positions exist in the current literature, but the general consensus is that electrodes should be placed along the muscle fibre orientation. For quadriceps stimulation, two electrodes are recommended, one over the muscle bellies of the rectus femoris and vastus intermedius, and the other over the vastus medialis]. Ackermann et al., in a 2024 review, pointed out that one major challenge of NMES is poor patient compliance, often stemming from improper electrode placement and discomfort during treatment. The study emphasised that optimising stimulation parameters, including electrode localisation, is crucial for improving comfort and therapeutic outcomes.

NMES-related outcome measures may be influenced by muscle length (i.e., joint angle), as muscle length is an important regulator of myofibrillar force-generating capacit. Muscle length affects contractile force production by altering the overlap between actin and myosin filaments; this mechanism also applies to NMES—however, it should be noted that electrically evoked contractions differ from voluntary contractions in motor unit recruitment patterns, so the optimal muscle length for NMES should be determined based on NMES-specific evidence rather than simply extrapolating from voluntary contraction studies.

4.5. Training Periodisation and Frequency

Optimisation of training frequency requires balancing stimulation adaptation and adequate recovery. The systematic review and meta-analysis by Kemmler et al. showed that WB-EMS effectively increases muscle mass and strength across a wide age range of 18–77 years, with training frequencies of 1–2 sessions per week being most common. In athletic training contexts, the network meta-analysis by Micke et al. further indicated that EMS effectiveness is highly dependent on protocol design; superimposed EMS is most likely to produce positive adaptations in athletes when delivered with relatively low training volume, high-intensity stimulation, and movement forms matched to sport-specific movement patterns. Regarding training cycle duration, existing high-quality studies mostly employ intervention periods of 4–16 weeks, with insufficient evidence to support superiority of any particular cycle length over others.

Notably, the detraining effect of EMS training is also a factor that must be considered in protocol design. Similar to conventional strength training, NMES-induced neuromuscular adaptations

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gradually subside after cessation of training. It is recommended that EMS be integrated into periodised training plans, with phased use rather than continuous high-intensity stimulation to maintain adaptations and avoid adaptive plateaus. In terms of training period arrangement, EMS can be used as a high-intensity supplementary phase to conventional strength training (e.g., 4–6 weeks), followed by a maintenance phase based primarily on voluntary training, thereby achieving fluctuating management of training stimuli.

5. Research Commentary

The effectiveness of neuromuscular electrical stimulation in strength gains has received substantial evidence-based support. Current studies indicate that, under strictly volume-matched conditions, standalone NMES training and conventional resistance training produce nearly identical improvements in lower-limb maximal strength, with the effect size difference failing to reach statistical significance. Whole-body electrical stimulation protocols, while significantly reducing training duration, can still achieve squat maximal strength gains equivalent to conventional resistance training, demonstrating their unique advantage in time efficiency. Moreover, superimposing NMES onto voluntary contraction training has been confirmed to produce superior muscle hypertrophy effects compared with resistance training alone, with an independent contribution reaching a small-to-moderate effect size and low inter-study heterogeneity.

However, the transfer of NMES-induced strength gains to functional motor performance shows clear divergence. The highest-quality systematic review and meta-analytic evidence indicates that neither WB-EMS superimposed protocols nor standalone applications produce significant positive effects on jump height, sprint performance or agility. Transfer effects may emerge only when NMES is combined with sport-specific dynamic training, such as plyometric training or movement forms matched to sport-specific movement patterns. This phenomenon suggests that the synchronised and spatially non-selective recruitment pattern induced by NMES, while conducive to maximal force output of isolated muscle groups, cannot readily translate into performance improvements in high-speed, multi-joint movement scenarios.

Regarding stimulation parameter modulation, frequency is the core variable determining the direction of strength adaptations. Meta-regression analysis revealed a trend whereby higher stimulation frequencies tend to correspond to larger effect sizes; high-frequency stimulation favours immediate maximal voluntary isometric contraction strength gains, while low-frequency stimulation may yield delayed muscle quality improvements. Stimulation intensity must reach the individual's maximally tolerated level, with a progressive incremental strategy to ensure adequate motor unit recruitment. Concurrently, electrode placement along muscle fibre orientation and selection of appropriate joint angles can effectively increase evoked torque and improve training tolerance. The existing literature generally agrees that integrating NMES into periodised training plans, with alternating phases of high-intensity stimulation and adequate recovery, is a key strategy for avoiding adaptive plateaus and maintaining training effects.

Although evidence for maximal strength gains and adjunctive hypertrophy is relatively clear, the field still has notable limitations. The high heterogeneity across studies in stimulation parameters, electrode positions and training protocols precludes establishment of unified optimal operational standards. Most intervention periods are concentrated in the 4- to 16-week range, lacking follow-up data on the rate of neuromuscular adaptation decay after detraining and the long-term effects of sustained electrical stimulation on voluntary neural drive efficiency. Future research should focus on standardising parameter reporting, exploring movement-synchronised triggered electrical stimulation protocols, and developing individualised

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prescriptions based on individual muscle fibre type characteristics, in order to overcome the current bottleneck in transferring NMES to sport-specific performance.

Localised electrical stimulation has a robust empirical basis for enhancing lower-limb maximal strength and assisting muscle hypertrophy, with outstanding time efficiency; however, in terms of transfer to explosive power and sport-specific performance, its independent effects cannot yet be compared with those of traditional high-intensity resistance training. The main limitation of current research lies in the excessive heterogeneity across studies in stimulation parameters, electrode placement and training protocols, making it difficult to formulate unified operational standards.

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