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ORIGINAL RESEARCH

The acute effect of neuromuscular electrical stimulation on optimum power performance in healthy individuals

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Abstract

Background: This study examines the acute effects of neuromuscular electrical stimulation (NMES) application on peak power (PP) and mean propulsive power (MPP) during a weighted squat jump (SJ_{Loaded}). **Methods**: Fourteen male students (age: 23.71 ± 2.30 years; height: 173.71 ± 6.89 cm; weight: 69.59 ± 9.08 kg; body mass index (BMI): 26.87 ± 3.49) from the Faculty of Sport Sciences participated voluntarily. PP and MPP values were measured during the SJ_{Loaded} movement, performed with an external load of 40% body weight, using a computer-integrated linear velocity transducer system (T-Force Dynamic Measurement System Ergotech Consulting SL, Murcia, Spain). NMES was bilaterally applied to the musculus hamstring and musculus quadriceps femoris for 20 minutes. The Shapiro-Wilk test, skewness and kurtosis values assessed data normality. **Results**: Differences between pre- and post-test PP and MPP power performances were analyzed using Paired Samples *t*-tests. Cohen's *d* (ES: effect size) and 95% confidence intervals (CI) were also calculated to assess the pairwise comparisons' magnitude. According to the analysis results, statistically significant improvements were observed in both PP ($t\,(13) = -2.612$, $p = 0.021$, d: −0.69 (−1.27; −0.10, 95% CI)) and MPP ($t\,(13) = -2.756$, $p = 0.016$, d: −0.73 (−1.32; −0.13, 95% CI), moderate effect) values after the NMES application. **Conclusions**: NMES significantly enhances PP and MPP during loaded squat jumps, highlighting its potential as a supplementary training tool for improving explosive power. Future studies should explore its long-term effects across different sports and populations, such as female athletes or older adults, to optimize training protocols. Research on NMES intensities and frequencies may provide insights into optimal parameters for power development and neuromuscular adaptation.

Keywords

Electrical stimulation; Power; Performance

1. Introduction

Neuromuscular electrical stimulation (NMES) is a technique that involves the application of pre-programmed electrical impulses through surface electrodes placed on the skin to elicit muscle contractions, leading to powerful muscle contractions [1, 2]. In other words, it is an intervention that can be easily administered with portable devices and involves both muscle re-education and facilitation, promoting the development of targeted neuromuscular tissue [3]. NMES was first introduced as a rehabilitation strategy to prevent lean tissue loss during periods of prolonged immobility as early as the 18th century [4]. Over time, this method became widely used in training protocols to enhance interventions, aiming to restore or maintain muscle function and mass in sports settings [5].

Although NMES does not require voluntary muscle contraction [6], initially limiting its use to healthcare settings, interest in its potential as an alternative method for enhancing athletic performance grew in the 1970s. This interest was partly driven by Russian researcher Yakov Kots's suggestion that even healthy individuals could be trained more effectively through NMES than with voluntary muscle contractions alone [4]. Studies have suggested that NMES interventions may offer equal or even greater benefits compared to traditional protocols involving voluntary exercise [2]. In a study by Mukherjee *et al.* [7] examining research from 2008 to 2020 on the effects of NMES on healthy adults, it was reported that NMES provided significant muscle strength and power gains across all studies reviewed and was deemed a safe strategy. Nonetheless, because NMES protocols are typically performed at submaximal intensity (maximum tolerable intensity), some argue that it is less effective than high-load voluntary resistance training for strength gains [3].

The patterns of motor unit recruitment underlying electrically stimulated contractions differ significantly from those that occur during voluntary contractions [2]. A motor unit, the structural element that triggers contraction in skeletal muscles, is composed of numerous muscle fibers [8], though the number of fibers per unit varies based on muscle function. The activation of more motor units results in greater force production. Thus, activating a single motor unit produces minimal force, multiple motor units produce a greater force, and the activation of all motor units results in maximal force production [9].

Moreover, voluntary contractions involve the progressive recruitment of motor units from smaller (type I) to larger soma units (type II), following Henneman's Size Principle. In contrast, NMES-recruited contractions reverse this order of recruitment, with larger motor units depolarized before smaller ones as current intensity increases [10]. This reversed recruitment pattern deviates from Henneman's principle. The inverse recruitment during electrical muscle stimulation is attributed to two main factors: the diameter of the primary motor neuron axon and the feedback effects of axonal branches and cutaneous afferents in the muscle [7]. Some researchers have noted that larger motor units are primarily located in the superficial regions of skeletal muscles, while smaller ones are generally found in deeper areas [10, 11]. This may explain why NMES predominantly recruits large motor units located directly beneath stimulation electrodes on the motor points of the targeted muscles, even though the deeper units are less frequently depolarized due to the rapid propagation of the electrical stimulus [11].

In NMES, oscillating pulses administered across multiple regions reduce motor unit discharge rates and increase the total accessible motor units by activating different units from each region, thereby first mitigating fatigue and then enhancing strength. Acute studies support the efficacy of these methods. The acute effects of NMES applications also include neuromodulatory influences that interact with neurotransmitter substances, potentially heightening the excitatory or inhibitory responses of receptors [12].

Theoretically, the premise of NMES applications aimed at increasing muscular strength is to generate more motor unit action potential than would normally occur during maximal voluntary muscle contractions [13]. Indeed, studies have demonstrated that advancements in technology, which allow for the modification of various waveforms and current modulations in electrical stimulation devices, have a positive impact on muscle strength [14–17]. In a study conducted on healthy individuals by Bircan *et al.* [15], the effects of bipolar interferential and low-frequency (symmetric biphasic) electrical stimulations on isokinetic muscle strength were investigated. In this study, participants received electrical stimulation at the maximum tolerable intensity for 15 minutes a day, five days a week, for three weeks while seated with their knees fully extended, and significant increases in isokinetic strength were observed in both groups. In a study aimed at determining whether exercise or electrical stimulation is more effective in increasing muscle strength, conducted on healthy women, it was found that both isometric exercises and stimulation applications using Russian current and high-voltage galvanic currents resulted in an increase in quadriceps femoris isometric muscle strength, but no statistically significant difference was observed between the groups in terms of strength gains [17]. Conversely, in a study comparing the effects of voluntary isometric contractions and NMES applications on muscle strength gains following anterior cruciate ligament (ACL) surgery, it was reported that greater strength gains occurred in the electrical stimulation group [14]. Moreover, during electrotherapy sessions applied to the m. quadriceps (musculus quadriceps) femoris and m. hamstring (musculus hamstring) muscle groups, not only muscle hypertrophy but also increases in mobility levels and electromyographic (EMG) activities were reported [3].

Power, regarded as a critical component and factor in athletic performance, is defined as the temporal rate of work (power = work/time) and is generally dependent on the ability to generate the maximum possible force [18]. Muscle strength is one of the primary biomarkers of physical performance in humans during actions and can be a key determinant of success, whether in athletes for sports activities or in individuals for daily activities [19]. Athletes need to possess a high level of power to perform fundamental movements such as jumps, throws, and sprints. Additionally, athletes participating in racket sports, team sports, martial arts, gymnastics, swimming, and diving must also have a well-developed power capacity. In many athletic movements, the success of performance is often linked to the amount of power applied to objects (*e.g.*, ground, ball, or sporting equipment), while success during specific athletic tasks completed in a short period depends on the athlete's capacity for power output [20].

Various parameters are used to assess power, with the most commonly applied being average power (AP), mean propulsive power (MPP), and peak power (PP) [21]. The AP refers to the mean value obtained from the sum of all positive values during the concentric phase, divided by the number of data points within the range of motion. MPP is the average power output during the propulsive phase of the concentric phase. PP is defined as the maximum power output across the entire concentric contraction range and is expressed as the peak power that reflects higher instantaneous power output over a 1 $\mathrm{m{\cdot}s^{-1}}$ period without observing a specific movement. Some authors describe this capacity as the maximum mechanical performance an athlete can generate in a movement, representing the moment at which threshold muscle performance is achieved [22].

Several studies have investigated the chronic effects of electrical stimulation on muscle strength after specific training periods. However, to the best of our knowledge, no studies have examined the acute effects of NMES (a method of electrical stimulation) on power parameters. Therefore, the present study aims to examine the acute effect of neuromuscular electrical stimulation (NMES) on peak power and mean propulsive power performance obtained during a weighted squat jump (SJ_{Loaded}) movement. The rationale for this study is that an increase in power is essential for successful performance in sports applications, and NMES may offer a positive contribution to power development in athletes due to its ease of use and time efficiency. Based on this, it is hypothesized that NMES application to the lower body will have a positive impact on the mean propulsive power and peak power values obtained during the concentric phase of the SJ_{Loaded} movement.

2. Materials and methods

2.1 Participants

Fourteen male students from the Faculty of Sport Sciences voluntarily participated in this study (Table 1). The minimum sample size for the current study was ascertained using G-power Software 3.1.9.7 (Heinrich Heine University Düsseldorf, Düsseldorf, NRW, Germany). A priori power analysis was conducted employing *t*-tests, in alignment with the study's design, which included a Paired Samples *t*-test. The design entailed two measurements at one time point. The parameters set for the analysis included an error probability (α) of 0.05 and a minimum effect size of 0.75. To achieve a power ($1 - \beta$ error probability) of 0.80, it was calculated that the minimum sample size required for statistical significance was 13 participants, thereby resulting in an actual power of 81.65%. The inclusion criteria for the study required participants to have no history of lower body muscle injuries in the last six months and to not be taking any medication that could negatively affect the study results. To minimize any potential negative impact on performance during testing, participants were instructed to abstain from alcohol and physical activity for 24 hours, smoking for more than two hours, consuming stimulants (*e.g.*, energy drinks and caffeine), and eating for more than three hours before the test. They were also asked to ensure they had sufficient sleep the night before the test (more than seven hours) and to perform the test protocol with maximal effort. Participants were provided with both written and verbal information regarding the study's purpose, test procedure, data collection process, and potential risks and benefits of participation. It was emphasized that they could withdraw from the study at any time, and written informed consent was obtained from each participant before the study. The experimental protocol was approved by the Igdir University Scientific Research and Publication Ethics Committee (SRPEC approval number: 10/27-3-2024), and the Declaration of Helsinki was conducted for all procedures.

2.2 Study design

A quasi-experimental crossover design, where participants served as their control, was used in this study. Before measurements, all participants underwent a standardized warm-up protocol consisting of a 10-minute low-intensity run on a treadmill (Trackmaster TMX425CP, Newton, KA, USA) at 40% of their maximum heart rate, followed by a 5-minute stretching routine targeting both lower and upper body muscles. After the warm-up, participants' peak power (PP) and mean propulsive power (MPP) values during the weighted squat jump (SJ_{Loaded}) movement were measured using a Smith machine (Hammer-Strength Equipment, Rosemont, IL, USA), which is a guided barbell system that moves along fixed vertical rails to ensure controlled movement. The exercise was performed with an external load equivalent to 40% of their body weight in two different sessions, ensuring consistent bar path and minimizing stabilization demands. The first measurement was performed without any intervention. Subsequently, the same test protocol was administered after participants underwent a 20-minute neuromuscular electrical stimulation (NMES) application. To eliminate the effects of fatigue and circadian rhythm, each test protocol was conducted 48 hours apart, within the same time window (09:00–11:00). One week before the measurements, an adaptation period was implemented to familiarize participants with the testing procedure. During this adaptation period, participants were provided with comprehensive instructions on the execution of the SJ_{Loaded} movement, ensuring they became sufficiently familiar with its performance. During the measurements, no verbal encouragement or additional motivational strategies were employed. The participants were recruited between 10 April and 18 April 2024, with all inclusion criteria being thoroughly evaluated and satisfied before their enrollment in the study. The experimental design of the study is visually represented in Fig. 1.

2.3 Anthropometric measurements

To determine the participants' height and body weight, a Seca 769 electronic measuring device (Seca GmbH & Co. KG, Hamburg, HH, Germany) with an accuracy of 0.001 m for height and 0.01 kg for weight was used, following a standardized procedure. Participants were allowed to wear only shorts and t-shirts to avoid affecting their body weight measurements, which were recorded in kilograms (kg). Height measurements were taken in centimeters (cm), ensuring that participants stood in a position where their body weight was evenly distributed on both feet. Body mass index (BMI) was calculated using the formula based on body weight and height (kg/m^2).

2.4 Neuromuscular electrical stimulation (NMES) protocol

Neuromuscular electrical stimulation (NMES) was applied bilaterally to the m. hamstring and m. quadriceps femoris muscles using a denervation-mode muscle rehabilitation device (Cefar Compex® Rehab, Cefar-Compex Medical AB, Malmö, Sweden) designed with various rehabilitation-specific programs. Although the participants were healthy with normal

TABLE 1. The characteristics of the participants.

	N	Minimum	Maximum	Mean ± SD
Age (yr)	14	21.00	30.00	23.71 ± 2.30
Height (cm)	14	161.00	185.00	173.71 ± 6.89
Body weight (kg)	14	57.30	86.00	69.59 ± 9.08
BMI (kg/m^2)	14	22.10	33.20	26.87 ± 3.49

BMI: body mass index; SD: Standard Deviation.

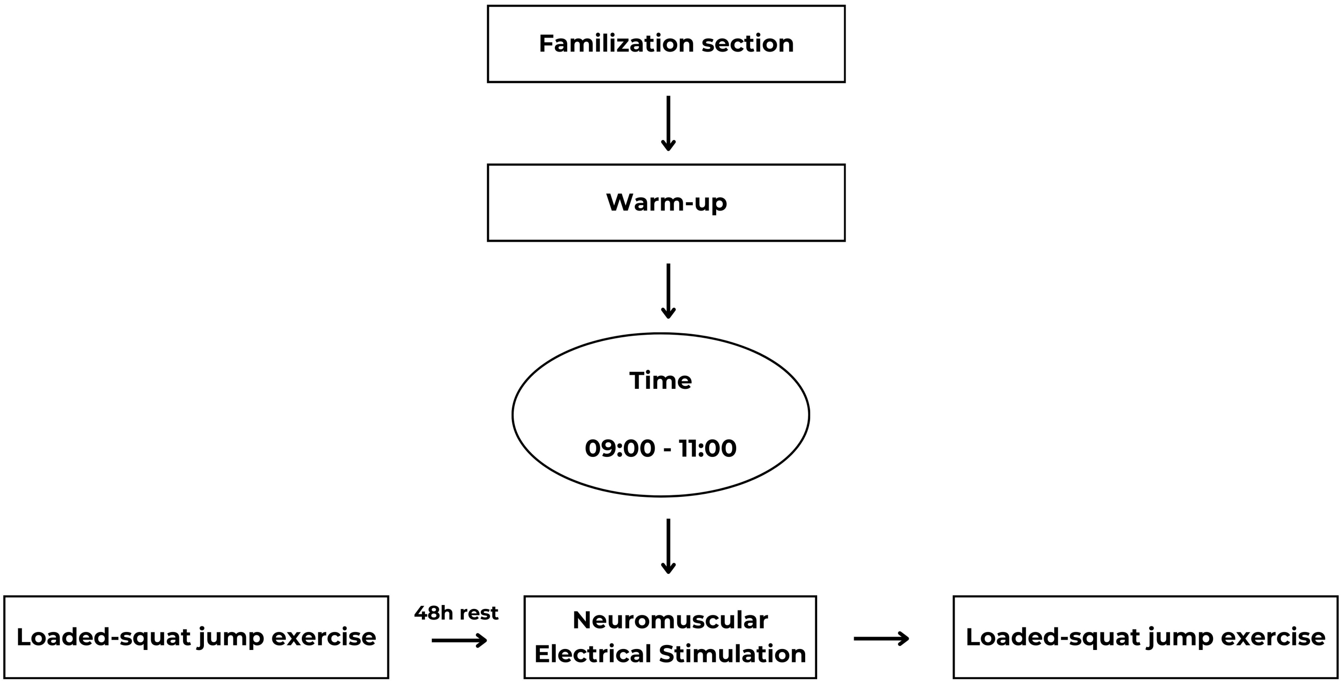

FIGURE 1. Experimental design of the study.

innervated muscles, a denervation-mode protocol was selected to ensure the direct and maximal recruitment of large motor units, which play a critical role in explosive power generation. This approach also provided a standardized and controlled environment to assess the acute effects of NMES on power performance, minimizing variability in muscle activation patterns typically seen with voluntary efforts. The placement of the electrodes was as follows: for the m. quadriceps femoris, the proximal electrode was placed 15 cm lateral to the spina iliaca anterior superior, while the distal electrode was positioned 4 cm proximal to the upper border of the patella, at the thickest point of the vastus medialis. For the hamstring muscle group, electrodes were placed at the origin of the musculus rectus femoris and at the motor point of the semitendinosus muscle (see Fig. 2). The electrical current was increased until a tetanic contraction was observed in the participants. During the 20-minute stimulation, if muscle contractions diminished, feedback was taken from the participants, and the current was adjusted to maintain consistent quality muscle contractions.

The stimulation protocol involved a 10-second stimulation phase followed by a 50-second rest period. This cycle was repeated for 10 repetitions in two sets, resulting in a total of 20 contractions over the 20-minute duration [16]. A pulsed current was applied at a frequency of 120 Hz with a maximum tolerance intensity, using a duration of 400 microseconds (μs) [23].

2.5 Determination of peak power and mean propulsive power

The participants' peak power (PP) and mean propulsive power (MPP) values were measured during the loaded squat jump (SJ$_{Loaded}$) movement, performed using a Smith machine (Hammer-Strength, Rosemont, IL, USA) with an external load corresponding to 40% of their body weight [24]. The measurements were recorded using a computer-integrated linear velocity transducer system (T-Force Dynamic Measurement System, Ergotech Consulting SL, Murcia, Spain). This system is widely used by sports scientists and strength and conditioning coaches to determine kinetics and kinematics in resistance exercises. Furthermore, the reason for utilizing a Smith machine instead of free weights for the SJ$_{Loaded}$ movement is its ability to restrict movement to a vertical plane, ensuring accurate and reliable measurements [25].

Given that the participant's body weight plays a crucial role in determining the external load for the SJ$_{Loaded}$ movement, each participant's body weight was measured before the test, and the corresponding external load for each individual was recorded. During the SJ$_{Loaded}$ movement, participants were instructed to flex their knees from a static position until their thighs were parallel to the ground and then jump upward as quickly as possible without losing contact between the bar and their shoulders. Since the power parameters are determined by the participant's ability to accelerate their total mass (external load and body weight), any incorrect or incomplete execution of the movement resulted in the repetition of the test [26].

2.6 Statistical analysis

Data analysis was conducted using the SPSS 26.0 (IBM Corp., Armonk, NY, USA) package program. The Shapiro-Wilk test results, considering skewness and kurtosis values, were evaluated to determine whether the data exhibited normal distribution. Based on these results, it was observed that the data exhibited normal distribution ($p > 0.05$). Differences between pre- and post-test peak (PP) and mean propulsive (MPP) power performances were analyzed using Paired Samples t-tests. Additionally, Cohen's d (ES: effect size) and 95% confidence intervals were calculated to measure the magnitude of pairwise

FIGURE 2. The placement of electrodes on the m. hamstring and m. quadriceps femoris.

comparisons. The magnitude of ES was classified as follows: trivial (<0.2), small (0.2 to 0.6), moderate (>0.6 to 1.2), large (>1.2 to 2.0), and very large (>2.0) [27]. Furthermore, changes in MPP and PP performance before and after electrical application were depicted using bar charts and line graphs. The graphs were created using GraphPad Prism 8.0.2.263 (GraphPad Software, San Diego, CA, USA). The significance level was considered as $p < 0.05$.

3. Results

As shown in Fig. 3, a statistically significant difference was found when comparing the MPP value before and after electrical application (t (13) = −2.756, p = 0.016, d: −0.73 (−1.32; −0.13, 95% CI), moderate effect). According to these results, it was observed that MPP performance significantly increased after electrical application.

As depicted in Fig. 4, it was found that there was a statistically significant improvement in PP performance after the electrical application when compared with the pre-test (t (13) = −2.612, p = 0.021, d: −0.69 (−1.27; −0.10, 95% CI), moderate effect).

4. Discussion

In recent years, there has been a noticeable shift in exercise forms and strategies, with new training principles and methods that aim to achieve desired exercise benefits while reducing training time. Although voluntary resistance training remains a traditional approach for strengthening muscles and achieving strength gains, there is growing interest in using electrical muscle stimulation (EMS) to replace the workload of voluntary resistance training for similar or even higher development outcomes. Therefore, NMES (also known as electrical muscle stimulation, electrostimulation or percutaneous electrical stimulation) is employed by researchers and practitioners today as an external training tool to efficiently improve strength in a time-effective manner [7]. NMES has been widely adopted as a rehabilitation and training method in both research and clinical settings [11].

Numerous studies have investigated the chronic effects of NMES applications on muscle strength after a specified training period. However, there is interest in determining whether NMES has an acute effect on PP (Peak Power) and MPP (Mean Peak Power) parameters achieved during the SJ_{Loaded} movement. Given that an increase in power is a critical factor for successful performance, NMES is thought to contribute positively to power development due to its ease of use and time efficiency. The findings indicate that the NMES application led to significant improvements in both MPP and PP performance during the SJ_{Loaded} movement. These results support the study's hypotheses, demonstrating that NMES can produce acute improvements in power generation, thus adding valuable insights to the literature.

In the current study, the focus was on the knee extensors (quadriceps) and flexors (hamstrings), which are the most frequently studied lower extremity muscles in the literature. The quadriceps and hamstrings are the primary muscle groups responsible for controlling knee movement and enhancing stability during any dynamic or functional movement, and strengthening these muscles plays a vital role in improving functional

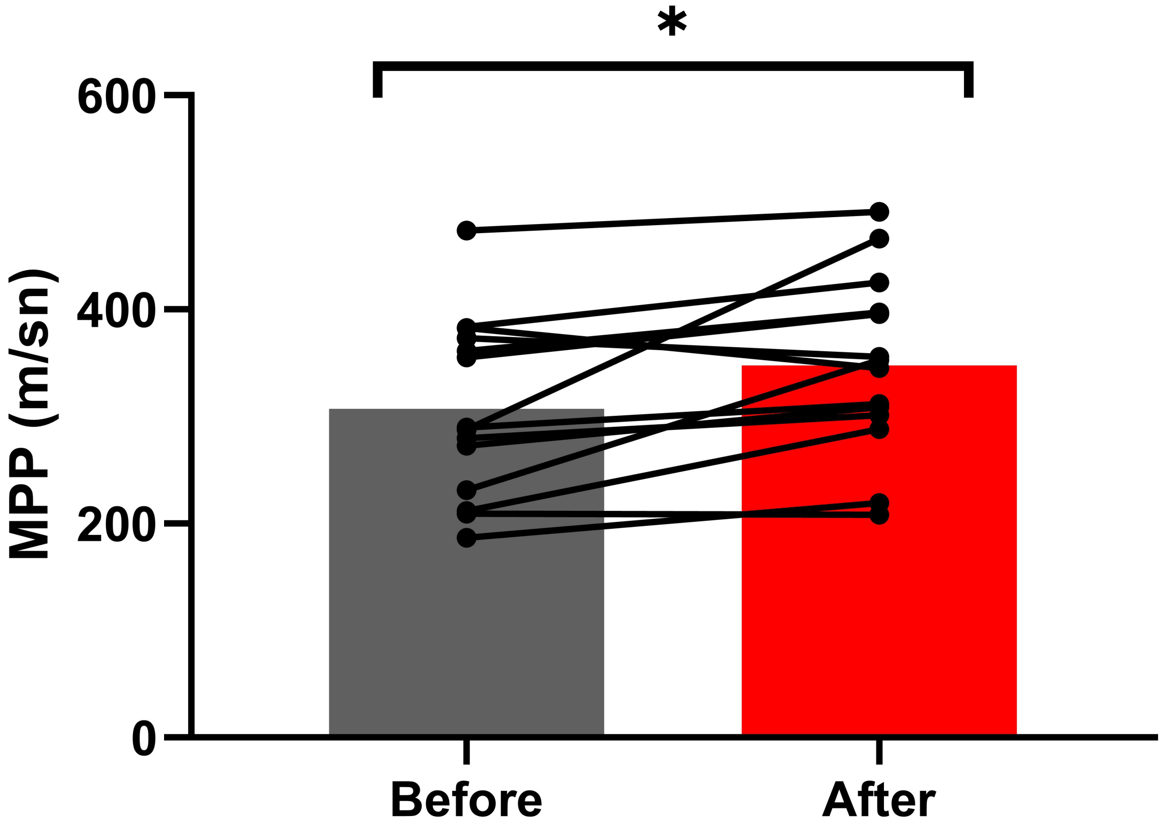

FIGURE 3. Changes in MPP (m/s) performance before and after electrostimulation application. MPP: mean propulsive. *Denotes a statistically significant difference between conditions at *p* < 0.05.

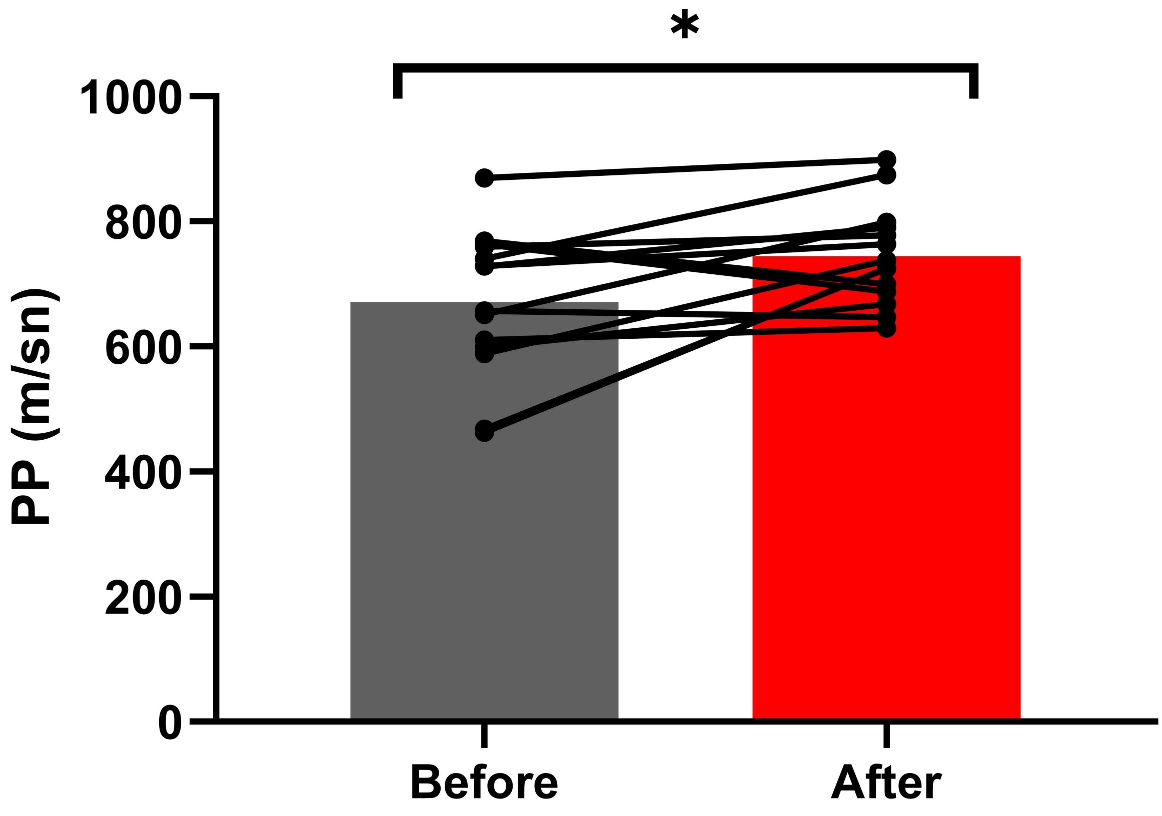

FIGURE 4. Changes in PP (m/s) performance before and after electrostimulation application. PP: Peak power. *Denotes a statistically significant difference between conditions at *p* < 0.05.

performance across various sports [5]. The popularity of selecting knee extensors and flexors is due to the abundance of existing evidence concerning these muscle groups, facilitating comparative analysis of findings [7]. Another possible reason is the focus on these muscle groups in the literature, as they play a vital role in functional and athletic performance. Additionally, the quadriceps and hamstrings are well-suited for evaluation using various testing methods, including force platforms, velocity transducers or isokinetic devices, facilitating comparative analysis across studies.

Additionally, the decision to avoid single-muscle NMES application in this study is due to its potential to induce muscle damage that can lead to up to a 20% reduction in muscle strength seven days post-application. There are two primary factors that directly or indirectly lead to these muscular tissue changes. During the repeated muscle fiber activation associated with NMES, direct damage may occur in weaker sarcomeres, similar to what has been suggested during muscle damage caused by voluntary eccentric exercises. Indirect damage, on the other hand, may arise from intramuscular strain and potential shear stress between the active and passive components of the stimulated muscles [28]. Additionally, Magnetic Resonance Imaging (MRI) findings have demonstrated that during contractions induced by single-muscle NMES, tissues outside the muscle (*e.g.*, connective tissues and/or intracellular structures) may also change [29]. Lastly, the decision to use bilateral NMES stimulation rather than single-muscle application in this study was based on its potential to distribute the workload more evenly across multiple muscle groups, thereby minimizing the risk of localized muscle strain and damage. Bilateral stimulation activates both agonist and antagonist muscle groups (*e.g.*, quadriceps and hamstrings), promoting neuromuscular coordination and reducing eccentric overload, which is a common cause of muscle damage. This approach ensured that the stimulation remained within a tolerable and safe range for healthy participants while achieving the desired neuromuscular activation. Functional tests of thigh muscle strength can also be performed using simple-to-administer and measure movements, such as squats and vertical jumps [7]. Therefore, the reason for employing the squat jump in the present study to assess lower body muscle strength is that this multi-joint movement is widely recognized as a reliable test for evaluating and developing explosive lower extremity muscle power [26, 30].

In the literature, although NMES is widely utilized as a training tool in the sports field due to its multiple effects on neuromuscular function [31], studies have also been conducted on its effects in healthy adult populations, albeit to a relatively lesser extent. These studies suggest that NMES could serve as an alternative method for strength gains in healthy adults. However, there are methodological variations among the protocols used in different studies, such as differences in intervention duration, pulse frequency, timing and type of NMES application, along with participants' training status, training duration and goals, targeted muscle groups and outcome measures. In addition to studies solely employing NMES, some studies combine voluntary resistance training with NMES applications.

Although the variations in NMES intervention protocols are tailored to the hypotheses, research questions and objectives of each study, the collective evidence indicates that while NMES has a positive effect on muscle strength, it does not have any significant impact on functional performance [7].

For instance, Bayrakdaroğlu [32] examined the effects of three different strength training programs (plyometric, complex and resistance) over 8 weeks on power parameters obtained from the loaded squat jump exercise. The analysis revealed that all three training methods significantly improved both peak power and mean propulsive power. Furthermore, when comparing which training method was more effective in developing power parameters, no statistically significant differences were found between the training protocols in terms of PP and MPP values. The lack of significant differences between the groups was attributed to the participants being active in combat sports (kickboxing, taekwondo, wrestling, boxing, Muay Thai and Wushu). These results align with the current study's findings, suggesting that different methods can similarly enhance power parameters, reinforcing the notion that NMES is an effective tool for power development regardless of the specific training approach used.

In a systematic review by Wang *et al.* [33], the effectiveness of plyometric and complex training methods, both widely applied to enhance explosive power, a critical factor in competitive sports, was investigated. The study analyzed 60 plyometric training and 27 complex training studies from the literature to determine which method better improved lower extremity explosive power. The review concluded that both complex and unloaded plyometric training methods had similar significant effects on explosive performance in the short term (within 10 weeks). However, loaded plyometric training showed a more pronounced effect. Furthermore, complex training was found to have a beneficial impact on maximal power compared to plyometric training, suggesting that unloaded or lightly loaded plyometric exercises should be applied during short pre-season periods, while complex training should be integrated into long-term or annual training cycles.

The positive effects of NMES on muscle strength and functional performance have been validated in numerous studies. In a study by Çalık *et al.* [17], both isometric exercises and NMES applications led to increases in quadriceps femoris muscle strength, though no statistically significant difference was found between the groups. This suggests that the effects of NMES on muscle strength may be as effective as traditional exercises. Similarly, Delitto *et al.* [14] reported that NMES resulted in greater increases in muscle strength following anterior cruciate ligament (ACL) surgery. Furthermore, in a study on healthy individuals by Bircan *et al.* [15] the beneficial effects of NMES on isokinetic muscle strength were demonstrated.

Lee *et al.* [34] also showed that NMES significantly contributed to the early restoration of deltoid muscle function following reverse total shoulder arthroplasty. According to the same researchers, NMES significantly improved shoulder external rotation range and strength during the postoperative period. Additionally, da Cunha *et al.* [35] demonstrated the positive effects of incorporating NMES into volleyball players' training programs, particularly on muscle strength and jumping ability. The study found significant improvements in both dominant and non-dominant lower extremity muscle strength following NMES application.

These findings are consistent with the results observed in the present study and further support the notion that NMES can be effectively integrated into athletes' training and rehabilitation processes. NMES has the potential to become a more widespread and impactful tool in improving athletic performance and aiding recovery.

The effectiveness of NMES in increasing muscle strength and enhancing functional performance is closely linked to physiological mechanisms. The process of strengthening nerve fibers as a result of NMES differs somewhat from other normal physiological mechanisms. Typically, with other physiological mechanisms, smaller diameter neurons are strengthened before larger motor neurons (alpha motor neurons) are reinforced [36]. Additionally, the long-standing theory suggests that the propagation speed of an action potential may increase by the square root of the corresponding nerve fiber's diameter [37]. In a study investigating the relationship between nerve fiber diameter and nerve conduction speed, it was found that NMES follows a "reverse recruitment" pattern in strengthening nerve fibers. According to this theory, the excitation threshold of nerves is inversely proportional to the diameter of the respective neuron, meaning that larger diameter fibers, which innervate fast-twitch, easily fatigable motor units, are preferentially activated [38]. While this pattern predisposes muscles to greater fatigability in prolonged or repetitive applications, the acute effects (enhanced performance in PP and MPP) observed in this study can be explained through specific physiological mechanisms: (1) synchronous activation of a large proportion of motor units generates high force output during short-duration tasks; (2) NMES-induced neuromodulation enhances motor neuron pool excitability, optimizing recruitment efficiency; (3) temporary increases in muscle-tendon unit stiffness improve force transmission during dynamic movements; and (4) preferential recruitment of fast-twitch fibers enhances the rate of force development. These mechanisms, supported by evidence from Blazevich *et al.* [12], Cavalcante *et al.* [39] and Gueugneau *et al.* [40], contribute to the significant improvements in peak and mean propulsive power observed after NMES application. Additionally, the controlled protocol in this study ensured fatigue was minimized, allowing the acute benefits of NMES to be fully realized.

Moreover, NMES-induced muscle activation is aligned with an increase in the content of Actin and Myosin proteins, which play a critical role in muscle contraction. The force generated through this activation enhances the muscle's ability to respond to tension. Similar to exercise, NMES causes an increase in the contractile protein content within muscle fibers [41, 42]. This process results in greater muscle strength and improved functional performance, making NMES a viable tool for both training and rehabilitation.

While the study shows promising findings, it comes with several limitations that must be acknowledged. Firstly, the sample size was limited to just 14 male participants, all of whom were university students without involvement in specific sports. This lack of diversity restricts the applicability of the results to a wider range of athletic populations, including female athletes, older adults or individuals engaged in sports with distinct physical requirements. Future research should strive to incorporate a more varied participant demographic to assess whether NMES yields similar outcomes across different groups and competitive levels. To eliminate participants' biases related to perceived effort or placebo effects and to enhance the validity of the results obtained, a placebo control group could be established in which participants receive a sham NMES application. Additionally, the current study focused solely on the immediate effects of NMES, evaluating performance right after the intervention. The long-term impact of NMES on power development remains unclear. It is uncertain if repeated sessions over a prolonged period would lead to sustained or improved power increases or if athletes might adapt in a way that diminishes NMES effectiveness over time. Future investigations should examine the chronic effects of NMES, assessing its role in long-term training regimens and its potential contribution to cumulative performance enhancements or hypertrophy. Another limitation pertains to the NMES protocol utilized in the study. NMES was applied bilaterally to the quadriceps and hamstrings at a standardized intensity and duration. However, individual responses to NMES can differ widely due to factors like muscle fiber composition, training history and neuromuscular efficiency. Some participants may need tailored intensities or electrode placements to achieve optimal outcomes. Thus, a more customized approach to NMES application could enhance its efficacy, and future studies should look into the effects of personalized NMES protocols on performance results. Lastly, the study used a single movement, the squat jump, to assess power performance. While this exercise is representative of lower-body explosive power, it does not fully capture the variety of movements and power demands encountered in different sports. To expand the practical applications of NMES, future studies should investigate its effects on various performance metrics, including sprinting, agility, upper-body power and sport-specific movements. This would provide a more comprehensive understanding of how NMES can enhance performance in specific sports contexts.

The results of this study highlight the potential of NMES to significantly improve both PP and MPP during dynamic movements like the loaded squat jump. This finding offers practical benefits for athletes across a wide variety of sports that require high levels of explosive power, such as sprinting, jumping, martial arts and team sports like basketball or soccer. For athletes seeking to optimize power output quickly—whether in preparation for a competition or as part of a regular strength and conditioning routine—NMES provides an efficient, non-invasive method to augment traditional training. The application of NMES could also be particularly useful in rehabilitation settings, where athletes recovering from injuries may face limitations in performing high-intensity, volitional exercises. NMES offers a way to maintain or even enhance muscular power without placing undue stress on the joints or tendons. Beyond the acute improvements in power, integrating NMES into a broader training regimen could help maintain power capacity during periods of reduced activity, such as during off-season or rehabilitation phases. Coaches and sports performance professionals can incorporate NMES into warm-ups or recovery sessions, utilizing its benefits to stimulate muscle contractions, improve motor unit recruitment and potentially reduce injury risks by enhancing muscle preparedness. For athletes in strength or power sports, the use of NMES could also serve as a supplementary technique to traditional resistance training, offering an additional tool for eliciting performance gains. Furthermore, NMES could be a valuable intervention for athletes who need to address muscular imbalances or weaknesses, particularly those returning from injury who may struggle to fully activate certain muscle groups. In practical settings, NMES devices are portable, easy to use and customizable, allowing practitioners to adjust intensity and duration according to the individual's needs. This flexibility makes NMES a versatile option for enhancing performance in both training environments and rehabilitation clinics. Overall, the findings of this study provide a compelling case for the incorporation of NMES in performance-enhancement programs across various athletic populations.

5. Conclusions

This study demonstrates that NMES application leads to significant increases in both PP and MPP performance during the loaded squat jump. These findings highlight the potential of NMES to enhance sports performance and support the development of muscle strength. Future research can expand the generalizability of these findings by investigating the effects of NMES in different sports and populations, thereby optimizing its use in training and rehabilitation processes. Additionally, a more detailed examination of the effects of NMES on the autonomic nervous system could provide a deeper understanding of the physiological mechanisms involved. Exploring innovative methods, such as the use of electrical impedance myography (EIM) to monitor muscle fatigue during NMES sessions, could further contribute to the safe and effective application of NMES.

ABBREVIATIONS

NMES, neuromuscular electrical stimulation; PP, peak power; MPP, mean propulsive power; SJ_{Loaded}, loaded squat jump; EMG, electromyographic; AP, average power; EMS, electrical muscle stimulation; ES, effect size; ACL, anterior cruciate ligament; SRPEC, Scientific Research and Publication Ethics Committee; EIM, electrical impedance myography; m. hamstring, musculus hamstring; m. quadriceps, musculus quadriceps; BMI, body mass index; CI, confidence intervals; MRI, Magnetic Resonance Imaging; SD, Standard Deviation.

AVAILABILITY OF DATA AND MATERIALS

The data used to support the findings of this study are available from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

İC and GY—Conceptualization. İC—methodology. SB, HİC—formal analysis. YB, SU, GES—investigation. İC, HİC, PTN—writing–original draft preparation. All authors writing–review and editing. All authors have read and agreed to the published version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The experimental protocol was approved by the Iğdır University Scientific Research and Publication Ethics Committee (SRPEC approval number: 10/27-3-2024), and all procedures were conducted following the Declaration of Helsinki. In addition, written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. Pantelis T. Nikolaidis is serving as one of the Editorial Board members of this journal. We declare that PTN had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to PP.

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