

Effects of electrical stimulation on neuromuscular efficiency, hypertrophy, and electromyographic activity in strength training practitioners

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Abstract:

Background: Neuromuscular Electrical Stimulation (NMES) has been widely used as a complementary strategy in rehabilitation and strength training; however, the segmented neuromuscular and morphological responses of individual quadriceps muscles when NMES is combined with resistance training remain insufficiently explored. **Objective:** To investigate the effects of 12 weeks of NMES combined with strength training on maximal isometric force, neuromuscular efficiency, segmented electromyographic activity, and muscle thickness of the quadriceps in resistance-trained individuals. **Methods:** Twenty resistance-trained adults (18–35 years) were randomly allocated into two groups: NMES combined with strength training (EES) and strength training only (CONT). Both groups performed leg extension training twice weekly for 12 weeks. The EES group additionally performed 40 maximal bilateral isometric contractions (7 s on/7 s off) using the Compex® 8.0 “Strength” program. Maximal voluntary isometric contraction (MVIC) was assessed via dynamometry. Surface electromyography (EMG) was recorded from Vastus Medialis (VM), Vastus Lateralis (VL), and Rectus Femoris (RF), analyzing Root Mean Square (RMS), Median Frequency, and Central Frequency. Muscle thickness was measured using B-mode ultrasonography. **Results:** The EES group demonstrated a significant increase in MVIC (66.29 ± 13.61 kg to 72.48 ± 13.37 kg; $p = 0.012$), while no significant change was observed in CONT. Significant reductions in mean RMS were found in VM ($p = 0.048$) and RF ($p = 0.0397$) in EES, despite increased force output, indicating improved neuromuscular efficiency. Spectral variables remained stable ($p > 0.05$), suggesting absence of neuromuscular fatigue. Ultrasonography revealed increased quadriceps muscle thickness in EES. **Conclusion:** NMES combined with resistance training promoted significant improvements in maximal strength, neuromuscular efficiency, and muscle hypertrophy, indicating synergistic neural and morphological adaptations in trained individuals.

Keywords: neuromuscular stimulation, surface electromyography, motor unit recruitment, muscle thickness, resistance exercise.

Introduction

The quadriceps femoris complex is crucial for knee extension, joint stabilization, and dynamic control during sports and daily activities. Adequate coordination among its components—Vastus Medialis (VM), Vastus Lateralis (VL), Rectus Femoris (RF), and Vastus Intermedius—supports optimal force output and may reduce injury risk through improved patellofemoral tracking and knee control (Kim et al., 2016). Surface electromyography (sEMG) is widely used to describe muscle activation patterns and infer changes in neural control under standardized conditions (De Luca, 1997).

Neuromuscular electrical stimulation (NMES) has been used for decades to increase strength and preserve or restore neuromuscular function. A proposed advantage of NMES is the recruitment of high-threshold motor units, potentially increasing the training stimulus when voluntary activation is limited or when the goal is to enhance neural drive (Gondin et al., 2005; Paillard, 2008). Evidence indicates NMES can improve strength and muscle architecture, and may contribute to hypertrophy when applied chronically (Gondin et al., 2011; Maffiuletti, 2010). More recent work also highlights that responses to NMES depend strongly on the protocol (e.g., frequency, duty cycle, intensity), electrode configuration, and whether NMES is superimposed on voluntary contractions (Cavalcante et al., 2025; Neves et al., 2025).

Although NMES is widely studied, many investigations focus on global quadriceps outcomes without analyzing segment-specific behavior (VM vs. VL vs. RF) under combined NMES and resistance training, particularly in resistance-trained adults. Additionally, studies often evaluate either functional strength or neuromuscular parameters in isolation. Integrating dynamometry (force output), segmented sEMG (neural

activation), and ultrasonography (morphology) offers a more robust framework to interpret whether strength gains are primarily neural (efficiency) and/or structural (hypertrophy) (Akagi, 2023).

Problem Statement: There is limited evidence describing segmented quadriceps neuromuscular adaptations (VM, VL, RF) and morphological changes when NMES is combined with resistance training in resistance-trained individuals.

Approach: This randomized controlled study applied a 12-week protocol combining leg extension strength training with NMES (Compex® 8.0 “Strength” program) and evaluated functional, neural, and morphological outcomes using MVIC dynamometry, segmented sEMG, and B-mode ultrasonography.

Therefore, the aim of this study was to determine whether NMES combined with resistance training enhances neuromuscular efficiency, maximal strength, and muscle thickness compared with strength training alone. We hypothesized that the combined protocol would potentiate strength gains and neuromuscular efficiency.



Photo I and II: Ultrasonography assessment position.



Photo III and IV: Position for the MVIC test.

Material & methods

Study design and ethics

This randomized, controlled, parallel-group field study was conducted at the Federal University of Uberlândia (CAAE: 90549524.7.0000.5152). All participants provided written informed consent.

Participants

Twenty adults (18–35 years), of both sexes, engaged in regular resistance training for at least 12 months, were recruited. Inclusion criteria were: (i) ≥ 12 months of consistent strength training; (ii) ability to perform the leg extension exercise with a minimum load equivalent to body weight; (iii) no current lower-limb pain limiting training/testing. Exclusion criteria included lower-limb musculoskeletal injury, neurological disorders, implanted electronic devices, or any contraindication to NMES.

Randomization and groups

Participants were randomized into:

- EES group: strength training (leg extension) + NMES
- CONT group: strength training only

Intervention protocols (12 weeks; 2 sessions/week)

Strength training (both groups): Leg extension exercise, 9 sets of 2–5 maximal repetitions (RM), with load adjusted every 4 weeks to maintain the target effort.

NMES (EES only): NMES applied using Compex® 8.0 SP (“Strength” program), consisting of 40 maximal bilateral isometric contractions of 7 s, interspersed with 7 s passive rest (7 s on/7 s off).

Outcome measures

Maximal voluntary isometric contraction (MVIC)

Quadriceps MVIC was measured using a load cell dynamometer (5000 N, EMG System do Brasil) with the knee fixed at 90° flexion (Konrad, 2005). Standardized verbal encouragement and consistent positioning were used.

Surface electromyography (sEMG)

sEMG signals were acquired using an 8-channel system (EMG System do Brasil 830C). Electrode placement followed SENIAM guidelines (Hermens & Freriks, 1997) for VM, VL, and RF. Acquisition parameters: 2000 Hz sampling rate; bandpass filter 20–500 Hz. The following variables were analyzed:

- RMS amplitude (peak and mean) in the time domain
- Median and central frequency in the frequency domain

RMS measures were normalized to MVIC.

Ultrasonography (muscle thickness)

Quadriceps muscle thickness was assessed with B-mode ultrasonography (SSD 4000, ALOKA Inc., Tokyo, Japan) using a linear probe (7.5 MHz; 60 mm). Measurements were taken at the midpoint between the greater trochanter and the superior patellar border, following established procedures (Ikezoe et al., 2014).

Data processing and statistical analysis

Data were analyzed in GraphPad Prism. Normality was tested using Kolmogorov–Smirnov. Intragroup pre- vs post-intervention comparisons were performed using paired Student’s t-tests. Significance was set at $p < 0.05$.

Results

Strength (MVIC) and Segmented Electromyography (EMG)

The 12-week combined training promoted significant strength gains in the EES Group, which increased its MVIC from 66.29 ± 13.61 kg pre-training to 72.48 ± 13.37 kg post-training ($p = 0.012$). The Control Group (TF only) did not show a statistically significant change in strength.

Table I summarizes the results for strength and segmented electromyographic parameters (RMS):

Table I – Mean values and standard deviation of maximal force (MVIC) and electromyographic parameters (pre- and post-intervention). Statistically significant difference ($p < 0.05$; paired Student’s t-test).

		EES-PRÉ	EES-PÓS	P Valor	CONT-PRÉ	CONT-PÓS	P Valor
STRENGTH (Kg)		66,29 ± 13,61	72,48 ± 13,37*	0,012	56,79 ± 15,77	58,51 ± 20,11	0,502
Vastus Medialis	RMS (pico)	2177,61 ± 1252,55	2280,72 ± 1592,51	0,719	1457,38 ± 834,24	1380,22 ± 762,93	0,587
	RMS	451,22 ± 268,31	347,32 ± 205,09	0,048	238,98 ± 130,01	245,31 ± 135,78	0,863
	F-CENTRAL	60,11 ± 6,34	60,65 ± 8,19	0,875	46,97 ± 7,13	48,63 ± 8,36	0,673
	F-MEDIANA	76,55 ± 13,48	76,37 ± 14,19	0,981	63,49 ± 9,79	61,33 ± 6,65	0,553
Vastus Lateralis	RMS (pico)	2453 ± 822,3	2666 ± 1187	0,4139	1253 ± 682,8	1376 ± 780,6	0,5705
	RMS	414,4 ± 140,8	375,2 ± 156,9	0,3411	197,2 ± 139,1	226,0 ± 120,4	0,3304
	F-CENTRAL	58,67 ± 10,69	55,10 ± 9,673	0,3271	57,97 ± 14,53	55,14 ± 16,15	0,1582
	F-MEDIANA	67,04 ± 15,11	68,35 ± 10,31	0,6971	79,43 ± 15,89	73,83 ± 16,27	0,1939
Rectus Femoris	RMS (pico)	1534 ± 616,3	2127 ± 1457	0,1565	954,8 ± 503,1	1095 ± 585,6	0,1635
	RMS	244,8 ± 110,4	186,5 ± 66,01	0,0397	204,6 ± 143,6	199,7 ± 96,24	0,9215
	F-CENTRAL	70,11 ± 11,80	67,87 ± 10,30	0,7603	59,60 ± 11,10	59,64 ± 10,49	0,9903
	F-MEDIANA	88,09 ± 10,75	90,30 ± 5,268	0,4995	73,16 ± 10,99	76,56 ± 13,55	0,0823

Figure VI illustrates the strength results.

Regarding Mean RMS activity, the EES Group showed a significant reduction in the Vastus Medialis (VM) and Rectus Femoris (RF) (Figure VII and Figure VIII, respectively), despite the increased maximal force production. This reduction indicates an optimization of neural control, or higher Neuromuscular Efficiency (ENM). The Vastus Lateralis (VL) did not show a significant change in RMS activity ($p = 0.3411$). The remaining EMG parameters are shown in Figures IX and X.

Spectral analyses (Central and Median Frequency) remained stable in all muscles and groups, with no significant changes observed pre- and post-intervention ($p > 0.05$).

Morphological Adaptations (Ultrasonography)

The ultrasonographic evaluation of muscle thickness supported the findings, revealing morphological adaptations in the EES Group, characterized by an increase in quadriceps muscle thickness, confirming hypertrophy and corroborating the strength gains induced by the combined protocol. (See Figure XI to XIV for ultrasonography results).

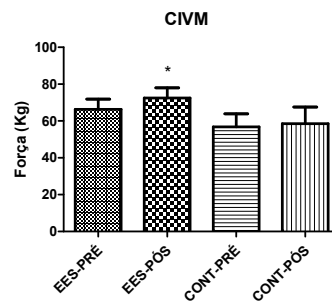


Figure I – Maximal Knee Extension Muscular Force

Caption: Means and standard deviations of maximal knee extension muscular force (MVIC) for EES and Control groups, pre- and post-intervention. MVIC: Maximal Voluntary Isometric Contraction; EES: Electrostimulation Group; CONT: Control Group; * denotes a statistically significant difference ($p < 0.05$; paired Student's t-test).

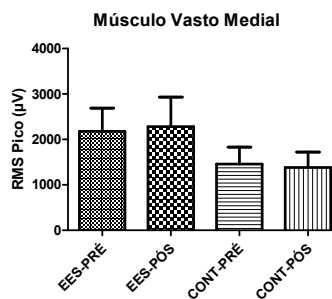


Figure II – Peak RMS (Vastus Medialis)

Caption: Means and standard deviations of Peak RMS (μV) values for the Vastus Medialis muscle in the EES and Control groups, pre- and post-intervention.

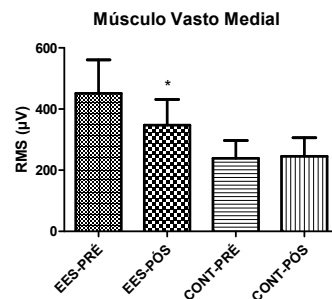


Figure III - Mean RMS (Vastus Medialis)

Caption: Means and standard deviations of Mean RMS (μV) values for the Vastus Medialis muscle in the EES and Control groups, pre- and post-intervention. * denotes a statistically significant difference ($p < 0.05$).

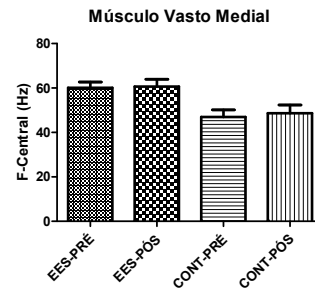


Figure IV – Central Frequency (Vastus Medialis)

Caption: Means and standard deviations of Central Frequency (Hz) for the Vastus Medialis muscle in the EES and Control groups, pre- and post-intervention.

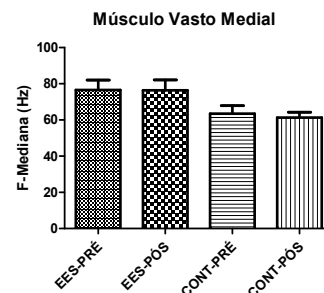


Figure V – Median Frequency (Vastus Medialis)

Caption: Means and standard deviations of the median frequency (Hz) of the Vastus Medialis muscle for the EES and Control groups, pre- and post-intervention.

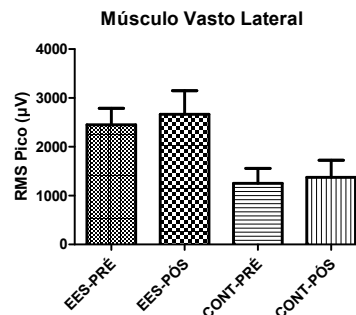


Figure VI – Peak RMS (Vastus Lateralis)

Caption: Means and standard deviations of the Peak RMS (μV) values of the Vastus Lateralis muscle for the EES and Control groups, pre- and post-intervention.

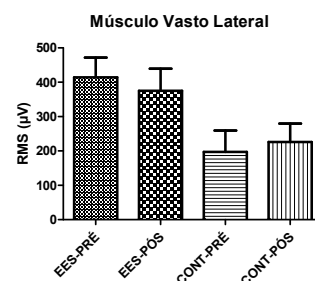


Figure VII – Mean RMS (Vastus Lateralis)

Caption: Means and standard deviations of the Mean RMS (μV) values of the Vastus Lateralis muscle for the EES and Control groups, pre- and post-intervention.

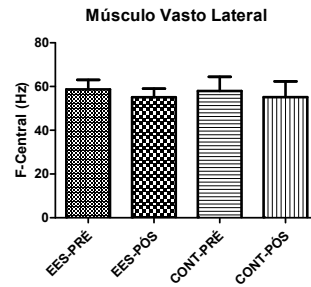


Figure VIII – Central Frequency (Vastus Lateralis)

Caption: Means and standard deviations of the central frequency (Hz) of the Vastus Lateralis muscle for the EES and Control groups, pre- and post-intervention.

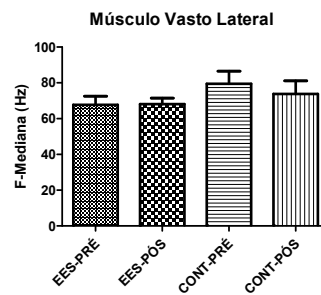


Figure IX – Median Frequency (Vastus Lateralis)

Caption: Means and standard deviations of the median frequency (Hz) of the Vastus Lateralis muscle for the EES and Control groups, pre- and post-intervention.

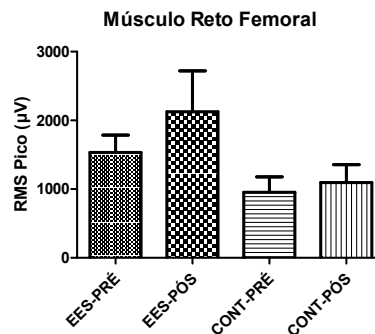


Figure X – Peak RMS (Rectus Femoris)

Caption: Means and standard deviations of the Peak RMS (μV) values of the Rectus Femoris muscle for the EES and Control groups, pre- and post-intervention.

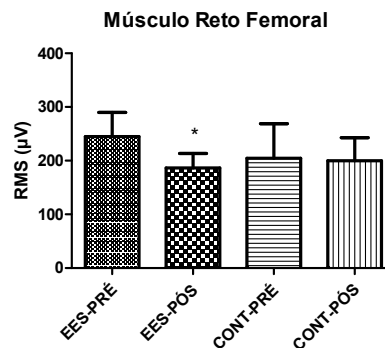


Figure XI – Mean RMS (Rectus Femoris)

Caption: Means and standard deviations of the Mean RMS (μV) values of the Rectus Femoris muscle for the EES and Control groups, pre- and post-intervention. * denotes a statistically significant difference ($p < 0.05$).

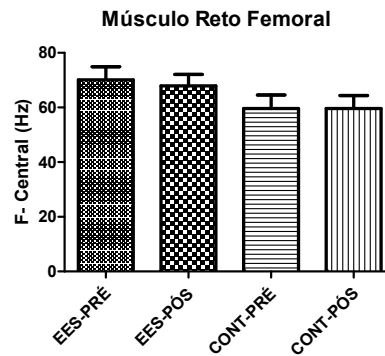


Figure XII – Central Frequency (Rectus Femoris)

Caption: Means and standard deviations of the central frequency (Hz) of the Rectus Femoris muscle for the EES and Control groups, pre- and post-intervention.

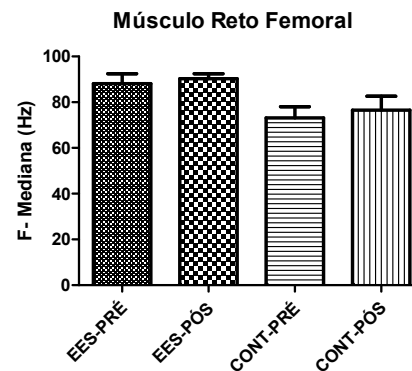


Figure XIII – Median Frequency (Rectus Femoris)

Caption: Means and standard deviations of the median frequency (Hz) of the Rectus Femoris muscle for the EES and Control groups, pre- and post-intervention.

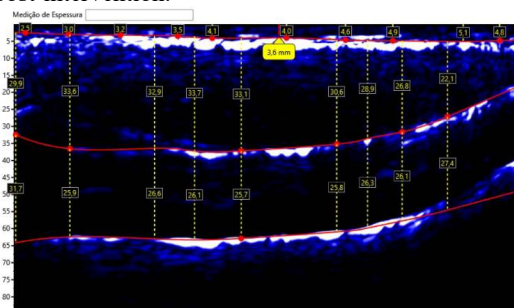


Figure XIV – Left Thigh – Pre-Training Assessment

Caption: Muscle thickness measurement obtained by ultrasonography at the midpoint of the left thigh, performed prior to the start of the electrostimulation associated with strength training protocol.

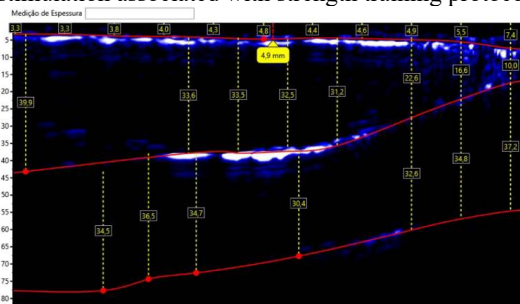


Figure XV – Right Thigh – Pre-Training Assessment

Caption: Muscle thickness measurement obtained by ultrasonography at the midpoint of the right thigh, performed prior to the start of the electrostimulation associated with strength training protocol.

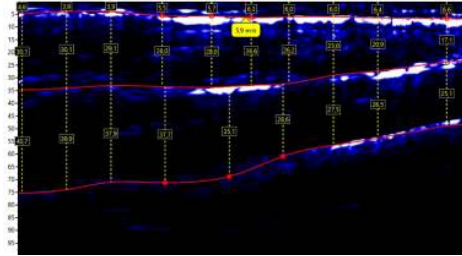


Figure XVI – Left Thigh – Post-Training Assessment

Caption: Muscle thickness measurement obtained by ultrasonography at the same anatomical point of the left thigh, following the electrostimulation associated with strength training protocol.

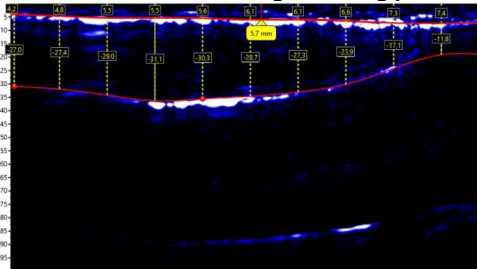


Figure XVII – Right Thigh – Post-Training Assessment

Caption: Muscle thickness measurement obtained by ultrasonography at the same anatomical point of the right thigh, following the electrostimulation associated with strength training protocol.

Dicussion

This study demonstrated that NMES combined with resistance training produced superior strength improvements compared with resistance training alone in resistance-trained individuals. The magnitude of strength increase in EES (from 66.29 kg to 72.48 kg; ~9.3%) supports previous evidence that NMES can augment voluntary training adaptations when appropriately prescribed (Paillard, 2008; Azevedo et al., 2018). Recent syntheses also emphasize that combined NMES and resistance training may enhance neuromuscular outcomes, although effects can vary with protocol parameters and participant status (Neves et al., 2025; Chen et al., 2025).

A key finding was the significant decrease in mean RMS in VM and RF concomitant with increased MVIC in EES. Reduced EMG amplitude for a given (or higher) force output is classically interpreted as improved neuromuscular efficiency, potentially reflecting better motor unit recruitment strategies, synchronization, or reduced antagonist co-activation (Aragão et al., 2014; Van Cutsem et al., 1998). This pattern suggests that the combined protocol promoted neural optimization rather than merely increasing excitation requirements to generate higher force.

Frequency-domain indices (median and central frequency) did not change significantly, suggesting that the protocol did not induce measurable chronic spectral shifts under the testing conditions. This stability is consistent with the interpretation that training-related adaptations were primarily neural and morphological, rather than reflecting fatigue-related spectral behavior at reassessment (De Luca, 1997).

The morphological findings via ultrasonography further indicated increased quadriceps muscle thickness in EES. NMES has been shown to influence muscle architecture and hypertrophy when applied chronically at sufficient intensity (Gondin et al., 2005; Akagi, 2023). The triangulation of outcomes—strength (MVIC), reduced RMS (efficiency), and increased thickness (morphology)—supports a combined mechanism involving both neural and structural adaptations. Importantly, the segmented analysis revealed non-uniform responses across quadriceps heads, with more pronounced changes in VM and RF than VL, which may be relevant for targeted rehabilitation or performance strategies when specific portions of the quadriceps are prioritized.

Practical implications

For resistance-trained individuals, adding NMES to a structured strength program may accelerate improvements in maximal force and neuromuscular efficiency without evident adverse spectral indicators under the present testing approach. This may be particularly useful when seeking a higher neural stimulus or when training time is limited.

Conclusions

Twelve weeks of NMES combined with resistance training significantly improved maximal strength, neuromuscular efficiency, and muscle thickness in resistance-trained individuals. The reduction in EMG amplitude alongside increased force output indicates enhanced neural efficiency, while ultrasonographic evidence confirms hypertrophic adaptation.

These findings support the integration of NMES as a complementary strategy in strength training programs, particularly for optimizing motor unit recruitment and accelerating performance gains. The triangulated methodological approach strengthens the validity of the results and contributes to the development of more precise neuromuscular training protocols.

Future research should explore long-term adaptations, different NMES parameters, and applications in clinical populations.

Conflicts of interest - The authors declare no conflicts of interest.

Limitations - This study used a relatively small sample and evaluated outcomes under specific NMES parameters and a single strength-training modality (leg extension). Findings may not generalize to other populations, protocols, or multi-joint training programs.

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