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Effects of neuromuscular electrical stimulation on torque and performance in recreational distance runners: A randomized controlled trial

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ABSTRACT

Introduction: Neuromuscular electrical stimulation (NMES) is used by athletes to improve muscle performance. However, evidence on the use of NMES in long distance runners is scarce. As such, this study aimed to evaluate the effects of NMES on the muscle torque and sports performance of long-distance recreational runners.
Methods: This was a blinded randomized controlled trial. Data from 30 volunteers were analyzed. Participants were randomly allocated to an experimental ($n = 15$) or control group ($n = 15$). The experimental group was submitted to running training (RT) and a strengthening protocol with NMES (1 kHz, modulated in 2 ms bursts, 50 Hz modulated burst frequency and 10% duty cycle, 15 min totaling 18 contractions per sessions) for 6 weeks, with 3 sessions per week, while controls were submitted to RT alone. The following variables were analyzed: peak isometric (ISO), concentric (CON), and eccentric (ECC) torque of the quadriceps muscle in voluntary contractions, ventilatory anaerobic thresholds (VATs), maximal oxygen uptake (VO2max), and oxygen cost of transport (OCT).
Results: The NMES group obtained higher values of ISO, 21.04% ($p = 0.001$), CON, 21.97% ($p = 0.001$) and ECC, 18.74% ($p = 0.001$) peak torque and VAT1, 9.56% ($p = 0.001$), as well as a statistically significant improvement in oxygen cost of transport at VAT1 when compared to controls ($p = 0.001$).
Conclusion: NMES was effective in improving peak isometric, concentric and eccentric quadriceps muscle torque, in addition to being an interesting resource for enhancing sports performance in long-distance recreational runners and future clinical trials should be performed to compare the use of NMES to different forms of training over longer training periods.
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1. Introduction

Neuromuscular electrical stimulation (NMES) involves the use of electrical currents to recruit skeletal muscles in order to improve and/or prevent the loss of muscle strength (Bax et al., 2005; Bellew et al., 2012; Oliveira et al., 2018). Although Kots et al. (1977) reported a 40% increase in muscle strength in Olympic athletes using a medium-frequency burst modulated alternating current (BMAC) with a 2.5 kHz carrier frequency and 50% duty cycle (Liebano et al., 2013), more recent studies suggest that BMACs with a 1 kHz carrier frequency (Ward et al., 2006), 10–20% duty cycle and 50 Hz modulated burst frequency produce better torque (Liebano et al., 2013; McLoda and Carnack 2000; Parker et al., 2011).

Several authors evidenced the increase to peak isometric (ISO), concentric (CON), eccentric (ECC) torque of the quadriceps muscle in voluntary contractions (Medeiros et al., 2017; Oliveira et al., 2018) and similar increases have been observed in muscle architecture and neural activity after few weeks of NMES training (Oliveira et al., 2018).

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In the sports environment, NMES is included in training protocols aimed at improving strength, power and speed in rugby, ice hockey, tennis, soccer, swimming, and weightlifting athletes (Babault et al., 2007; Brocherie et al., 2005; Maffiuletti et al., 2009; Oliveira et al., 2018; Pichon et al., 1995; Billot et al., 2010; Delitto et al., 1989; Modesto et al., 2019). It also improves jumping and isometric and isokinetic strength in basketball and volleyball athletes (Maffiuletti et al., 2000, 2002; Malatesta et al., 2003), enhancing performance (Gondin et al., 2011; Filipovic et al., 2011). However, there are no studies related to the use of NMES in professional or recreational sprinters or long-distance runners.

Among the various resources for improving runner performance, muscle strengthening stands out (Noakes 1988). Increased strength due to resistance training can improve mechanical efficiency, muscle coordination and motor recruitment patterns (Noakes 1988; Sale 1988), and may improve running economy (Sale 1988). Certain markers are often used to quantify the sports capacity of long-distance runners, including maximum oxygen consumption (VO2max), ventilatory anaerobic thresholds (VAT1 and VAT2), muscle strength (MS), and running economy, also known as cost of oxygen transport per unit of distance (COT) (Jung 2003). Given that neuromuscular stimulation is an important resource already used in sports and the lack of evidence regarding its application in long-distance runners, the objective of this study was to evaluate the effects of NMES on muscle torque and sports performance in long-distance recreational runners.

2. Materials and methods

2.1. Participants

Data from 40 subjects were collected. Inclusion criteria were being male, aged between 30 and 45 years, having engaged in recreational long-distance running for at least one year (running 15 km–40 km per week) and not using NMES for muscle training. Exclusion criteria were muscle injuries and/or lower limb joint injuries in the six months prior to the study, contraindications to NMES, isokinetic or ergospirometric testing. Participants who met the eligibility criteria were invited to participate in the study.

The effect size was calculated using Cohen's d, whereby values between 0.0 and 0.20 are classified as small; 0.21–0.50 medium; 0.51–0.80 large; and >0.8023 very large. Sample size was calculated considering a 27% difference in isometric torque between the NMES group and CG, with an estimated standard deviation of 22.6%. For a significance level of 0.05 and 80% power, it was estimated that 15 participants would be needed in each group (Minitab version 17, State College, PA, USA).

2.2. Procedure

Before data collection, all participants were informed about the research and study objectives, and provided written informed consent. This was a single-blind randomized controlled trial carried out over a period of six weeks. It was in line with the ethical principles defined in the Declaration of Helsinki and approved by the institutional research ethics committee (Universidade Cidade de São Paulo, Brasília, Brazil, CAAE: 80812717.8.0000.0064) prior to data collection.

Following ethical approval, the clinical trial was registered at www.clinicaltrials.gov under registration number NCT03653286. The study is reported according to the Consolidated Standards of Reporting Trials (CONSORT) Statement for Randomized Trials of Nonpharmacologic Treatments and the Template for Intervention Description and Replication (Hoffman, 2014).

Participants were randomly allocated to an experimental (n = 15) or control group (n = 15). Participants in the experimental group underwent running training (RT) and another strengthening protocol with NMES, while controls were submitted to RT alone.

Randomization was performed by a physical therapist not involved in assessment, intervention and data analysis. Allocation concealment was ensured via sealed envelopes stored away from the assessment location, not accessible to the researcher responsible for the evaluation. These were signed, dated and opened by the researcher responsible for the intervention, who then left the site after data collection. All assessments for the primary and secondary outcomes were performed by a researcher (AMS) blinded to group allocations.

2.3. Interventions

Running training: participants ran a total of 15–40 Km per week in two to three training sessions. Sprint training was not included. A distance of 5 km–15 km was covered in each session, and participants were instructed to maintain their heart rate within 70% of maximum capacity either manually or with a digital monitor. These limitations were based on the cardiopulmonary training guidelines of The American College of Sports Medicine (ACSM) (Noakes 1988), in order to minimize confounding factors of cardiopulmonary performance. Participants did not engage in any other form of physical training during the intervention period.

Neuromuscular electrical stimulation: the strengthening protocol using NMES was developed by the physical therapists who conducted this study. The exercise protocol for quadriceps strengthening with NMES (Neurodyn Aussie Sport device, IBRAMED, Amparo, Brasil) used a medium frequency alternating current, with 1 kHz carrier frequency; 2 ms burst duration; 50 Hz modulated burst frequency; 10% duty cycle; 1:3 ratio (ON = 12s and OFF = 36s); and 15 min of stimulation, totaling 18 contractions per session. Participants were instructed to keep their leg muscles as relaxed as possible, at an initial position of 90° knee flexion. During isometric contraction of the quadriceps muscle, the knee was extended to approximately 60°. Contraction intensity was controlled using load cells (EMG System do Brasil, São José dos Campos, São Paulo), and maximal voluntary isometric contraction (MVIC) was evaluated in all sessions. The intensity of electrically-induced contractions was at least 30% of the MVIC and stimulation lasted 12 s, followed by a 36-s rest (1:3 ratio), with 3-s ramp-up and 3-s ramp-down (Babault et al., 2007), (Pichon et al., 1995); Malatesta et al., (2003). The total daily training time was 900 s (15 min), with 18 contractions per session and three weekly sessions for six weeks (Thompson et al., 2013). Two 8 × 13cm self-adhesive electrodes were used (Valutrode - Axelgaard, Indústria de Manufatura Limitada, São Paulo, SP, Brazil). The proximal electrode was placed over the motor point of the rectus femoris and the distal electrode on the motor point of the vastus medialis (Liebano et al., 2013; Stevens-Lapsley et al., 2012). The NMES group was familiarized with NMES one week before starting the training protocol, and underwent the pre-test experiment with electrical stimulation and evaluation equipment (EMG System do Brasil, São José dos Campos, São Paulo). NMES training was performed three times a week, but not on consecutive days.

2.4. Measures

2.4.1. Isokinetic dynamometer (primary outcome)

Computerized isokinetic muscle assessment was performed using a Cybex Norm 6000 isokinetic dynamometer (Cybex International, Inc., Ronkonkoma, NY, USA), at the Physical Therapy Clinic of the City University of São Paulo (UNICID). Isometric, concentric, and eccentric knee extensor contractions were performed with the dominant lower limb to measure peak torque, at an angle of 90° (flexion) to 0° (extension). Three maximum voluntary contractions were performed, but only the highest peak torque value was considered in statistical analysis (in accordance with American Society of Exercise Physiologists guidelines (ASEP) (Lee and Joseph 2001; Holcomb et al., 2007).

Participants warmed up for 5 min on an exercise bike with low resistance (70 rpm at 50 W) to raise muscle temperature. The trunk and thighs were stabilized with straps for all the contractions analyzed. Knee range of motion was between 90° (flexion) and 0° (extension) and the lever arm was positioned on the distal third of the leg. Torque was corrected for gravity and the dynamometer calibrated before each session, with movements executed in the following order: three consecutive concentric contractions at $60°s^{-1}$, three 5-s isometric contractions (60°) with a 30-s interval between them, and three eccentric contractions at $60°s^{-1}$. A 90-s rest was allowed between sets of contractions (concentric, isometric and eccentric) (Lee and Joseph 2001; Andrade et al., 2013).

2.4.2. *Ergospirometry (secondary outcome)*

2.4.2.1. Maximum oxygen consumption. Prior to testing, participants lay at rest for 10 min for initial collection of ventilatory and heart rate (HR) data. The test protocol consisted of treadmill running (model ATL, Inbrasport Ltda., Brazil) at an initial speed of 10 km/h, followed by 1 km/h increments every 1 min until exhaustion (Andrade et al., 2013). Ventilatory parameters were collected at rest and at each respiratory cycle throughout the tests, and analyzed as means every 20 s using a computerized gas analyzer (model VO2000, Inbrasport Ltda., Brazil). The gas analyzer was calibrated for standard gas volume and concentration immediately before the first test of the day and re-calibrated after each test, as per manufacturer instructions (Andrade and Brito 2002). HR was recorded continuously throughout the tests using a heart monitor (Sport Test model, Polar Electro OY, Finland). After exhaustion, two 2-min recovery periods were allowed, at 50 and 25% of the highest velocity reached. Only HR was monitored during these periods (Andrade and Brito 2002).

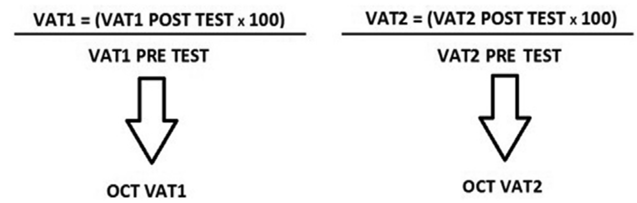
The criteria for determining peak VO2 and exhaustion were the occurrence of a plateau in VO2 (characterized by increases of 2 ml/kg/min or less) and inability to maintain running speed, respectively. Peak VO2 corresponded to the highest velocity reached during the test (Andrade and Brito 2002).

2.4.3. *Ventilatory anaerobic threshold analysis*

Ventilatory anaerobic thresholds (VATs) were determined based on ventilatory equivalents (VE/VO2 and VE/VCO2), final expired fractions (FEO2 and FECO2) and respiratory quotient (RQ), and expressed as a function of VO2 (in ml/kg/min). VAT1 was defined as the lowest VE/VO2 value before a constant increase and the onset of an abrupt and continuous rise in RQ, and VAT2 as the point at which nonlinear increases in VE/VO2, VE/VCO2 and FEO2 coincided with a drop in FECO2 (Andrade and Brito 2002).

2.4.4. *Oxygen cost of transport per unit of distance*

Also known as running economy, oxygen cost of transport can be defined as the ratio between metabolic capacity and mechanical performance in a given physical activity, expressed in (mL.kg-1 .km-1) (Abe et al., 2015). The following equations were used to compare oxygen consumption relative to body mass at the initial and final anaerobic thresholds (pre and post-tests), in order to determine the percentage (delta) variation:



Participants were reassessed immediately after the last training session and then submitted to the same procedures described for isokinetic and ergospirometry evaluation.

2.5. *Statistical analyses*

Data analysis was performed using the Statistical Package for the Social Sciences (SPSS) for Windows, version 15.0. and significance was set at 5% ($p \leq 0.05$). Initially, descriptive statistics were used to assess the frequency, mean, and standard deviation of the variables of interest. Quantitative data are presented as mean ± standard deviation. The means of the variables isometric, concentric and eccentric peak torque, VAT1 and 2, maximum oxygen uptake and oxygen cost of transport were compared using the Mann-Whitney test due to their non-normal characteristics, and verified by the Shapiro-Wilk test (Vickers, 2005). The effect size was calculated using Cohen's d, with values of 0.0–0.20 classified as low; 0.21–0.50 medium; 0.51–0.80 large; and >0.80 very large (Gaskin and Happell, 2014). Sample size was calculated considering a 27% difference in isometric torque between the NMES group and CG, with an estimated standard deviation of 22.6% (Billot et al., 2010). For a significance level of 0.05 and 80% power, it was estimated that 15 participants would be needed in each group (Minitab version 17, State College, PA, USA).

3. Results

A total of 70 runners were assessed according to the eligibility criteria, 40 of whom were excluded for the following reasons: age (McLoda and Carnack 2000), injuries (Ward et al., 2006), availability (Ward et al., 2006), and refusal to take part in the study (Andrade and Brito 2002) (Fig. 1). Thirty recreational long-distance runners were included in the study, conducted between July 2018 and February 2019. Each group (NMES and Control) contained 15 participants each. There was one dropout in the NMES group, who could not be reached to provide a reason, and two among the controls, one of whom could not be reached and the other sustained a tibial fracture. Thus, 27 individuals completed the study.

The demographic characteristics of the runners are described in Table 1, divided according to group, demonstrating that the groups were homogeneous. The variables are expressed as mean and standard deviation.

Table 2 presents the means and standard deviations of (ISO), (CON) and (ECC) peak torque values, as well as ventilatory anaerobic thresholds and maximal oxygen consumption. Also shown are the differences in the means of the control and NMES groups and their respective standard deviations, indicating a statistically significant intergroup difference for the following outcomes: isometric ($p = 0.001$), concentric ($p = 0.001$) and eccentric ($p = 0.001$) peak torque and VAT1 ($p = 0.001$, Mann-Whitney Test). A large effect size (ES) was also obtained for the following outcomes: isometric, concentric, and eccentric peak torque and VAT1.

The Mann-Whitney test demonstrated higher VAT1 values and peak isometric, concentric and eccentric torque in the NMES group after six weeks of intervention when compared to controls.

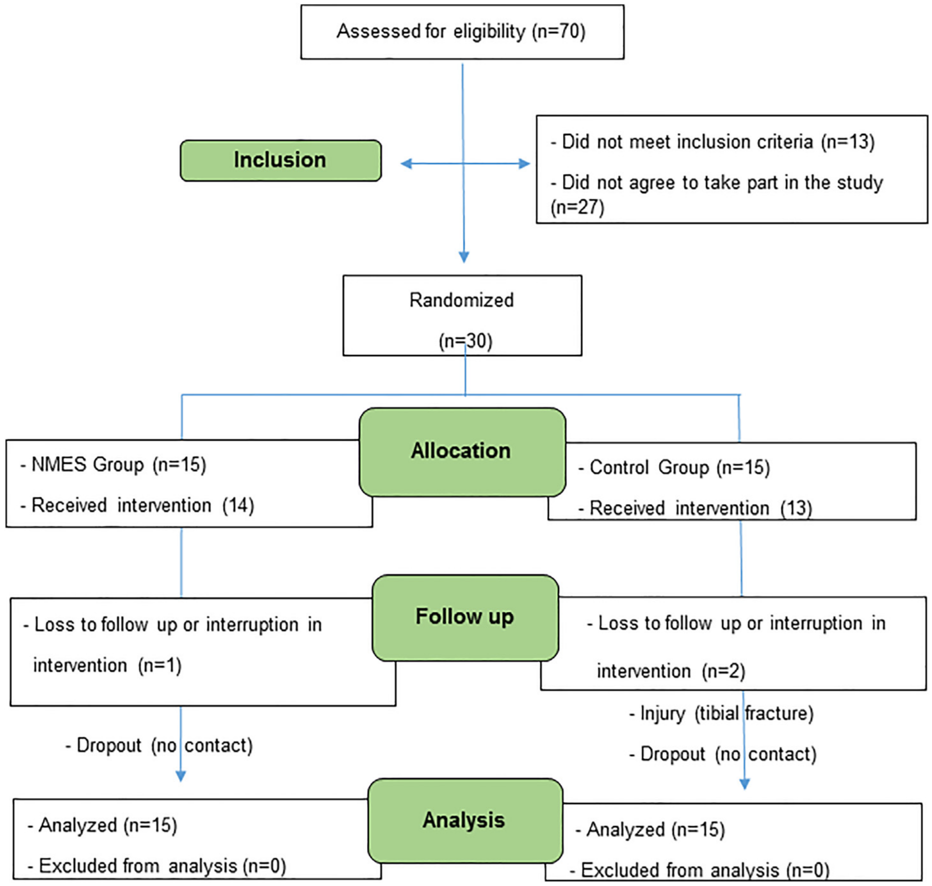


Fig. 1. Study flow chart.

Table 1
Demographic characteristics of study patients (n = 30).

Variables	Group NMES (n = 15)	Control Group (n = 15)
Anthropometric Data		
Body Mass (kg)	80.13 ± 7.46	71.20 ± 9.53
Height (cm)	178 ± 6.38	174.93 ± 8.76
BMI (kg/m^2)	25.29 ± 1.96	23.22 ± 2.25
Sex (M/F)	15/0	15/0
Age (years)	34 ± 3.20	35 ± 3.60
Dominant Lower Limb (R/L)	12/3	10/5
Clinical/Sports Data		
Injury in the last 6 months (n.%)	0 (0)	0 (0)
Time of Sports Practice (years)	10 ± 5.97	10 ± 5
Weekly training volume (km)	31.00 ± 8.49	28.33 ± 8.79
Others		
Marital Status (Single/Married/Widowed)	3/11/0	2/13/0
Smoking (n.%)	0 (0)	1 (6.6)
Alcohol (n.%)	0 (0)	0 (0)

Data are shown as mean ± standard deviation and absolute numbers (percentage).
BMI = body mass index, km = kilometers.

However, the use of NMES did not influence maximum oxygen consumption ($p = 0.124$) or VAT2 ($p = 0.819$) after six weeks of intervention.

As shown in Table 3, the NMES group exhibited a statistically significant difference ($p = 0.001$) for oxygen cost of transport at ventilatory anaerobic threshold 1 (OCT VAT1), but not ($p = 0.772$) at ventilatory anaerobic threshold 2 (OCT VAT2), as demonstrated by the Mann-Whitney test. Effect size (d) was classified as high for OCT VAT1.

4. Discussion

This study is the first on the use of NMES in long-distance runners aimed at increasing muscle torque in both dynamic and isometric conditions. The difference in mean isometric, concentric and eccentric peak torque values was greater in the NMES group than the CG. Similar results were found in other studies using NMES in rugby (Babault et al., 2007), ice hockey (Brocherie et al., 2005), volleyball (Maffiuletti et al., 2002), (Malatesta et al., 2003),

Table 2
Values obtained with isokinetic dynamometry and ergospirometry in the pre-intervention (baseline) and post-intervention (6th week) periods in the NMES and control groups.

	Groups				Difference			
	Baseline		6th Week					
	NMES	Control	NMES	Control	NMES	Control	p	ES (*d*)
Dynamometry								
Isometric Peak Torque	238.53 ± 28.97	189.67 ± 53.95	288.73 ± 43.96	184.33 ± 61.85	50.20 ± 33.46	- 5.34 ± 42.06	0.001*	0.58
Concentric Peak Torque	199.87 ± 41.22	157.53 ± 61.21	243.80 ± 47.95	155.27 ± 70.98	43.93 ± 28.79	- 2.26 ± 19.14	0.001*	0.68
Eccentric Peak Torque	277.13 ± 42.15	243.93 ± 56.08	329.07 ± 44.75	219.27 ± 64.77	51.94 ± 44.45	- 24.66 ± 33.29	0.001*	0.69
Ergospirometry								
VAT1	58.46 ± 7.01	60.33 ± 6.77	64.05 ± 7.15	59.87 ± 7.15	5.59 ± 4.09	- 0.46 ± 2.59	0.001*	0.66
VAT2	82.45 ± 3.45	78.95 ± 7.27	83.05 ± 2.56	78.62 ± 7.65	0.60 ± 3.32	- 0.33 ± 1.25	0.819	0.18
VO_2max	39.62 ± 6.33	44.79 ± 4.07	40.10 ± 5.81	44.91 ± 3.75	0.48 ± 2.61	0.13 ± 1.10	0.124	0.08

The continuous variables are expressed as mean and standard deviation (±). VAT1 - ventilatory anaerobic threshold 1; VAT2 - ventilatory anaerobic threshold 2; VO2max - maximum oxygen consumption; ES - Effect Size (Cohen's d).
* Represents statistically significant difference (p = 0.001).

Table 3
Values obtained with the difference between the means of the ergospirometry data in the pre-intervention (baseline) and post-intervention (6th week) periods in the NMES and control groups.

	Groups			
	NMES	Control	p	ES (*d*)
Ergospirometry				
OCT VAT1	9.96 ± 8.09	- 0.80 ± 4.14	0.001[a]	0.64
OCT VAT2	0.89 ± 4.15	- 0.37 ± 1.53	0.772	0.19

The continuous variables are expressed as mean and standard deviation (±). COT VAT1 - oxygen cost of transport per unit of distance at ventilatory anaerobic threshold 1; OCT VAT2 - oxygen cost of transport per unit of distance at ventilatory anaerobic threshold 2; ES - Effect Size (Cohen's d).
[a] Represents statistically significant difference (p = 0.001).

basketball (Maffiuletti et al., 2000), soccer (Billot et al., 2010), tennis (Maffiuletti et al., 2009), swimming (Pichon et al., 1995), handball (Oliveira at al 2018) and weight lifting (Delitto et al., 1989) .

Our protocol applied NMES to the belly of the quadriceps muscle (Liebano et al., 2013; Stevens-Lapsley et al., 2012), which is essential for running mechanics to act effectively and eccentrically (Hammer 2010). This muscle is largely responsible for braking and support during the shock absorption phase, and the magnitude of its contribution is about twice that of the horizontal deceleration peak and 50% of the vertical deceleration peak (Hammer and Seth 2010).

Friedebold et al. (1957) suggested that increased peak torque values are associated with greater motor unit synchronization (Friedebold et al., 1957). Improved motor recruitment results in better motor control during running and force transfer to distal segments (Hakkinen et al., 1988), enhancing running efficiency over time (Hakkinen et al., 2003; Balsalobre-Fernandez et al., 2016).

The result of the combination of muscle activation level (motor unit recruitment) and the coding rate or increased activation frequency of already active motor units (Fuglevand et al., 1993) establishes the energy cost, since the rate of energy use depends on the number of fibers activated (Friedebold et al., 1957). Although positive results were obtained for increased ISO, CON and ECC peak torque as well as OCT LAV1 and LAV1, no significant intergroup differences in means were observed pre and post-intervention for VO2max, VAT2, and OCT LAV2. This may be due to the duration of the protocol used. Sedano et al. (2013) found significant improvements in these parameters in longer strengthening programs (12 weeks) (Sedano et al., 2014), while Vikmoen et al. (2016) observed similar results in 11-week protocols (Vikmoen et al., 2016) .

As the first randomized controlled trial using NMES to improve strength in distance runners, this study takes a pragmatic approach since strengthening was performed individually, similarly to clinical practice. In regard to how the study was conducted, we believe it was efficient given its high systematic rigor and the fact that the researchers responsible for the evaluations and interventions were highly experienced in the techniques applied. The inclusion criteria can be justified by sample standardization.

Limitations of the study include the fact that the runners did not undergo explosive training, despite being a common practice in sports. Explosive training improves maximal oxygen uptake performance (Jung 2003), making it impossible to control its intensity for individual participants. Given that resistance training is critical to the performance of distance runners (Hammer et al., 1957; Vikmoen et al., 2016; Paavolainen et al., 1999; Spurrs et al., 2003; Yamamoto et al., 2008) and that NMES has proven to be a viable resource in improving strength, power, speed (Babault et al., 2007; Brocherie et al., 2005; Maffiuletti et al., 2009; Pichon et al., 1995; Billot et al., 2010; Delitto et al., 1989) and isometric and isokinetic strength (Maffiuletti et al., 2000, 2000; Malatesta et al., 2003) in athletes from different sports, the present study tested a medium-frequency alternating current during the six-week intervention. In the present study, medium-frequency burst modulated alternating current (BMAC) was used. This current and low-frequency pulsed current (PC) are the most common currents used to recruit skeletal muscles. Both currents have similar efficiency for inducing isometric knee extension torque and self-reported discomfort in healthy individuals (da Silva et al., 2015; Medeiros et al., 2017; Oliveira et al., 2018). Future clinical trials should compare the use of NMES to different forms of training over longer training periods.

5. Conclusions

Neuromuscular electrical stimulation increased quadriceps isometric, concentric and eccentric peak torque in recreational distance runners. Furthermore, improvements were observed in their sports performance for the secondary outcomes related to oxygen cost of transport at ventilatory anaerobic threshold 1, as well as ventilatory anaerobic threshold 1 itself.

Data sharing statement

All patients signed a data sharing statement and the data are available upon request.

Public Trials Registry and Registration Number

NCT03653286 Protocol available at clinicaltrials.gov.

Contributorship

None declared.

Data sharing statement

All patients signed a data sharing statement and the data are available upon request. Public Trials Registry and Registration Number: NCT03653286 Protocol available at clinicaltrials.gov.

CRediT authorship contribution statement

Gustavo R. Thomé: Writing – original draft, Formal analysis, Investigation. **Renata A. Costa:** Formal analysis, Investigation. **Marcelo L. Marquezi:** Formal analysis, Methodology. **Juliana M.L. Aparecido:** Formal analysis, Investigation. **João Luiz Q. Durigan:** Methodology, Writing – review & editing. **César F. Amorim:** Methodology, Software. **Richard E. Liebano:** Conceptualization, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors certify that there are no conflicts of interest with any financial organization regarding the material discussed in the manuscript.

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