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# Muscle Fatigability Responses to Pulsed and Kilohertz-Frequency Currents With Different Phase Durations: A Randomized Crossover Trial

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# Abstract

**Purpose**

To determine whether current type (pulsed current [PC] vs kilohertz-frequency alternating current [KFAC]) or phase duration (200 vs 500 μs) primarily influences contraction fatigability, neuromuscular electrical stimulation (NMES) efficiency, sensory discomfort, and neurophysiological responses of the triceps surae.

**Methods**

In this randomized, participant- and assessor-blinded crossover trial, 44 healthy adults (24.4 ± 4.9 years) completed four NMES conditions separated by at least 7 days: PC 200, PC 500, 2.5-kHz KFAC 200, and 1-kHz KFAC 500. Each fatigability protocol comprised 20 evoked contractions initiated at 20% of maximal voluntary contraction. Outcomes included maximal voluntary and evoked torque, torque-time integral (TTI), TTI decline, NMES efficiency, sensory discomfort, electromyographic activity, spinal excitability, and central activation. Repeated-measures analyses of variance assessed current type, phase duration, and time.

**Results**

The 500-μs conditions produced greater total TTI and higher NMES efficiency than the 200-μs conditions ($P \leq 0.001$). Voluntary torque, evoked torque, and electromyographic root mean square amplitude decreased after the fatigability protocol ($P < 0.001$). Current type did not affect fatigability or sensory discomfort, and no current type × time interaction was detected for spinal excitability or central activation. The absence of significant current-type effects should not be interpreted as equivalence because equivalence testing was not performed.

**Conclusion**

Phase duration was more influential than current type under the tested conditions. A 500-μs phase duration improved evoked work and NMES efficiency without increasing sensory discomfort, highlighting phase duration as a physiologically relevant parameter when NMES protocols are designed to sustain repeated contractions.

**Clinical Trial:** NCT05894044 on 2023-05-23.


# 1. INTRODUCTION

Neuromuscular electrical stimulation (NMES) is a rehabilitation tool that is commonly used in clinical practice to reduce muscle atrophy and other disuse-related complications (Cavalcante et al., 2022; Durigan, Ito, et al., 2025; Pinto Damo et al., 2021). Declines in contraction force induced by NMES represent performance fatigability, defined as a decline in an objective measure of performance over a discrete period of time, hereafter referred to as “contraction fatigability” or simply “fatigability”(ENOKA &

DUCHATEAU, 2016). The early onset of muscle fatigability remains a significant limitation of NMES, potentially restricting its effectiveness in certain orthopedic and neurological rehabilitation settings (Ainsley et al., 2020; Barss et al., 2018; Bastos et al., 2021; Jakovacz et al., 2024). However, during a voluntary contraction, motor units (MUs) are recruited in an orderly fashion according to Henneman's size principle (Barss et al., 2018; Vaz & Frasson, 2018), whereas during a maximal evoked muscle contraction, all MUs in the stimulated area are activated at the same time. As a result, NMES can be more fatiguing than voluntary contractions due to the simultaneous and continuous activation of the same MUs regardless of size and type (Barss et al., 2018). Additionally, it is well established that high stimulation intensities can elicit sensory discomfort, which may further compromise the clinical effectiveness of NMES (De Oliveira et al., 2018; Modesto et al., 2020; Vaz et al., 2012) .

Different NMES waveforms are employed to induce muscle contractions, one of the objectives was to minimize muscle fatigability while preserving optimal NMES efficiency. Traditional NMES uses pulsed currents (PC) with phase durations < 500 μs at 20–100 Hz(da Silva et al., 2015; Vaz & Frasson, 2018). Kilohertz-frequency alternating currents (KFAC) operate at 1–10 kHz(da Silva et al., 2015); the Russian current, developed in the 1970s to enhance muscle strength, delivers 2.5 kHz carrier bursts at 1–200 Hz(Kots YV, 1977; Vaz & Frasson, 2018); and the Aussie current, another commonly used KFAC, uses a 1.0 kHz carrier with 1–200 Hz bursts and was designed to reduce fatigability and sensory discomfort(Ward et al., 2002). While some studies have demonstrated that KFAC leads to greater muscle fatigability compared to PC(Laufer et al., 2001; Laufer & Elboim, 2008; Paz et al., 2023), other investigations found no significant differences between the two NMES modalities (Aldayel et al., 2010, 2011). These discrepancies may be attributed to methodological variations, including differences in stimulation frequency, phase duration, and on-off cycles, all of which influence the total duty cycle of NMES.

KFAC may generate multiple cycles within each burst, which could influence motor-unit activation and fatigability(Ward, 2009). Although KFAC has been proposed to reduce discomfort and increase force under some conditions(Ward, 2009), a scoping review concluded that it generally produces similar or lower force, equal or greater fatigability, and similar or greater discomfort than PC(Vaz & Frasson, 2018). Two systematic reviews with meta-analyses likewise found no clear differences in evoked torque or sensory discomfort between KFAC and PC in healthy participants(da Silva et al., 2015; Iijima et al., 2018). More recently, phase duration, but not waveform, was shown to influence the relative recruitment of sensory and motor axons in the human tibial nerve, with shorter phase durations preferentially recruiting motor axons and longer phase durations preferentially recruiting sensory axons(Durigan, Kelly, et al., 2025). Nevertheless, the mechanisms underlying fatigability during KFAC and PC remain incompletely understood(Vaz & Frasson, 2018). Accordingly, we compared four protocols: 2.5 kHz KFAC (Russian current; 200 μs phase duration), 1 kHz KFAC (Aussie current; 500 μs phase duration), and PC with 200 μs or 500 μs phase durations. We evaluated fatigability-related mechanical outcomes and explored potential neuromuscular contributors using the H-reflex, M-wave, TTI, electromyographic root mean square amplitude and median frequency, and the central activation ratio. We hypothesized that phase duration would have a greater influence than current type on evoked work and contraction fatigability.

# 2. METHODS

### Trial Design

This randomized, participantand assessor-blinded crossover trial was conducted after all participants had provided written informed consent. The protocol was approved by the Institutional Review Board of the University of Brasília (protocol 67915523100008093), and the study is reported in accordance with CONSORT (see Supplementary Material). Assessments were conducted at the Laboratory of Muscle and Tendon Plasticity, University of Brasília, Brasília, Brazil. The trial was registered at ClinicalTrials.gov (NCT05061056).

### Participants

To be included in the study, participants were required to be between 18 and 45 years of age, physically active, with a normal range of motion in the ankle joint, and report no previous experience with NMES, and no history of neuromuscular injury or disease(Pinto Damo et al., 2021). Exclusion criteria included the use of nonsteroidal anti-inflammatory drugs (NSAIDs) or nutritional supplements, skin lesions or allergies, neuromuscular disorders, external fixation devices, or metal implants in the lower limbs, and intolerance to NMES due to fear or hypersensitivity.

### Randomization and allocation concealment

The order of the four NMES conditions was randomized using computer-generated sequences from random.org (Table 1): (1) PC with a 500 μs phase duration (PC 500), (2) PC with a 200 μs phase duration (PC 200), (3) a 500 μs phase duration and low carrier frequency (KFAC 500: 1 kHz/Aussie current), and (4) a 200 μs phase duration and high carrier frequency (KFAC 200: 2.5 kHz/Russian current). A researcher (LBC) prepared sealed, numbered opaque envelopes to define the order of NMES conditions.

Table 1
Overview of the physical parameters for the four types of neuromuscular electrical stimulation currents.

| Type of current | Current frequency (Hz) | Phase duration (μs) | Burst duration (ms) | Interburst duration (ms) | Burst frequency (Hz) |
|---|---|---|---|---|---|
| **PC500** | 50 | 500 | | | |
| **PC200** | 50 | 200 | | | |
| **KFAC500** | 1000 | 500 | 2 | 18 | 50 |
| **KFAC200** | 2500 | 200 | 10 | 10 | 50 |

**Legend.** PC, pulsed current; KFAC, kilohertz-frequency alternating current. The 6-s on-time and 60-s off-time applied to MET assessment; the fatigability protocol used 20 s on and 20 s off.

### Blinding

The researcher responsible for administering the NMES currents (LAS) and the participants were blinded to the treatment allocation. A second researcher (LBC), who was aware of the treatment allocation and current intensity, programmed the NMES parameters and covered the device panel with an opaque shield, ensuring that the current intensity was only visible to him, while blinding both LAS and the participants.

**Experimental procedures**

Participants completed five sessions in total: one familiarization session and four experimental sessions, each separated by at least 7 days. One NMES condition was tested in each experimental session. All assessments were conducted at the same time of the day by the same assessor. Participants were asked to avoid stimulants (e.g., alcohol, caffeine, chocolate) and exercise on testing days. The first session served as familiarization, during which participants were informed about the recommendations, study criteria, and testing protocols(De Oliveira et al., 2018; Paz et al., 2021; Pinto Damo et al., 2021). The height, body mass, and body mass index (BMI) were recorded for all participants. Each experimental session began with a warm-up, followed by an NMES-induced fatigability phase consisting of 20 isometric evoked contractions at 20% of MVC. Two MVCs were performed prior to the fatigability protocol. During each randomized NMES session, two maximally tolerated evoked contractions were conducted to determine the participant's maximum tolerable intensity, with an "on" time of 6 s of constant stimulation, followed by a 60-s "off" time for recovery and the maximal evoked torque (MET) value was recorded. Spinal excitability (via H-reflex and M-wave) and central activation (via CAR) were assessed, with all outcomes measured before and after the fatigability protocol (Fig. 1). All NMES protocols were applied to the participants' right side (Pinto Damo et al. 2021; De Oliveira et al. 2018), with 50 Hz frequency/bursts delivered (Fig. 1; Table 1). NMES currents were administered, and the visual analogue scale (VAS) was used to measure sensory discomfort after the MET and during the fatigability protocol (first, tenth, and twentieth contractions) (De Oliveira et al. 2018).

# 2.4 Outcomes

The primary outcomes were indices of contraction fatigability and NMES performance: MVC, MET, total TTI, TTI decline, fatigability index, number of contractions until a 50% decline, and NMES efficiency. Secondary outcomes were NMES-induced sensory discomfort, spinal excitability (H-reflex and M-wave), central activation ratio (CAR), and EMG root mean square (RMS) amplitude and median frequency (MDF). Detailed methods and results for H-reflex, M-wave, CAR, and EMG outcomes are provided in Electronic Supplementary Material (See Supplementary Material 1).

**Warm-up and maximal voluntary isometric contraction (MVC)**

Participants sat in the chair of an isometric dynamometer (Cefise, Nova Odessa, SP) with their right foot secured to the footplate. Procedures were performed on the right leg, with the hip, knee, and ankle at ~ 90°(Modesto et al., 2024). The warm-up consisted of six submaximal isometric plantar flexions (6-sec each) with a 10-sec rest between them. After a 1-min rest, two 6-sec MVCs were performed with a 1-min

interval, and the highest torque was recorded. The MVC torque was calculated over a 6-sec window(De Oliveira et al., 2018) and reassessed post- fatigability using the same procedure.

**Maximum Evoked Torque - MET**

Participants were instructed to relax while seated upright on the isometric dynamometer. NMES was delivered using a stimulator (DIGITIMER DS8R, London, UK) connected to two pairs of 25 cm² self-adhesive electrodes (Valutrode, São Paulo, Brazil). After shaving and cleaning the skin, two electrodes were placed below the knee near the proximal insertion of the medial and lateral gastrocnemius, and two approximately 5 cm above the Achilles tendon(De Oliveira et al., 2018; Grosprêtre et al., 2018). Evoked torque was calculated over a 6-sec window and normalized to maximal voluntary torque using the formula: [(NMES-evoked torque ÷ maximal voluntary torque) × 100](Pinto Damo et al., 2021). Two minutes after MVC testing, two METs were recorded at the highest tolerated below the pain threshold NMES intensity, as determined during familiarization. This procedure was repeated after the fatigability protocol. The current intensity was maintained within the motor level to prevent participants from reaching their pain threshold (De Oliveira et al., 2018; Malone et al., 2014; Vitry et al., 2019) .

**Fatigability outcomes**

The torque-time integral (TTI), representing the isometric work, was defined as the area under the torque-time curve. Total TTI was calculated by summing the TTIs of all NMES-evoked contractions during the fatigability protocol (Bergquist et al., 2014). The TTI decline was expressed as the percentage decrease in work, calculated as the ratio between the average TTI of the first five and the last five evoked contractions (Laufer and Elboim 2008) (Durigan et al. 2025).

TTI decline (%) = [(mean TTI of the first five contractions – mean TTI of the last five contractions) / mean TTI of the first five contractions] × 100.

The muscle fatigability index was calculated as the ratio of the average torque from the first to the last evoked contraction, across the 20 NMES-elicited contractions, with each torque value expressed as a percentage of MVC for each protocol (Laufer and Elboim 2008).

To identify fatigability onset, evoked torque values from the first to the twentieth contraction were normalized to the initial contraction. The contraction at which torque dropped to 50% of the initial value marked the point of significant fatigability during the NMES protocol (Laufer and Elboim 2008).

**NMES Efficiency Assessment**

NMES efficiency was assessed by calculating the ratio of NMES-evoked torque to current intensity (Nm/mA), using the evoked torque values recorded during the 20th contraction of the fatigability protocol(Laufer & Elboim, 2008) .

**Sensory discomfort**

VAS was used to evaluate sensory discomfort on a scale from 0 (no discomfort) to 10 (maximum discomfort), being administered after NMES-evoked contractions during the maximum evoked torque and at the first, tenth, and twentieth contractions of the fatigability protocol(Pinto Damo et al., 2021) .

# 2.5 NMES fatigability protocol

Immediately following the assessment of the H-reflex and M-wave, the stimulation intensity was gradually increased from 1 mA, until reaching 20% MVC(Hermens et al., 2000). The current intensity remained constant from the first contraction of the fatigability protocol, thus avoiding progressive recruitment of MUs during fatigability(Pinto Damo et al., 2021). The fatigability protocol involved 20 evoked contractions at 20% MVC. Each contraction had a 20-second duration with a 20-second interval between them. The submaximal evoked torque (SET) was expressed as a percentage of the torque values obtained during the MVC, normalized using the equation [SET x voluntary torque (-1)) x 100](Pinto Damo et al., 2021).

# 2.6 Statistical analysis

An a priori calculation in G*Power version 3.1.3 (University of Trier, Trier, Germany) used $\alpha = 0.05$, 80% power, and an effect size of 0.52 for change in TTI over time, yielding 36 participants. The target was increased by 20% for potential attrition, resulting in 44 participants. Data are reported as mean with 95% confidence interval (CI), unless otherwise stated. Normality was assessed using the Shapiro–Wilk test and homogeneity of variance using Levene's test. Two- and three-factor repeated-measures analyses of variance evaluated current type (PC vs KFAC), phase duration (500 vs 200 μs), and time (pre- vs post-fatigability), with Tukey-adjusted post hoc comparisons. Partial eta squared ($\eta p^2$) quantified effect size. Analyses were conducted in STATISTICA version 12.5.192.0 (StatSoft Inc., Tulsa, OK, USA), with two-sided $\alpha = 0.05$. Figures were prepared in GraphPad Prism version 6.0 (GraphPad Software, San Diego, CA, USA).

# 3. RESULTS

# 3.1 General Observation

All 44 randomized participants completed all five sessions and were included in the analyses (Fig. 2). Mean ± SD age was 24.4 ± 4.9 years, body mass was 67.7 ± 14.1 kg, height was 1.696 ± 0.08 m, and body mass index was 23.4 ± 3.9 kg/m². No adverse events occurred during any NMES condition.

**Voluntary and evoked torque**

No interaction was found between time and condition for MVC ($F = 1.201$, $P = 0.311$, $\eta p^2 = 0.020$; Table 2), but there was a main effect of time ($F = 42.446$, $P < 0.001$, $\eta p^2 = 0.197$), indicating reduced voluntary torque across all four currents after the fatigability protocol. No main effect of condition was observed ($F = 0.096$, $P = 0.962$, $\eta p^2 = 0.001$). Similarly, for MET, no time × current interaction was found ($F = 2.635$, $P = 0.051$, $\eta p^2 = 0.043$), but a main effect of time was observed ($F = 13.124$, $P < 0.001$, $\eta p^2 = 0.070$), showing

reduced MET after fatigability across all currents. No main effect of condition was observed (F = 0.835, P = 0.476, ηp² = 0.014).

Table 2
Results of different NMES currents and phase durations before (PRE) and after (POST) the fatigability protocol.

| | PC 500 | | PC 200 | | KFAC 500 | | KFAC 200 | |
|---|---|---|---|---|---|---|---|---|
| | PRE | POST | PRE | POST | PRE | POST | PRE | POST |
| **MVC*** | 87.82 | 79.85 | 90.77 | 82.27 | 89.98 | 83.73 | 87.28 | 83.7 |
| **(Nm)** | (77.64-98) | (70.42–89.28) | (81.11-100.43) | (73.69–90.86) | (81.04–98.92) | (74.68–92.78) | (79.53–95.04) | (74.85–92.55) |
| **MET*** | 64.59 | 58.37 | 58.55 | 58.30 | 64.59 | 59.65 | 59.28 | 54.19 |
| **(Nm)** | (57.78–71.4) | (52.23–64.51) | (51.58–62.72) | (51.45–65.13) | (57.78–71.4) | (53.2-66.11) | (51.41–67.16) | (48.70-59.68) |
| **Discomfort** | 2.50 | 2.57 | 2.50 | 2.91 | 3.43 | 3.14 | 3.09 | 3.16 |
| **(VAS: 0–10)** | (1.92–3.07) | (1.92–3.21) | (1.82–3.17) | (2.17–3.64) | (2.73–4.12) | (2.34–3.93) | (2.39–3.78) | (2.32–3.99) |

**Legend:** Data are reported as mean (95% CI). ***** = Time effect condition (p < 0.001). KFAC, kilohertz-frequency alternating current; MET, maximal evoked torque; MVC, maximal voluntary contraction; PC, pulsed current; VAS, visual analogue scale.

**Fatigability and efficiency**

Total TTI showed a current type × phase duration interaction (F = 12.268, P = 0.001); the 500-μs conditions produced greater total TTI than the 200-μs conditions (P = 0.001; Fig. 3a). NMES efficiency at the twentieth contraction showed a main effect of phase duration (F = 16.893, P < 0.001, ηp² = 0.227), with greater efficiency for 500 μs than 200 μs (P < 0.001; Fig. 3b).

The current type × phase duration interaction was not significant for the number of contractions until a 50% decline (F = 0.219, P = 0.642, ηp² = 0.005). Descriptively, the threshold occurred at contraction 4 for KFAC 200, contraction 9 for PC 200, and contraction 16 for PC 500; KFAC 500 did not reach a 50% decline during the protocol (Fig. 3c). These descriptive thresholds were not supported by a significant interaction and therefore should not be interpreted as between-condition differences.

The TTI trajectory showed no condition × time interaction (F = 1.083, P = 0.357, ηp² = 0.018), but there was a main effect of time (F = 76.520, P = 0.001, ηp² = 0.029; Fig. 3d) and no main effect of condition (F = 0.885, P = 0.449, ηp² = 0.015). Neither the torque fatigability index (F = 0.013, P = 0.051) nor the TTI fatigability index (F = 0.057, P = 0.056) differed significantly among conditions. Condition-level estimates are displayed in Fig. 3 and Online Resource 1.

**Sensory discomfort**

Sensory discomfort showed no condition × time interaction ($F = 1.405$, $P = 0.211$, $\eta p^2 = 0.023$; Table 2), no main effect of time ($F = 0.311$, $P = 0.732$, $\eta p^2 = 0.001$), and no main effect of condition ($F = 0.918$, $P = 0.433$, $\eta p^2 = 0.015$).

**Neuromuscular outcomes**

RMS amplitude decreased after fatigability in the soleus and lateral gastrocnemius (both $P < 0.001$). M-wave and H-reflex amplitudes showed time effects in selected muscles, whereas the Hmax/Mmax ratio and CAR were unchanged. No consistent current-type interaction was identified for these outcomes; complete analyses are provided in Online Resource 1.

# 4. DISCUSSION

The present study aimed to compare the fatigability-related responses, torque output, NMES efficiency, and sensory discomfort induced by PC and KFAC using two phase durations (200 μs and 500 μs). Our findings demonstrate that phase duration, rather than current type, is the primary determinant of NMES efficiency and fatigability resistance. The 500 μs phase duration protocols (both PC500 and KFAC500) consistently outperformed their 200 μs counterparts in terms of TTI, fatigability resistance, and NMES efficiency, regardless of current type. Based on these results, physical therapists should carefully consider phase duration, as it may exert a greater influence than current type on optimizing muscle work, mitigating fatigability, and maintaining comfort during NMES.

Regarding the fatigability index, KFAC200 demonstrated the most severe fatigability (77.91% reduction), followed by PC200 (58.83%), while the wide-pulse protocols (KFAC500: 41.86%; PC500: 31.99%) led to less fatigability. Our results partially align with those of Aldayel et al.(Aldayel et al., 2010), who reported no differences between PC and KFAC for acute muscle torque production, hormonal/metabolic markers, or perceived exertion during bilateral knee extensor NMES using 400 μs pulses at 75 Hz. Similarly, our findings showed no differences between KFAC and PC, at the same phase durations, in fatigability or NMES efficiency, reinforcing the conclusion that waveform type alone may not significantly influence acute mechanical outcomes when phase duration and frequency are matched. However, our findings contrast with Laufer et al.(Laufer et al., 2001; Laufer & Elboim, 2008) and Paz et al.(Paz et al., 2023), who observed greater fatigability and/or lower torque with KFAC compared to PC. Laufer and colleagues showed that monophasic and biphasic PC waveforms induced greater torque and less fatigability than polyphasic KFAC, and Paz et al. confirmed higher fatigability and lower TTI for KFAC in a submaximal fatigability protocol. The inconsistency across studies suggests that waveform labels alone are insufficient and that phase duration, burst structure, duty cycle, contraction number, and muscle group must be considered.

Paz et al. reported greater fatigability and lower TTI with 2.5-kHz alternating current than with PC during 80 contractions delivered with 5 s on and 10 s off. By contrast, our protocol comprised 20 contractions

with 20 s on and 20 s off.. Laufer and Elboim also reported that the Russian current (2.5 kHz KFAC with 25 cycles per burst at 50 Hz) was more fatiguing than low-frequency PC, particularly due to its higher number of cycles per second. However, that study compared KFAC with varying burst durations (10 vs. 25 cycles), introducing differences in total charge delivery that could account for the greater fatigability observed with KFAC. In contrast, our study controlled for phase duration (200 vs. 500 μs) across all current types, minimizing variability in delivered charge per pulse. Muscle group may further explain divergent findings: earlier studies predominantly examined the quadriceps (Aldayel et al. 2010, 2011), whereas we examined the triceps surae, whose architecture, fiber composition, and activation patterns may produce different fatigability responses. The descriptive TTI trajectories reached a 50% decline at contraction 4 for KFAC 200, contraction 9 for PC 200, and contraction 16 for PC 500; KFAC 500 did not reach that threshold. Because the interaction was not significant, these thresholds are exploratory rather than confirmatory. Nevertheless, they are compatible with evidence that phase duration influences evoked torque and the balance of sensory and motor axon recruitment(Laufer et al., 2001; Laufer & Elboim, 2008; Ward, 2009). The superior performance of wide phases for mitigating fatigability induced by NMES may be attributed to their ability to activate a larger proportion of sensory afferents(Iijima et al., 2018), potentially facilitating central recruitment mechanisms that follow the size principle (smaller, fatigability-resistant MUs recruited first)(Barss et al., 2018; ENOKA & DUCHATEAU, 2016; Kent-Braun, 1999). In fact, previous studies demonstrated that NMES-evoked torque is directly related to the phase duration. Damo et al.(Pinto Damo et al., 2021) and Medeiros et al(Medeiros et al., 2017) reported that increasing the phase duration from 200 μs to 500 μs resulted in ~ 30% and 23% greater torque output, respectively. Although no interaction between current type and time was observed for MVC, RMS, or spinal excitability (see Supplementary Material), the consistent advantage of 500 μs over 200 μs pulses suggests that longer durations deliver a greater NMES charge, enhancing MU recruitment and delaying fatigability. Taken together, the increase in torque generation and mitigation of fatigability induced by NMES are supported by research demonstrating that wider phase durations preferentially activate sensory axons compared to narrow phase durations, due to their lower rheobase and longer strength-duration time constants compared to motor axons(ENOKA & DUCHATEAU, 2016; Pinto Damo et al., 2021) .

Sensory discomfort, a critical factor that can affect NMES therapeutic efficacy, did not differ during our fatigability protocol. Although few studies have evaluated sensory discomfort during or after submaximal fatigability protocols comparing PC and KFAC, our results are consistent with prior research involving 15 to 30 contractions, which similarly found no differences(Gorgey et al., 2006; Grimby & Wigerstad-Lossing, 1989; Laufer et al., 2001; Laufer & Elboim, 2008). However, these results contrast with those of Vaz et al. (Vaz et al., 2012), who reported differences in sensory discomfort, potentially attributable to the different waveforms (rectangular for PC and sinusoidal for KFAC). This distinction is relevant, as sinusoidal currents are generally perceived as more uncomfortable than rectangular currents(Lyons et al., 2005), whereas we utilized only rectangular waveforms for all four currents tested, possibly accounting for the observed similarity in discomfort levels.

The current study presents some limitations. First, our assessment focused on plantar flexor muscles, and the results cannot be generalized to muscles with different fiber compositions(Durigan, Kelly, et al., 2025; Maffiuletti, 2010; Pinto Damo et al., 2021). Second, submaximal NMES intensities were used, and the findings might differ at higher intensities that recruit more high-threshold Mus(Durigan, Kelly, et al., 2025; Medeiros et al., 2017). Although phase duration was key for fatigability, other parameters such as the current amplitude, electrode size, and duty cycle were held constant, limiting analysis of their combined effects on NMES-fatigability and efficiency(Szecsi et al., 2014). In addition, the sample comprised young, healthy adults and only the plantar flexors were examined, limiting generalizability to other muscles, older adults, and clinical populations. Future research should examine long-term NMES adaptations across phase durations and current types (KFAC vs. PC) and investigate effects in clinical populations to optimize rehabilitation protocols.

# 5. CONCLUSION

KFAC and PC, applied with the same phase duration, induced similar levels of fatigability, NMES efficiency, and sensory discomfort, with no clear differences in the mechanisms of fatigability between them. However, currents with smaller phase durations induced greater and more rapid fatigability, with lower NMES efficiency compared to wide pulses, regardless of current type (KFAC or PC). Clinically, currents with wider phase durations (500 μs) resulted in improved NMES efficiency and greater resistance to fatigability, making them more suitable for applications where endurance is required or early-onset fatigability is present during rehabilitation, such as in post-injury training, neuromuscular re-education, or in populations with limited exercise tolerance.

# Abbreviations

ANOVA
analysis of variance
BMI
body mass index
CAR
central activation ratio
CI
confidence interval
CONSORT
Consolidated Standards of Reporting Trials
EMG
electromyography / electromyographic
F
F statistic used in ANOVA tests
Hz
hertz (unit of frequency)

H-reflex
Hoffmann reflex
kHz
kilohertz (one thousand hertz)
KFAC
kilohertz-frequency alternating current
KFAC 200
kilohertz-frequency alternating current with 200 μs phase duration
KFAC 500
kilohertz-frequency alternating current with 500 μs phase duration
mA
milliampere
MDF
median frequency of the EMG power spectrum
MET
maximum evoked torque
maximum evoked torque M-wave
compound muscle action potential (M-wave)
MVC
maximal voluntary contraction
NCT
National Clinical Trial number
Nm
newton meter (unit of torque)
NMES
neuromuscular electrical stimulation
NSAIDs
nonsteroidal anti-inflammatory drugs
p
p value (probability value in significance testing)
PC
pulsed current
PC 200
pulsed current with 200 μs phase duration
PC 500
pulsed current with 500 μs phase duration
RMS
root mean square amplitude of the EMG signal
SD
standard deviation

SET
submaximal evoked torque
TTI
torque-time integral
VAS
visual analog scale
$\eta p^2$
partial eta squared (effect size measure in ANOVA)
µs
microsecond (unit of pulse phase duration)

# Declarations

### AVAILABILITY OF DATA AND MATERIALS

The data and materials in this paper are available from the corresponding author on request.

### COMPETING INTEREST AND FUNDING

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines. The authors declare no competing interests. The current study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil (CAPES), Finance Code 001, Fundação de Apoio à Pesquisa do Distrito Federal (FAPDF) (grant numbers 00193-00001261/2021-23 and 00193-00001623/2024-29), and the National Council for Scientific and Technological Development (CNPq; process number 308519/2025-6; 402816/2023-4). We also thank Robin Hambly for reviewing the English.

### AUTHOR CONTRIBUTION STATEMENT

LA, VN, MV and JD conceived and designed research. LA and LC conducted experiments. VR contributed new analytical tools. LA, LC, CS and GR analyzed data. LA and JD wrote the manuscript. All authors read and approved the manuscript.

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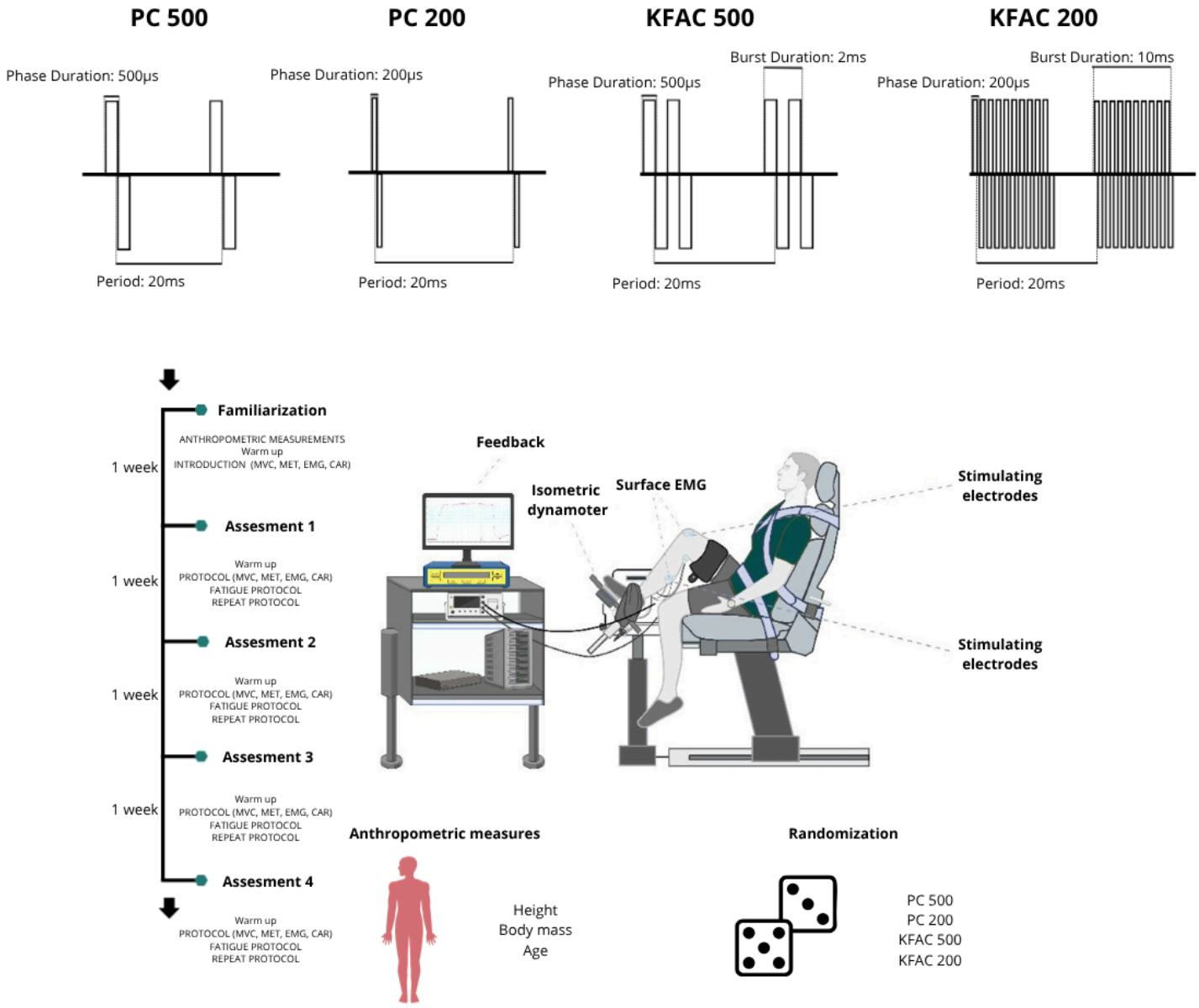
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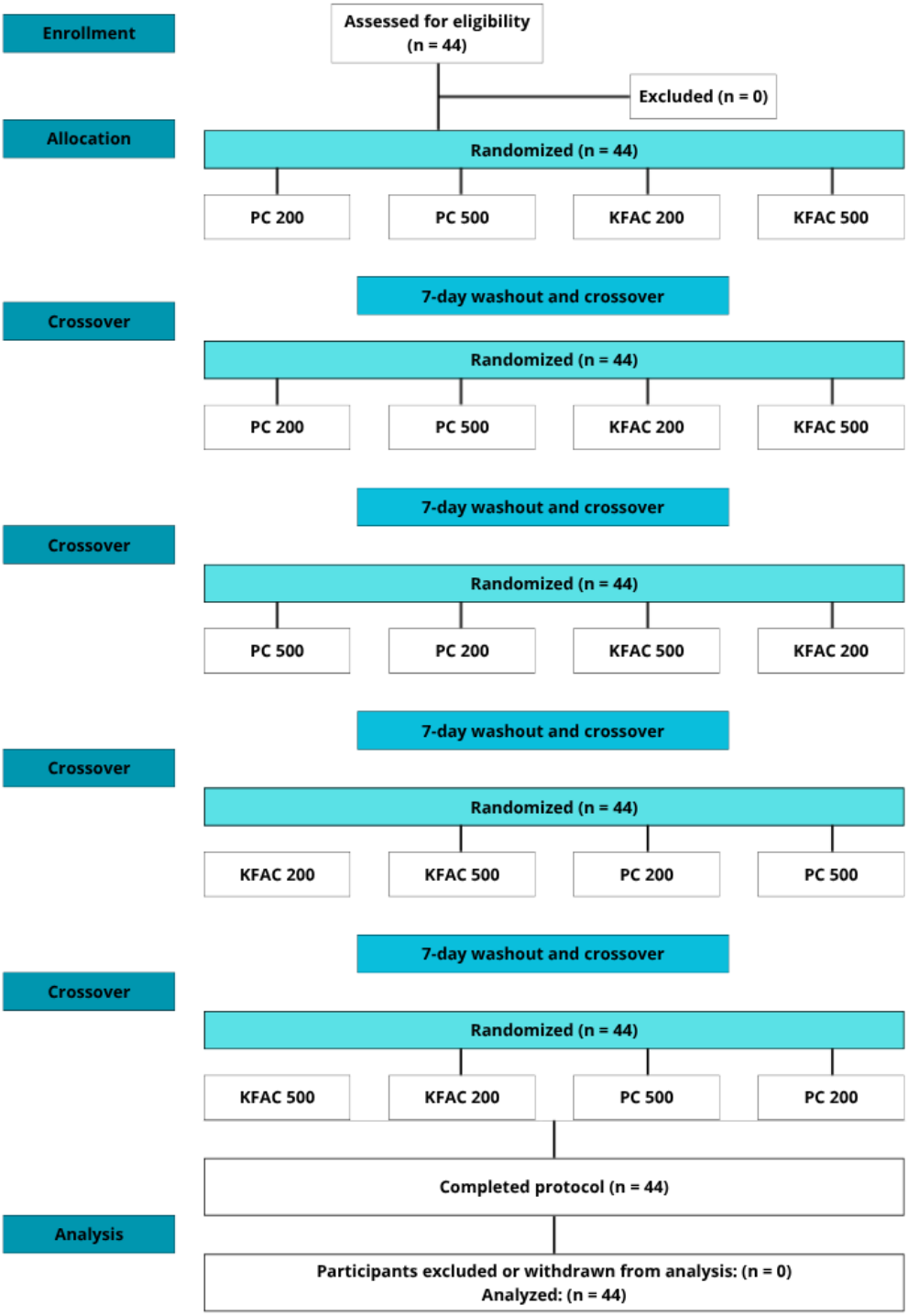
# Figures




## Figure 1

Neuromuscular electrical stimulation conditions and randomized crossover study design. (A) The four stimulation conditions applied to the right triceps surae were pulsed current with a 500 µs phase duration (PC 500; 50 Hz), pulsed current with a 200 µs phase duration (PC 200; 50 Hz), kilohertz-frequency alternating current with a 500 µs phase duration (KFAC 500; 1 kHz carrier frequency, 50 Hz burst frequency, 2 ms burst duration, and 18 ms interburst interval), and kilohertz-frequency alternating current with a 200 µs phase duration (KFAC 200; 2.5 kHz carrier frequency, 50 Hz burst frequency, 10 ms burst duration, and 10 ms interburst interval). (B) Participants attended five sessions separated by at least 7 days. Session 1 included familiarization, anthropometric assessment, determination of the maximum tolerated stimulation intensity for each condition, and randomization of the condition sequence. During

sessions 2–5, each participant completed one of the four NMES conditions per session in randomized order. Each experimental session comprised a warm-up; pre-fatigability assessment of maximal voluntary contraction, maximum evoked torque, H-reflex and M-wave responses, central activation ratio, and electromyographic activity; an NMES fatigability protocol consisting of 20 electrically evoked contractions initiated at 20% of maximal voluntary contraction, with 20 s of stimulation and 20 s of rest; and repetition of the assessments after the fatigability protocol. Sensory discomfort was recorded using a visual analogue scale after the maximum evoked torque assessment and after contractions 1, 10, and 20 of the fatigability protocol. CAR, central activation ratio; EMG, electromyography; H-reflex, Hoffmann reflex; KFAC, kilohertz-frequency alternating current; MET, maximum evoked torque; MVC, maximal voluntary contraction; NMES, neuromuscular electrical stimulation; PC, pulsed current; VAS, visual analogue scale.




## Figure 2

Flow diagram of experimental design and number of participants. PC = pulsed current; KFAC =kilohertz-frequency alternating current.

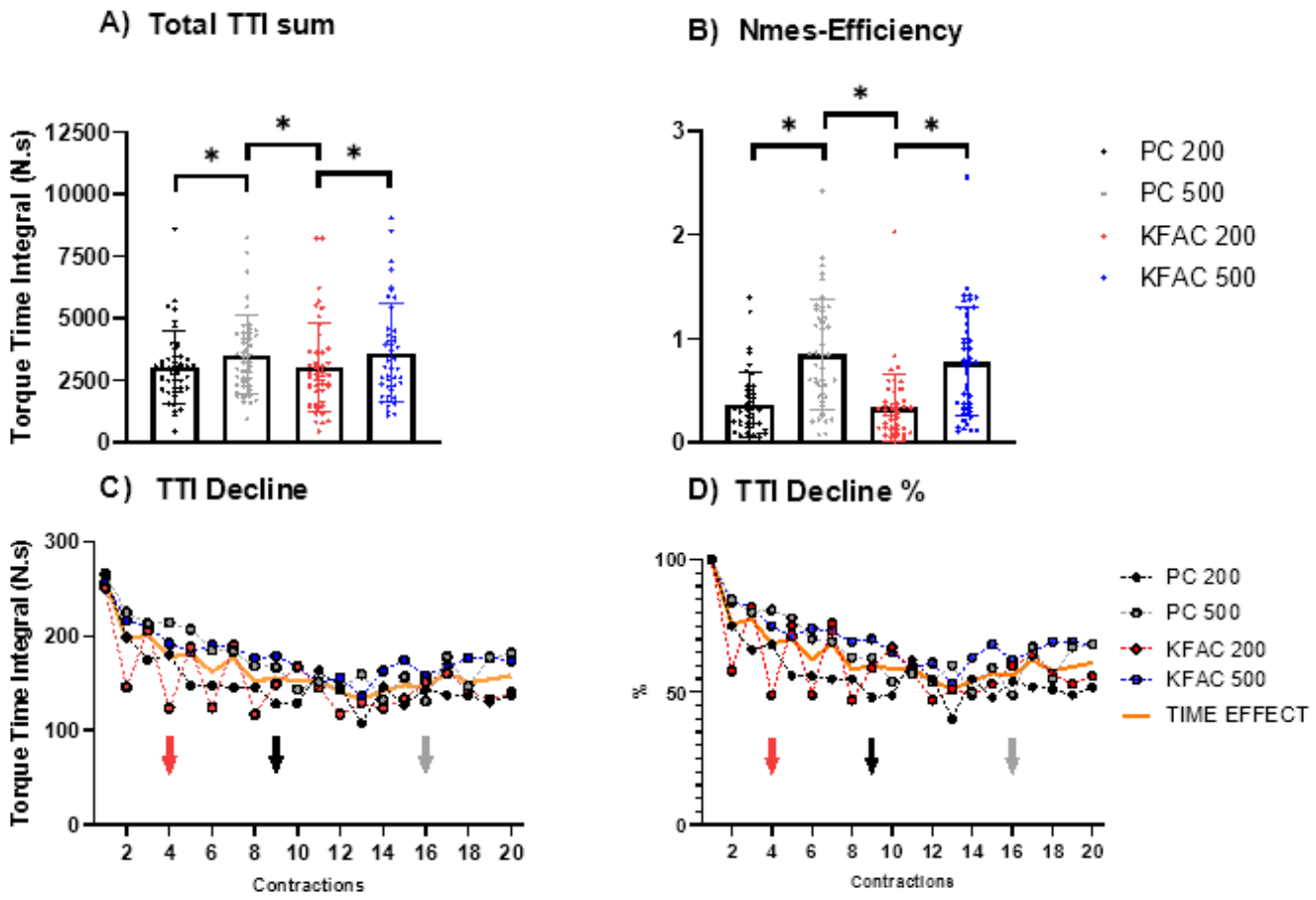



**Figure 3**

**A:** Currents with a 500µs pulse phase duration showing a higher total torque-time integral (TTI) when compared to the 200µs pulse phase currents (p = 0.001). **B:** Currents with a 500µs phase duration showing higher NMES efficiency compared to the 200µs phase duration currents (p = 0.0001). **C:** TTI decline during the fatigability protocol (p = 0.001). **D:** TTI decline during the fatigability protocol normalized by the maximal voluntary contraction (p = 0.001). Arrows pointing down indicate a 50% drop in TTI in KFAC 200, PC 200, and PC 500 currents.

## Supplementary Files

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