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A FREQUÊNCIA DE 10 KHZ FAZ DIFERENÇA? RESPOSTAS MOTORAS E
SENSORIAIS A CORRENTES DE ALTA FREQUÊNCIA COM FASES
CORRESPONDENTES

Brasília – DF
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Dedication

I dedicate this work to my beloved grandfather, who, despite growing up in extremely humble circumstances, always recognized the value of education and was the only one among his siblings to earn a university degree.

Acknowledgements

First and foremost, I thank God for granting me the strength, wisdom, and perseverance to carry out and complete this work.

I am deeply grateful to my mother for her unconditional support, constant encouragement, and for standing by my side throughout this journey, from beginning to end.

To my grandparents, Raquel, Edinei, and Renilda, I express my heartfelt gratitude for their love, encouragement, and the example they have set throughout my life. You have always been my greatest supporters and my constant source of inspiration.

Finally, I would like to express my sincere gratitude to my advisor, João Durigan, for believing in my potential from the very beginning, for the trust he placed in me, for his guidance, dedication, and mentorship, and for the countless opportunities that have contributed to both my personal and professional growth.

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Brasília – DF
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Resumo

Objetivo: Investigar como a variação das frequências de corrente e das durações de fase influencia o recrutamento sensório-motor e o desconforto percebido. **Métodos:** Foi realizado um estudo randomizado, duplo-cego e cruzado. Trinta participantes receberam estimulação elétrica dos flexores plantares utilizando quatro correntes alternadas em quilohertz (KFAC: 10, 5, 2,5 e 1 kHz), quatro correntes pulsadas com fase correspondente (PC: 0,05, 0,1, 0,2 e 0,5 ms) e uma corrente monofásica de 1 ms. As curvas de recrutamento foram geradas a partir de 40 estímulos para obtenção da onda M e do reflexo H do músculo sóleo, seguidos de 20 estímulos submáximos, correspondentes a 3–7% e aproximadamente 20% do Mmax. O recrutamento sensório-motor foi avaliado por meio das respostas normalizadas da onda M e do reflexo H, e o desconforto percebido foi mensurado utilizando uma escala visual analógica (EVA) de 0–10 cm. **Resultados:** As correntes PC e KFAC produziram amplitudes de Mmax comparáveis quando as larguras de fase foram correspondidas. Entretanto, a PC exigiu menores intensidades de estimulação do que a KFAC nas durações de 0,1–0,5 ms, enquanto o pulso monofásico de 1 ms exigiu intensidades menores do que a maioria das outras condições (exceto na duração de 0,5 ms). As amplitudes de Hmax foram, em geral, semelhantes entre PC e KFAC, exceto em 0,2 ms, condição em que surgiram diferenças, e o pulso de 1 ms evocou Hmax maior do que as durações mais curtas ($\leq 0,2$ ms). As razões H/M foram comparáveis em 0,05 e 0,5 ms, mas foram maiores para a PC em 0,1–0,2 ms. O desconforto percebido, medido pela EVA, não diferiu entre PC e KFAC nas durações de fase correspondidas; contudo, considerando todas as condições, o pulso de 1 ms foi classificado como o mais confortável. **Conclusão:** Quando a duração de fase é correspondida, KFAC e PC evocam respostas motoras e sensoriais equivalentes e níveis semelhantes de desconforto. Durações de pulso mais amplas (0,5–1 ms) otimizam o recrutamento sensorial e reduzem a necessidade de intensidades elevadas, confirmando a duração de fase como o principal parâmetro para protocolos de EENM (NMES) eficientes e confortáveis.

Palavras-Chave: Reflexo H, onda M, KFAC, PC, EENM.

Abstract

Objective: To determine how kilohertz-frequency alternating currents (KFAC) and phase-matched pulsed currents (PC) influence sensory-motor recruitment and discomfort during tibial nerve stimulation. **Methods:** In this randomized, double-blind, crossover study, 30 healthy adults received single 1-ms stimuli to the tibial nerve using four KFAC conditions (10, 5, 2.5, and 1 kHz), four phase-matched PC conditions (0.05, 0.1, 0.2, and 0.5 ms), and one 1-ms monophasic pulse. Recruitment curves were generated using 40 stimuli to elicit soleus M-wave and H-reflex responses. This was followed by 20 submaximal stimuli delivered at intensities of 20% of Mmax. Sensory–motor recruitment was assessed using the Hmax/Mmax ratio, and perceived discomfort was evaluated using a 0–10 cm visual analogue scale. **Results:** PC and KFAC produced comparable Mmax at matched phase durations. However, PC required lower intensities than KFAC at 0.1–0.5 ms, whereas 10 kHz required lower intensities than the 0.05-ms PC condition. Hmax was generally similar between waveforms, except at 0.2 ms, where PC elicited greater responses than 2.5 kHz KFAC. Hmax/Mmax ratios were comparable at 0.05 and 0.5 ms but higher for PC at 0.1–0.2 ms. Discomfort did not differ between phase-matched waveforms, and the 1-ms monophasic pulse was the most comfortable condition. **Conclusion:** When phase duration is matched, KFAC and PC evoke equivalent motor and sensory responses and similar discomfort. Wider pulse durations (0.5–1 ms) optimize sensory recruitment and reduce intensity demands, confirming phase duration as the key for efficient and comfortable NMES protocols.

Keywords: H-reflex, M-wave, KFAC, PC, NMES

List of Figures

Fig 1. Experimental design. A–I, Current modulations.....	16
Fig 2. Representative single-participant.	18
Fig 3. Recruitment curves illustrating the effects of phase duration and stimulation type on evoked responses.	18
Fig 4. Submaximal responses at 20% Mmax illustrating the effects of phase duration and stimulation type.	19
Fig 5. Submaximal responses at 3–7% Mmax illustrating the effects of phase duration and stimulation type.	20
Fig 6. Visual analogue scale (VAS) scores for perceived discomfort across stimulation conditions	21

Table of Contents

.....	Erro! Indicador não definido.
Dedication.....	4
Acknowledgements	5
Resumo	7
Abstract.....	8
List of Figures.....	9
Introduction	12
Literature Review	13
2.1. Neuromuscular Electrical Stimulation	13
2.2. Pulsed Current.....	13
2.3. Kilohertz-frequency alternating current (KFAC).....	13
2.4. The Hoffman reflex and M-wave	13
Aims and Hypothesis.....	14
Methods	14
Trial design.....	14
Participants	14
Blinding, randomization and allocation concealment	15
Torque	15
Electromyography (EMG)	15
Peripheral nerve stimulation	15
Protocol.....	15
Warm-up	15
Recording of M-wave and H-reflex recruitment curve (RC)	15
H-reflex and M-wave size at 20%	17
Perceived sensory discomfort	17
Data analysis	17
Statistical analysis and sample size	17
Results	18
Single participant.....	18
Torque values.....	18

M-wave analysis.....	18
Mmax	18
H-reflex Analysis	19
H/M analysis.....	19
Submaximal Responses	20
20% Mmax	20
3-7% Mmax.....	21
Discomfort	24
Discussion.....	25
Conclusion.....	29
Practical Implications of the Findings for Society	30
References	31
Appendices	36
Appendix 1. Ethics Committee approve	36
Products Developed During the Master's Program	38
Product 1.	38
Product 2	39
Product 3.	40
Link to the video	41

Introduction

Neuromuscular electrical stimulation (NMES) is already well established as an important tool for rehabilitation and pain control in individuals with neuromuscular diseases, effectively minimizing atrophy and weakness [1], [2], [3], [4]. NMES, whether applied over a mixed nerve or muscle belly, activates both motor and sensory axons, delivering signals to muscles and the central nervous system (CNS), respectively [4], [5], [6]. The balance of motor and sensory axon recruitment can be influenced by adjusting stimulation pulse parameters; using pulses with longer durations (≥ 0.5 ms) increases signal strength and favors sensory axon activation [5], [7]. As a result, phase durations of ~ 0.5 – 1 ms are commonly recommended for eliciting H-reflexes [8], while shorter pulses (0.1 – 0.5 ms) are typically used for motor-focused applications, like functional electrical stimulation [6], [9]. At a phase duration of 1 ms, axonal excitability increases, allowing stimulation with broader pulses and lower intensities [10]. These recommendations regarding stimulation parameters, particularly the use of longer phase durations (~ 0.5 – 1 ms) to favor sensory axon recruitment and shorter durations (0.1 – 0.5 ms) for motor-focused applications, are largely based on studies using monophasic stimulation, defined as pulses with a single depolarizing phase [4], [5], [10], [11]. However, it remains unclear whether similar recruitment patterns apply to high-frequency waveforms, such as kilohertz-frequency alternating currents (KFAC) or low-frequency pulsed currents (PC) [11], [12], [13].

NMES is typically delivered using KFAC or PC [9]; KFAC uses 1 – 10 kHz carrier frequencies applied at burst frequencies of 1 – 100 Hz, with a duty cycle of 10% or more [11], [12], [13] and PC is delivered at 1 – 100 Hz (0.2 – 0.5 ms of phase duration). KFAC was introduced in the 1970s in Russia and is characterized by a 2.5 kHz carrier frequency, initially proposed to enhance muscle strengthening while reducing sensory discomfort [14]. However, findings from systematic reviews have challenged this assumption, reporting no significant differences in evoked torque or perceived discomfort between KFAC and biphasic waveforms [9], [13], [15]. Evidence suggests that, regardless of whether KFAC or PC currents are used, a wider phase duration is associated with increases in both evoked torque and perceived discomfort when pulse duration is matched [12].

Kilohertz-frequency stimulation paradigms, particularly 10 kHz waveforms commonly used in transcutaneous spinal cord stimulation (tSCS), have recently gained attention because of their proposed therapeutic and comfort-related advantages [2], [16]. Early studies suggested that 10 kHz stimulation may selectively block small-diameter nociceptive fibers, thereby allowing higher stimulation amplitudes with less discomfort [2], [17]. However, accumulating evidence indicates that 10 kHz tSCS may instead modulate dorsal horn networks rather than act through selective fiber recruitment, broadening its potential relevance for chronic pain management and motor rehabilitation [18]. In addition, Formento et al. proposed that high-frequency stimulation may facilitate temporal summation through the Gildemeister effect, whereby repetitive low-amplitude pulses progressively accumulate membrane depolarization and allow comparable motoneuron excitation at lower recruitment thresholds [19]. This mechanism has been suggested as a potential explanation for the reduced motor and sensory thresholds observed during some 10 kHz stimulation protocols. Despite growing interest in high-frequency KFAC, to date, no studies have systematically compared multiple frequencies while controlling for phase duration and perceived discomfort. Moreover, discomfort inherent to NMES limits greater stimulation

intensities and, consequently, muscle activation, representing a major barrier to effective rehabilitation [12], [20].

Literature Review

2.1. Neuromuscular Electrical Stimulation

Neuromuscular electrical stimulation (NMES) is a tool widely used with the aim of increasing strength in certain populations. When NMES is applied through the skin to elicit muscle contractions, either over a mixed nerve or directly over the muscle belly, it activates motor and sensory axons, generating signals that are conveyed to the muscles and the central nervous system (CNS) [11], [21] and its effects are determined by some physical parameters such as amplitude, frequency, and pulse duration; external factors such as the type of electrode used and its size; and finally, physiological factors such as the type of contraction, the target muscle, and the size of the myotendinous junction [22]. With monophasic waveforms, increasing pulse duration (>0.5 ms) promotes greater recruitment of sensory axons relative to shorter pulses. This effect is likely explained by differences in ion channel properties between motor and sensory axons [4], [7], [11].

2.2. Pulsed Current

Pulsed currents typically involve electrical pulses characterized by relatively short pulse durations (<400 ms), applied at low to moderate stimulation frequencies (15–50 Hz) and relatively high stimulation intensities. It is described as a pulsed current because each phase of stimulation is separated by a noticeable interval of time, known as the interpulse interval [15]. The resulting pulsed waveforms may take different shapes, including rectangular, sinusoidal, or asymmetric patterns, and can consist of a single positive phase (monophasic, MP) or a sequence of positive and negative phases (biphasic, BP) [15].

2.3. Kilohertz-frequency alternating current (KFAC)

Kilohertz-frequency alternating current (KFAC) is applied at frequencies ranging from 1 kHz to 10 kHz [1], [14]. In theory, KFAC has a greater potential to generate muscle force while producing less discomfort, and it can be delivered either continuously or in bursts [15]. The evoked torque and the level of discomfort are influenced not only by the type of current but also by the stimulation parameters applied, such as frequency, pulse duration, intensity, and the burst duty cycle [15].

2.4. The Hoffman reflex and M-wave

The Hoffmann reflex, also known as the H-reflex, is a response to electrical stimulation that recruits motor neurons and consequently results in muscle activation. It is commonly used to assess the excitability of spinal motoneurons [15], [23]. When stimulation of a nerve trunk is strong enough to generate an action potential in afferent axons and the postsynaptic excitatory potential reaches the firing threshold of the motoneuron, the resulting action potential is transmitted to the neuromuscular junction of the innervated muscle,

thereby producing a muscle contraction [13], [23]. The intensity of the stimulus determines the amplitude of the reflex, producing an electromyographic response in which the highest amplitude point of the wave corresponds to the peak reflex value (Hmax) [24], [25].

Based on the amplitude of the wave, it is possible to identify the level of activation: small reflex amplitudes indicate the recruitment of low-threshold motor units, whereas larger reflex amplitudes indicate the recruitment of motor units with higher firing thresholds [16], [26]. Thus, as stimulus intensity increases, a greater number of motoneurons are recruited through afferent pathways [23], [27]. The H-reflex and the M-wave are commonly used to examine potential effects of interventions such as neuromuscular electrical stimulation (NMES) on the central contribution to muscle activation. Therefore, studying these responses is highly important for the development of rehabilitation protocols involving electrical stimulation. However, the literature still does not clearly indicate which type of current, or stimulation parameters are most effective for achieving higher H-reflex and M-wave values.

Aims and Hypothesis

Understanding how frequency and phase duration interact to influence motoneuron output is therefore critical for optimizing NMES protocols [28], in addition, assessing submaximal stimulation levels is clinically relevant, as submaximal intensities are commonly used in clinical and rehabilitation settings rather than maximal stimulation levels [12]. Thus, the purpose of the current study was to compare the effects of four KFAC frequencies (0.05 ms at 10 kHz, 0.1 ms at 5 kHz, 0.2 ms at 2.5 kHz, and 0.5 ms at 1 kHz) with phase-matched pulsed currents (PC: 0.05, 0.1, 0.2, and 0.5 ms) on the relative recruitment of sensory versus motor axons and perceived discomfort. For comparisons, a 1 ms monophasic pulse was also evaluated, given the well-established H-reflex amplitude under NMES conditions [7], [11]. We hypothesized that waveform type (KFAC vs. PC) would not influence outcome measures, and that increasing phase duration would preferentially recruit sensory axons relative to motor axons, accompanied by greater perceived discomfort.

Methods

Trial design

This study was a randomized, cross-over, double-blind trial that compared a KFAC protocol with a PC NMES condition. The research project was reviewed and approved by the Research Ethics Committee of the Faculty of Science and Technology, University of Brasília (approval number: CAAE 72475623.9.0000.809), in accordance with the Declaration of Helsinki. All participants provided written informed consent before inclusion in the study.

Participants

Thirty healthy adults with no history of neuromuscular injury or disease participated in the experiment (nineteen women and eleven men; age: 22.5 ± 1.86 years; body mass: 67.4 ± 16.3 kg; height: 1.60 ± 0.10 m; body mass index (BMI): 23.2 ± 3.5 kg/m²). Inclusion criteria were young adults male and female, aged 18–45 years, classified as physically active according to the International Physical Activity Questionnaire (IPAQ) or engaging in recreational physical activity. The participants were instructed to avoid caffeine for 12 hours and strenuous

exercise for 6 hours before each testing session [29].

Blinding, randomization and allocation concealment

The researcher responsible for administering the NMES (VSN) and the participants were blinded to the treatment allocation. To ensure this blinding, a separate researcher (SGOL) programmed the NMES device and covered its panel with an opaque shield, concealing all parameters except for the stimulation intensity. Randomization cards were generated using www.random.org, and the numbered stimulation protocols were randomly assigned to each participant and securely archived.

Torque

Participants were seated in an isometric dynamometer chair (Cefise, Nova Odessa, SP), with their right foot firmly secured to the footplate. Two maximal voluntary isometric contractions (MVICs) were then performed for 6 s each, with a 1-min interval between attempts, and the highest torque achieved during these MVICs was recorded. All procedures were conducted on the right leg, with the hip, knee, and ankle positioned at $\sim 90^\circ$ [11].

Electromyography (EMG)

The skin was shaved and cleansed with alcohol, after which two self-adhesive electrodes (Medi-Trace 100, Kendall) were placed ~ 1 cm apart over the soleus, distal to the gastrocnemii and along the mid-line, with the ground electrode on the tibia (Figure 1J). EMG activity was recorded using a portable surface EMG system (MP160, Biopac Systems, Aero Camino, Goleta, CA, USA). Signals were acquired with a 14-bit resolution, 2LSB noise level, and common-mode rejection ratio of 110 dB.

Peripheral nerve stimulation

The stimulation electrodes were pressed into the popliteal fossa over the right tibial nerve (cathode, self-adhesive electrode with 8 mm) and below the patella (anode, self-adhesive electrode with 5 X 10 cm Valutrode Arktus, São Paulo, Brazil) and then moved to the position that provided the greatest visible contraction of the soleus (Figure 1J) [30]. A biphasic constant current stimulator (DIGITIMER, DS8R, London, United Kingdom) was used to deliver one single stimulus of all currents, applied to the tibial nerve (Figure 1A-I for further details).

Protocol

Warm-up

A warm-up was performed, consisting of six submaximal isometric contractions (plantar flexion) of six seconds, interspersed with ten seconds of rest (Figure 1K).

Recording of M-wave and H-reflex recruitment curve (RC)

RCs were collected using four durations for the PC current (0.05, 0.1, 0.2, and 0.5 ms, phase duration), the same phase duration but with four different frequencies for the KFAC current (0.05 ms 10 kHz, 0.1 ms 5kHz, 0.2 ms 2.5 kHz and 0.5 ms 1 kHz), and one phase duration for the monophasic current (1 ms phase duration), since the H-reflex amplitude is well characterized under these conditions [7], [11]

For maximal recruitment curve acquisition, stimulation intensity, was gradually increased

from below motor threshold until the maximal M-wave amplitude (Mmax) was identified [11]. Once Mmax was established, 40 stimuli were delivered at varying intensities in a pseudo-random order, ranging from below the threshold required to evoke a detectable response to approximately $1.4\times$ the lowest intensity that elicited Mmax. An interstimulus interval of approximately 8–12 s was used across all protocols to minimize potential fatigue or habituation effects. By comparing changes in Hmax relative to Mmax we were able to observe neural changes at the spinal level [31].

Current intensities varied across conditions, ranging from 5-226 mA (1 ms), 5-918 mA (0.05 ms), 5-1000 mA (0.1 ms), 5-157 mA (0.2 ms), and 5-110 mA (0.5 ms) for PC. 5-737 mA (0.05 ms/10 kHz), 5-405 mA (0.1 ms/5 kHz), 5-301 mA (0.2 ms/2.5 kHz), and 5-150 mA (0.5 ms/1 kHz) for KFAC.

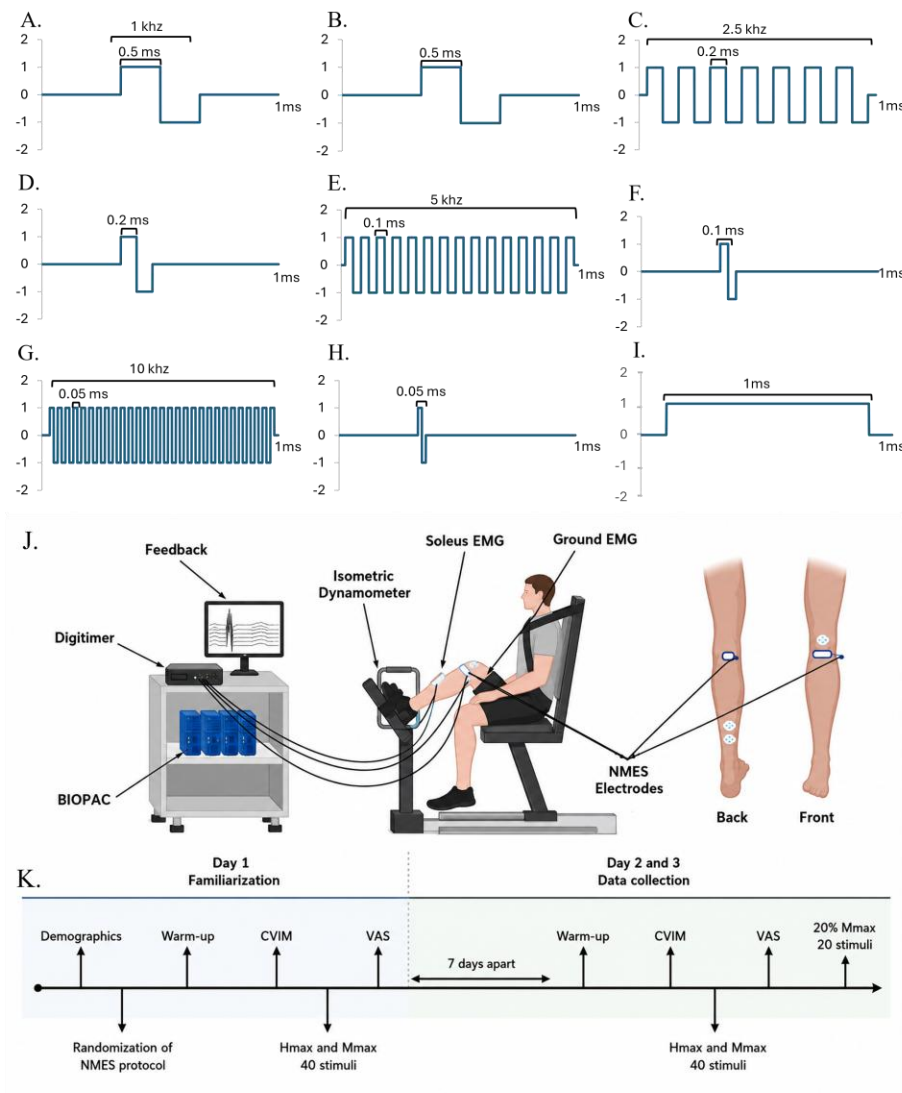


Fig 1. Experimental design. A–I, Current modulation. Nine single stimuli were applied in randomized orders. Four kilohertz frequency alternating current (KFAC) conditions were tested: A, 1 kHz with 0.5 ms phase duration; C, 2.5 kHz with 0.2 ms phase duration; E, 5 kHz with 0.1 ms phase duration; and G, 10 kHz with 0.05 ms phase duration. Four biphasic pulsed-current (PC) conditions were tested: B, 0.5 ms; D, 0.2 ms; F, 0.1 ms; and H, 0.05 ms. All stimuli had a total duration of 1 ms. A 1 ms monophasic current was also assessed (I), because H-reflex amplitude is well characterized under this

condition [7], [11]. J, Study setup. K, Study protocol. The study involved two laboratory visits. During the first visit, participants underwent eligibility screening, anthropometric assessment, and familiarization. Stimulation conditions were randomized individually. During the second visit, conducted seven days later, participants completed a standardized warm-up followed by assessments of Hmax, Mmax, recruitment curves, and submaximal responses.

H-reflex and M-wave size at 20%

All the NMES conditions were tested in an additional set of trials. A submaximal response was defined as 20% of the Mmax amplitude obtained from the recruitment curve. The stimulation intensity was progressively increased until the target M-wave amplitude (20% of Mmax) was achieved. Once this level was reached, twenty stimuli were delivered, at an intensity that produced M-waves that were ~20% Mmax [32].

Perceived sensory discomfort

A visual analogue scale (VAS) was used to measure the perceived sensory discomfort [12]. This scale is made up of numbers from 0 to 10, where 0 corresponds to no discomfort and 10 corresponds to the maximum discomfort. The VAS was presented to the participants after the RC was recorded.

Data analysis

Data was averaged across the 30 participants. Peak-to-peak amplitudes were measured for individual H-reflexes and M-waves, using Acknowledge software (BIOPAC Systems Inc., Goleta, CA, USA). The following parameters are presented: (A) Mmax (highest M-wave evoked at the RC), (B) intensity Mmax (intensity that M-wave reached its maximum), (C) Hmax (highest H-reflex evoked at the RC), (D) intensity Hmax (intensity where H reflex reached its maximum), (E) H/M ratio (division between the values of Hmax and Mmax), (F) intensity H/M (ratio between the stimulation intensities required to evoke Hmax and Mmax). For submaximal responses, (G) Mmax 20% (mean amplitude of the three highest M-waves evoked at 20%), (H) Hmax 20% (mean amplitude of the three highest H-reflexes evoked at 20%), (I) H/M ratio 20%, (J) intensity 20% (intensities to reach 20%). An interval corresponding to 3–7% of the maximal M-wave from the recruitment curve was calculated. This window was selected because it represents the ascending portion of the recruitment curve, where the H-reflex typically reaches its maximal amplitude relative to the M-wave, making it sensitive for detecting differences in sensory axon recruitment between conditions, (K) M-wave 3-7% (mean amplitude of evoked M-waves between 3-7%), (L) H-reflex 3-7% (mean amplitude of H-reflexes evoked when M-waves were between 3-7%), (M) H/M ratio 3-7% (ratio between M-wave and Hmax), and (N) intensity 3-7%.

Statistical analysis and sample size

The Generalized Estimating Equations (GEE) method was adopted, using “group” as factors for the main outcomes. The independence model criterion was used to select the best functional correlation structure in the GEE analyses. Bonferroni was used as a post-hoc test. Given the large number of pairwise comparisons performed for each variable (36 comparisons), Bonferroni correction was applied to control the familywise error rate. Effect sizes were calculated for all pairwise comparisons using Cohen’s d_z , the recommended index for within-subject crossover designs [33]. This metric was calculated as the mean of the individual paired differences between conditions divided by the standard deviation of

those differences across the 30 participants. Effect sizes were interpreted using conventional benchmarks: trivial <0.2, small = 0.2–0.49, medium = 0.5–0.79, and large ≥ 0.8 [34]. Statistical analyses were performed with SPSS 22.0 (IBM Corporation, Armonk, NY, USA), and values were considered significant at $P < .05$. Graphpad Prism 8.3.0 software (San Diego, California, USA) was used to construct the graphs. The sample size of thirty participants was determined using an F-test for intergroup comparisons of means, with a significance level of 0.05 and statistical power of 0.80. The calculation was based on detecting differences in Hmax/Mmax ratios due to the main effect of phase duration (1.0 ms vs. 0.5 ms), with expected values of 61.1% and 50.6%, respectively, as reported in a previous study [11].

Results

Single participant

Figure 2 shows representative soleus M-waves and H-reflexes across stimulation conditions. Compared with phase-matched PC and KFAC waveforms, the 1 ms monophasic current consistently elicited comparable or larger H-reflexes, while M-wave amplitudes remained similar across conditions.

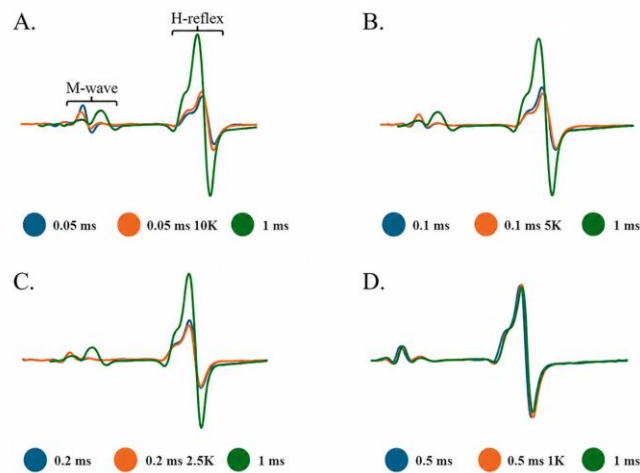


Fig 2. Representative single-participant. M-wave and H-reflex responses obtained from recruitment curves. A = 0.05 ms (PC) and 0.05 ms 10 kHz (KFAC); B = 0.1 ms (PC) and 0.1 ms 5 kHz (KFAC); C = 0.2 ms (PC) and 0.2 ms 2.5 kHz (KFAC); and D = 0.5 ms (PC) and 0.5 ms 1 kHz (KFAC). Blue lines indicate PC currents, orange lines indicate KFAC currents, and the green line indicates the 1 ms monophasic current. Stimulation artifacts were not displayed to improve visualization of the evoked responses.

Torque values

All protocols presented a similar MVIC value resulting in a mean torque of 60.56 ± 36.56 Nm.

M-wave analysis

Mmax

Although the GEE revealed a significant main effect of condition for Mmax (Wald $\chi^2(8) = 31.86$, $p < 0.001$), Bonferroni-corrected post hoc comparisons showed no differences in Mmax between KFAC and PC at matched phase durations 0.05 ms: Mean difference =

-0.09, 95% Confidence Interval [-0.43, 0.25], p -value = 1.000, Cohen's d_z = 0.152; 0.1 ms: 0.13 [-0.05, 0.32], p = 0.964, d_z = 0.398; 0.2 ms: -0.03 [-0.24, 0.16], p = 1.000, d_z = 0.107; 0.5 ms: -0.03 [-0.16, 0.10], p = 1.000, d_z = 0.135; Supplementary Table I, Fig. 3A). The 1 ms monophasic stimulus did not differ from any other condition ($p \geq 0.314$; d_z = 0.075–0.471; Supplementary Table I). A main effect of condition was observed for the stimulation intensity required to evoke Mmax (Wald χ^2 (8) = 9725.38, p < 0.001; Fig. 3B). Bonferroni-corrected post hoc comparisons showed that, for phase durations of 0.1 ms: -37.63 [-66.08, -9.18], p = 0.001, d_z = 0.759, 0.2 ms: -28.86 [-46.60, -11.11], p = 0.001, d_z = 0.934, and 0.5 ms: -9.24 [-18.16, -0.32], p = 0.033, d_z = 0.595. PC required lower intensities than the corresponding KFAC conditions, whereas at 0.05 ms: 197.92 [134.13, 261.71], p = 0.001; d_z = 1.781, PC required higher intensities. The 1 ms monophasic stimulus required lower intensities than all other conditions, 0.05 ms/PC: 397.44 [309.80, 485.08], p = 0.001, d_z = 2.603; 0.05 ms 10kHz: 199.52 [142.63, 256.41], p = 0.001, d_z = 2.013; 0.1 ms/PC: 56.65 [38.19, 75.10], p = 0.001, d_z = 1.761; 0.1 ms 5kHz: 94.28 [66.62, 121.94], p = 0.001, d_z = 1.956; 0.2 ms/PC: 15.83 [6.17, 25.49], p = 0.001, d_z = 0.941; 0.2 ms 2.5kHz: 44.69 [25.89, 63.49], p = 0.001, d_z = 1.364, except when compared with 0.5 ms/PC: -8.18, 95% [-19.05, 2.69], p = 0.581; d_z = 0.432 and 0.5 ms/1 kHz: 1.06 [-9.03, 11.16], p = 1.000; d_z = 0.060; Supplementary Table II.

H-reflex Analysis

The GEE showed a main effect of condition (Wald χ^2 (8) = 62.40, p < 0.001) for Hmax. Bonferroni-corrected post hoc tests revealed no differences in H-reflex amplitude between KFAC and PC at matched phase durations, 0.05 ms: -0.16 [-0.58, 0.24], p = 1.000, d_z = 0.229; 0.1 ms: 0.24 [-0.18, 0.68], p = 1.000, d_z = 0.329; 0.5 ms: 0.006 [-0.11, 0.12], p = 1.000, d_z = 0.028), except for 0.2 ms 2.5 kHz versus 0.2 ms/PC: 0.28 [0.08, 0.49], p = 0.001; d_z = 0.801. The 1 ms monophasic stimulus produced larger Hmax values than the shorter phase durations, 0.05 ms 10kHz: -0.80 [-1.22, -0.37], p = 0.001, d_z = 1.085; 0.05 ms/PC: -0.96 [-1.44, -0.48], p = 0.001, d_z = 1.155; 0.1 ms 5kHz: -0.73 [-1.11, -0.34], p = 0.001, d_z = 1.089; 0.1 ms/PC: -0.48 [-0.93, -0.03], p = 0.022, d_z = 0.615; 0.2 ms 2.5kHz: -0.63 [-1.01, -0.26], p = 0.001, d_z = 0.972 and 0.2 ms/PC: -0.35 [-0.70, -0.001], p = 0.047, d_z = 0.577, but did not differ from 0.5 ms 1 kHz: -0.32 [-0.66, 0.01], p = 0.089; d_z = 0.543 or 0.5 ms/PC: -0.31 [-0.64, 0.01], p = 0.080; d_z = 0.549; Supplementary Table III. A significant main effect of condition was observed for the stimulation intensity to evoke Hmax (Wald χ^2 (8) = 7822.334, p < 0.001). Post hoc tests showed that shorter phase durations, 0.05 ms: 171.56 [112.92, 230.20], p = 0.001; d_z = 1.679 and 0.1 ms: -21.27 [-36.44, -6.09], p = 0.001; d_z = 0.804, required higher stimulation intensities. At 0.2 ms, both KFAC and PC required lower intensities than the other conditions ($p \leq 0.001$; d_z = 1.25). No difference was found between KFAC and PC at 0.5 ms: -7.01 [-14.80, 0.78], p = 0.145; d_z = 0.516. The 1 ms monophasic stimulus required lower intensities than all other conditions (all p = 0.001; d range = 0.85–2.05), except when compared with 0.5 ms 1kHz: 0.86 [-8.46, 10.19], p = 1.000; d_z = 0.053 and 0.5 ms/PC: -6.14 [-14.09, 1.80], p = 0.486; d_z = 0.443; Supplementary Table IV; Fig. 3D.

H/M analysis

A main effect of condition was observed (Wald χ^2 (8) = 60.123, p < 0.001). Post hoc tests showed no differences in the H/M ratio between KFAC and PC at 0.05 ms: -0.02 [-0.09,

0.04], $p = 1.000$, $d_z = 0.168$ and 0.5 ms: 0.004 [-0.02, 0.03], $p = 1.000$, $d_z = 0.143$; Fig. 3E. At 0.1 ms: 0.06 [0.02, 0.11], $p = 0.001$; $d_z = 0.813$ and 0.2 ms: 0.05 [0.02, 0.09], $p = 0.001$; $d_z = 0.926$, PC produced higher ratios than the corresponding KFAC conditions. The 1 ms current elicited higher H/M ratios than most conditions, 0.05 ms 10kHz: -0.15 [-0.22, -0.08], $p = 0.001$, $d_z = 1.295$; 0.05 ms/PC: -0.17 [-0.26, -0.08], $p = 0.001$, $d_z = 1.165$; 0.1 ms 5kHz: -0.14 [-0.22, -0.07], $p = 0.001$, $d_z = 1.155$; 0.1 ms/PC: -0.08 [-0.15, -0.006], $p = 0.018$, $d_z = 0.624$; 0.2 ms 2.5kHz: -0.13 [-0.20, -0.05], $p = 0.001$, $d_z = 1.006$; 0.2 ms/PC: -0.07 [-0.14, -0.007], $p = 0.014$, $d_z = 0.638$; 0.5 ms 1kHz: -0.07 [-0.14, -0.009], $p = 0.043$, $d_z = 0.621$, except when compared with 0.5 ms/PC: -0.06 [-0.13, 0.001], $p = 0.068$, $d_z = 0.583$; Supplementary Table V. A significant main effect of condition was observed for the intensity of the H/M ratio (Wald $\chi^2(8) = 174.550$, $p < 0.001$); however, post hoc analyses indicated no differences between KFAC and PC at matched phase durations, 0.05 ms: 0.10 [-0.01, 0.22], $p = 0.138$, $d_z = 0.525$; 0.1 ms: -0.003 [-0.13, 0.13], $p = 1.000$, $d_z = 0.014$; 0.2 ms: -0.03 [-0.12, 0.05], $p = 1.000$, $d_z = 0.856$; 0.5 ms: -0.08 [-0.24, 0.08], $p = 1.000$, $d_z = 0.292$; Fig. 3F. Differences emerged across phase durations, with shorter durations (0.05 and 0.1 ms for both KFAC and PC) requiring higher stimulation intensities to achieve the same H/M ratio (all $p \leq 0.001$). The 1 ms monophasic stimulus differed only from the shorter phase durations, 0.05 ms 10kHz: 0.15 [0.05, 0.26], $p = 0.001$, $d_z = 0.874$; 0.05 ms/PC: 0.26 [0.18, 0.34], $p = 0.001$, $d_z = 1.973$; 0.1 ms 5kHz: 0.17 [0.05, 0.28], $p = 0.001$, $d_z = 0.856$; 0.1 ms/PC: 0.16 [0.07, 0.25], $p = 0.001$, $d_z = 1.099$; Supplementary Table VI.

Submaximal Responses

20% Mmax

At 20% Mmax, a significant main effect of condition was observed (Wald $\chi^2(8) = 18.543$, $p < 0.001$). Post hoc analyses revealed no differences in M-wave amplitudes, 0.05 ms: 0.17 [-0.19, 0.55], $p = 1.000$, $d_z = 0.273$; 0.1 ms: -0.08 [-0.38, 0.22], $p = 1.000$, $d_z = 0.151$; 0.2 ms: -0.08 [-0.33, 0.17], $p = 1.000$, $d_z = 0.180$; 0.5 ms: 0.13 [-0.22, 0.49], $p = 1.000$, $d_z = 0.220$; Supplementary Table VII; Fig. 4A, or H-reflex amplitudes between KFAC and PC at matched phase durations (Wald $\chi^2(8) = 44.029$, $p < 0.001$), 0.05 ms: -0.36 [-0.99, 0.26], $p = 1.000$, $d_z = 0.332$; 0.1 ms: -0.04 [-0.48, 0.38], $p = 1.000$, $d_z = 0.061$; 0.2 ms: 0.22 [-0.30, 0.76], $p = 1.000$, $d_z = 0.245$; 0.5 ms: -0.02, [-0.45, 0.39], $p = 1.000$, $d_z = 0.047$; Supplementary Table VIII; Fig. 4B. The 1 ms monophasic stimulus elicited larger H-reflexes than ≤ 0.1 ms currents, 0.05 ms 10kHz: -0.61 [-1.12, -0.11], $p = 0.003$, $d_z = 0.704$; 0.05 ms/PC: -0.98 [-1.61, -0.34], $p = 0.001$, $d_z = 0.888$; 0.1 5kHz ms: -0.55 [-1.00, -0.11], $p = 0.002$, $d_z = 0.715$; 0.1 ms/PC: -0.60 [-1.20, -0.006], $p = 0.044$, $d_z = 0.580$ but did not differ from 0.5 or 0.2 ms (KFAC and PC); (all $p = 1.000$; d_z range: 0.005–0.197). H/M ratios followed a similar pattern (Wald $\chi^2(8) = 40.742$, $p < 0.001$; Supplementary Table IX; Fig. 4C). At 20% Mmax, KFAC required higher intensities than PC at 0.1 ms: -22.64 [-32.57, -12.71], $p = 0.001$, $d_z = 1.319$ and 0.2 ms: -15.17 [-22.73, -7.60], $p = 0.001$, $d_z = 1.151$, whereas the 1 ms monophasic stimulus required lower intensities than all conditions, 0.05 ms 10kHz: 104.66 [82.54, 126.77], $p = 0.001$, $d_z = 2.716$; 0.05 ms/PC: 171.85 [130.37, 213.33], $p = 0.001$, $d_z = 2.378$; 0.1 ms 5kHz: 52.86 [37.24, 68.47], $p = 0.001$, $d_z = 1.943$; 0.1 ms/PC: 30.21 [22.42, 38.00], $p = 0.001$, $d_z = 2.307$; 0.2 ms 2.5kHz: 24.75 [16.33, 33.16], $p = 0.001$, $d_z = 1.688$; 0.2 ms/PC: 9.58 [6.10, 13.06], $p =$

0.001, $d_z = 1.581$; 0.5 ms 1kHz: 5.59 [0.26, 10.91], $p = 0.028$, $d_z = 0.603$ except 0.5 ms/PC: 0.60 [-6.11, 7.33], $p = 1.000$, $d_z = 0.603$; Supplementary Table X; Fig. 4D.

3-7% Mmax

At 3–7% Mmax, a significant main effect of condition was observed (Wald $\chi^2(8) = 19.068$, $p = 0.015$); however, M-wave amplitudes were comparable across all matched conditions, 0.05 ms: 0.02 [-0.04, 0.09], $p = 1.000$, $d_z = 0.381$; 0.1 ms: -0.009 [-0.05, 0.05], $p = 1.000$, $d_z = 0.374$; 0.2 ms: -0.008, [-0.05, 0.03], $p = 1.000$, $d_z = 0.170$; 0.5 ms: 0.02 [-0.04, 0.08], $p = 1.000$, $d_z = 0.118$; Fig. 5A. For H-reflexes, only 0.2 ms/PC differed from 0.2 ms/2.5 kHz: 0.56 [0.07, 1.05], $p = 0.007$, $d_z = 0.748$; Fig. 5B.

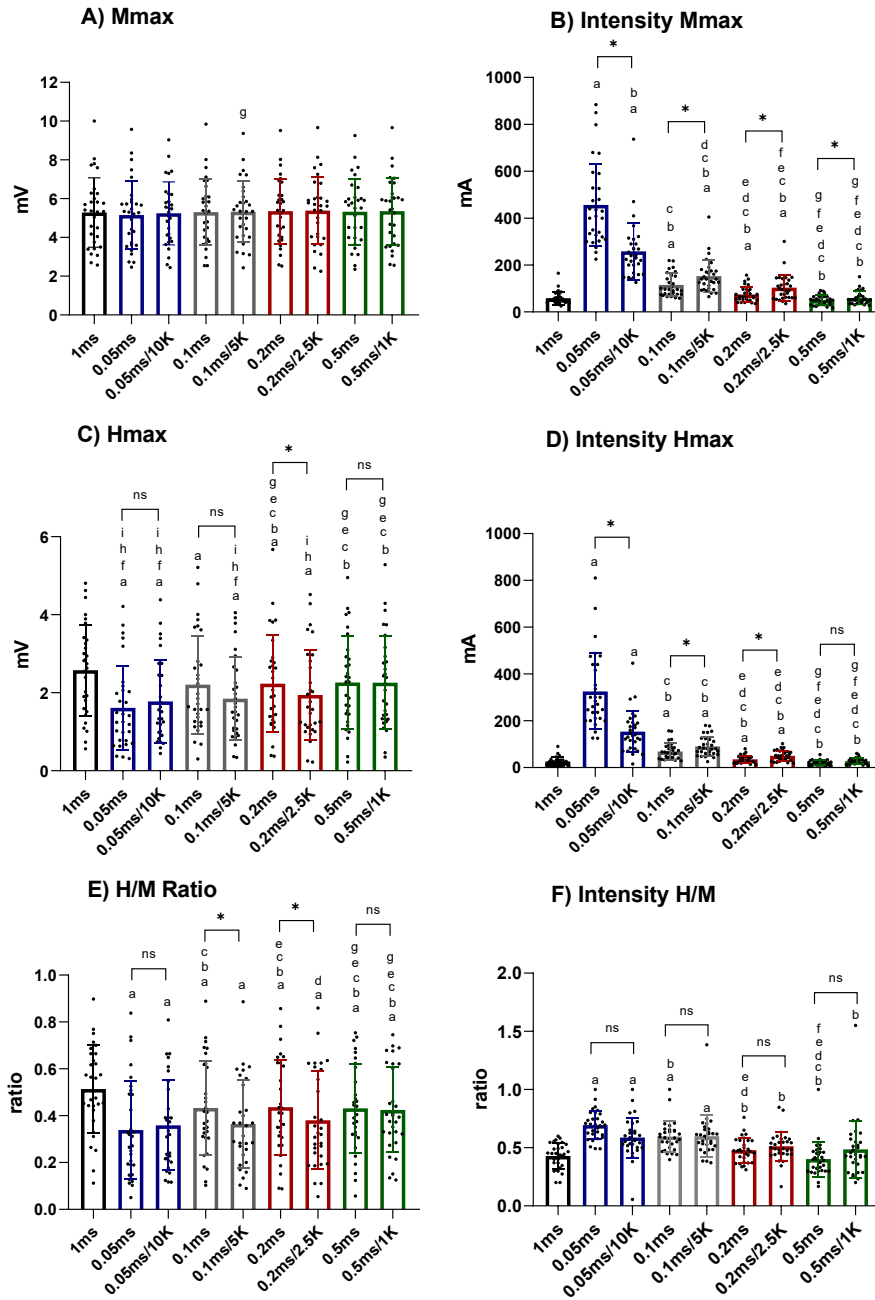


Fig. 3. Recruitment curves illustrating the effects of phase duration and stimulation type on evoked responses. A–F, recruitment curve outcomes for pulsed current (PC) and kilohertz-frequency alternating current (KFAC) conditions. Letters indicate conditions significantly different from: a, 1 ms; b, 0.05 ms; c, 0.05 ms/10 kHz; d, 0.1 ms; e, 0.1 ms/5 kHz; f, 0.2 ms; g, 0.2 ms/2.5 kHz; h, 0.5 ms; and i, 0.5 ms/1 kHz. Asterisks (*) indicate statistically significant differences between phase-matched PC and KFAC conditions. “ns” indicates non-significant difference

The 1 ms monophasic stimulus produced larger H-reflexes than the shorter phase durations, 0.05 ms 10kHz: $-1.39 [-2.06, -0.72]$, $p = 0.001$, $d_z = 1.145$; 0.05 ms/PC: $-1.36 [-2.04, -0.68]$, $p = 0.001$, $d_z = 1.089$; 0.1 ms 5kHz: $-1.30 [-1.92, -0.68]$, $p = 0.001$, $d_z = 1.185$; 0.1 ms/PC: $-0.95 [-1.64, -0.27]$, $p = 0.001$, $d_z = 0.854$; 0.2 ms 2.5kHz: $-0.98 [-1.70,$

−0.25], $p = 0.001$, $d_z = 0.925$ but did not differ from 0.2 ms/PC: −0.41 [−1.09, 0.26], $p = 1.000$, $d_z = 0.406$, 0.5 ms/1 kHz: −0.50 [−1.25, 0.23], $p = 1.000$, $d_z = 0.541$ or 0.5 ms/PC: 0.03 [−0.65, 0.72], $p = 1.000$, $d_z = 0.164$; Supplementary Table XII, Fig. 5B. H/M ratios followed a similar pattern (Supplementary Table XIII; Fig. 5C). For stimulation intensity, only 0.05 ms/PC differed from 0.05 ms/10 kHz: 74.00 [50.71, 97.29], $p = 0.001$, $d_z = 1.471$; all other matched comparisons were non-significant, and the 1 ms monophasic stimulus did not differ from 0.2 ms/PC: 4.41 [−2.47, 11.29], $p = 1.000$, $d_z = 0.300$ or 0.5 ms/1 kHz: −0.89 [−4.99, 3.20], $p = 1.000$, $d_z = 0.425$; Supplementary Table XIV; Fig. 5D.

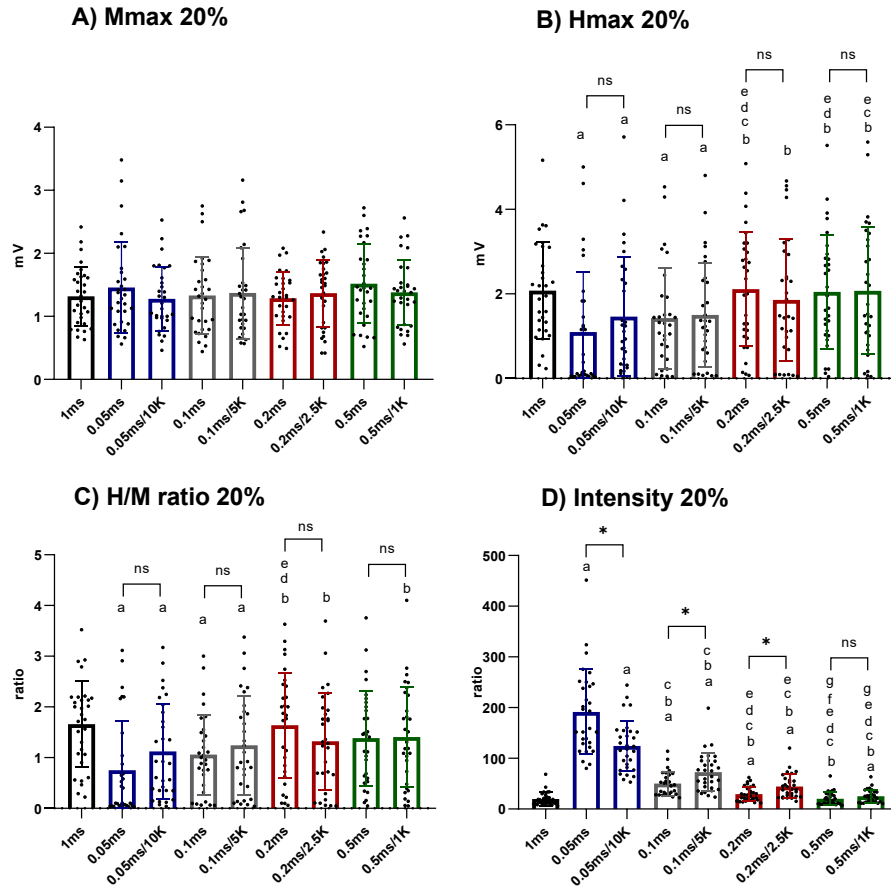


Fig. 4. Submaximal responses at 20% Mmax illustrating the effects of phase duration and stimulation type. A–D, responses for pulsed current (PC) and kilohertz-frequency alternating current (KFAC) conditions. Letters indicate conditions significantly different from: a, 1 ms; b, 0.05 ms; c, 0.05 ms/10 kHz; d, 0.1 ms; e, 0.1 ms/5 kHz; f, 0.2 ms; g, 0.2 ms/2.5 kHz; h, 0.5 ms; and i, 0.5 ms/1 kHz. Asterisks (*) indicate statistically significant differences between phase-matched PC and KFAC conditions. “ns” indicates non-significant differences.

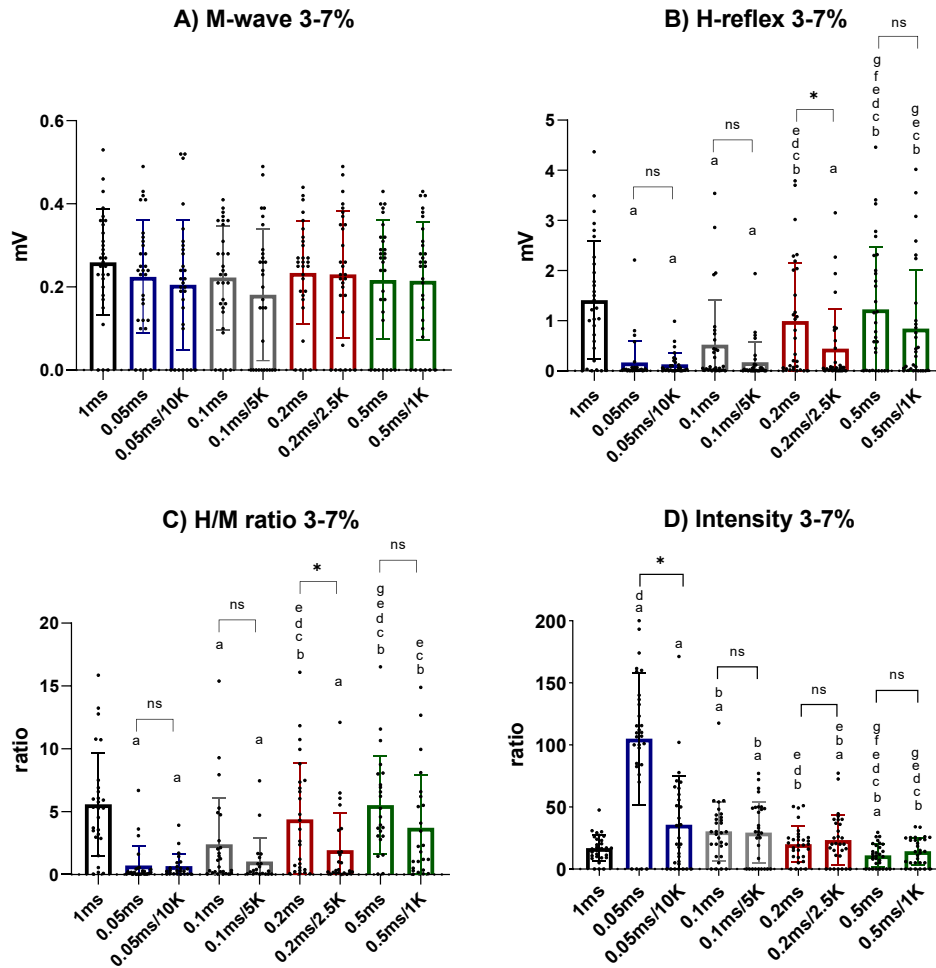


Fig. 5. Submaximal responses at 3–7% Mmax illustrating the effects of phase duration and stimulation type. A–D, responses for pulsed current (PC) and kilohertz-frequency alternating current (KFAC) conditions. Letters indicate conditions significantly different from: a, 1 ms; b, 0.05 ms; c, 0.05 ms/10 kHz; d, 0.1 ms; e, 0.1 ms/5 kHz; f, 0.2 ms; g, 0.2 ms/2.5 kHz; h, 0.5 ms; and i, 0.5 ms/1 kHz. Asterisks (*) indicate statistically significant differences between phase-matched PC and KFAC conditions. “ns” indicates non-significant differences.

Discomfort

Perceived sensory discomfort measured by the VAS showed a main effect of condition (Wald χ^2 (8) = 72.95, $p < 0.001$). Post hoc tests revealed no differences between KFAC and PC at matched phase durations, 0.05 ms: 1.14 [−0.004, 2.33], $p = 0.070$, $d_z = 0.554$; 0.1 ms: −0.23 [−1.07, 0.60], $p = 1.000$, $d_z = 0.160$; 0.2 ms: −0.04 [−0.83, 0.74], $p = 1.000$, $d_z = 0.111$; 0.5 ms: 0.35 [−0.33, 1.03], $p = 1.000$, $d_z = 0.266$, indicating that waveform type did not influence discomfort. In contrast, phase duration had a clear effect: the 1 ms monophasic stimulus was rated as more comfortable than the 0.05 ms/10 kHz: 1.09 [0.07, 2.11], $p = 0.024$, $d_z = 0.615$, 0.05 ms/PC: 2.23 [1.12, 3.35], $p = 0.001$, $d_z = 1.150$, 0.1 ms/5 kHz: 1.20 [0.25, 2.15], $p = 0.002$, $d_z = 0.728$ and 0.1 ms/PC: 0.97 [0.03, 1.90], $p = 0.034$, $d_z = 0.593$ conditions. Ratings for the 1 ms stimulus did not differ from the intermediate durations of 0.2 ms 2.5kHz: 0.64 [−0.35, 1.36], $p = 1.000$, $d_z = 0.440$, 0.2 ms/PC: 0.60 [−0.16, 1.36], $p = 0.428$, $d_z = 0.452$, 0.5 ms 1kHz: 0.40 [−0.25, 1.05], $p = 1.000$,

$d_z = 0.353$ and $0.5\text{ ms}: 0.75 [-0.15, 1.65]$, $p = 0.289$, $d_z = 0.482$; Supplementary Table XV; Fig. 6.

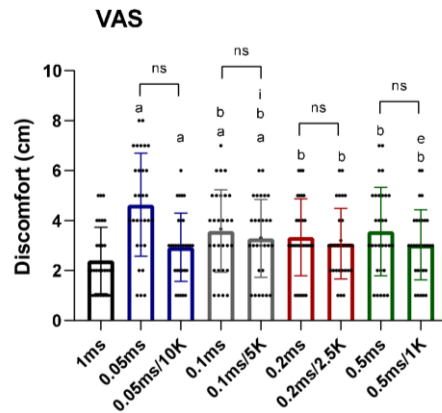


Fig. 6. Visual analogue scale (VAS) scores for perceived discomfort across stimulation conditions. Letters indicate conditions significantly different from: a, 1 ms; b, 0.05 ms; c, 0.05 ms/10 kHz; d, 0.1 ms; e, 0.1 ms/5 kHz; f, 0.2 ms; g, 0.2 ms/2.5 kHz; h, 0.5 ms; and i, 0.5 ms/1 kHz. “ns” indicates non-significant differences.

Discussion

The results of the present study demonstrate that phase duration, rather than stimulation frequency, is the primary determinant of neuromuscular activation patterns during NMES, with no significant differences in perceived sensory discomfort between KFAC and PC. These findings challenge the presumed superiority of KFAC and provide practical guidance for optimizing NMES protocols in clinical settings. For applications targeting primarily motor activation, such as muscle strengthening or functional electrical stimulation, narrow phase durations ($\sim 0.2\text{ ms}$) with PC may be optimal, offering lower intensity requirements with equivalent effectiveness. Conversely, for interventions aiming to modulate spinal excitability or enhance sensorimotor integration, such as neurorehabilitation or spasticity management, longer phase durations ($>0.5\text{ ms}$) should be prioritized, independent of current type (KFAC or PC).

The absence of significant differences in Mmax amplitudes between KFAC and PC at matched phase durations demonstrates that both stimulation modalities produce comparable motor unit recruitment, since the M-wave represents the compound action potential of all recruited motor units, with Mmax indicating complete motor neuron pool recruitment [35], [36]. This finding challenges the clinical claim that KFAC leads to superior motor activation during evoked contractions [9], [15]. Moreover, none of the matched phase duration currents differed from the 1 ms monophasic current for Mmax amplitude, the reference condition known to elicit more motor and sensory axons responses [7], [11]. Notably, although KFAC and PC produced comparable motor activation, KFAC consistently required higher stimulation intensities to achieve the same level of recruitment for 0.1 ms, 0.2 ms, and 0.5 ms conditions. While Qu et al. reported differences in motor threshold using similar frequency parameters, their study used a phase width of 1 ms, which was longer than that used in the present study [30]. In contrast, the phase-matched comparisons tested here revealed a clear intensity disadvantage for KFAC, except at the narrowest phase duration tested (0.05 ms). Interestingly, at the narrowest phase duration tested in the present study (0.05 ms at 10 kHz), KFAC required lower stimulation intensities than PC. A similar pattern

was observed under submaximal conditions, corresponding to 3–20% of Mmax. These findings are consistent with those of Luu et al., who showed that, for a 10 kHz biphasic waveform, increasing the number of pulses reduced the current required to activate both sensory and motor axons [37]. Notably, this effect was not observed at longer phase durations, where KFAC typically required similar or higher intensities. Although higher intensity requirements may increase discomfort, potentially limiting the stimulation dose and the muscle activation achievable in rehabilitation settings [38], this relationship was not observed in the present study. While VAS scores remained similar across most conditions despite differences in Mmax intensity, the 0.05 ms pulsed current condition showed both higher stimulation intensities compared to the 10 kHz and increased perceived discomfort when compared with the 1 ms monophasic current [38].

This apparent efficiency likely arises because the 10 kHz condition may facilitate temporal summation, as demonstrated by Luu et al., [37]. The present findings show a frequency-dependent divergence in axonal recruitment efficiency that goes beyond a simple KFAC-versus-PC comparison. At the shortest phase duration tested (0.05 ms, 10 kHz), KFAC required lower stimulation intensities than phase-matched PC. This agrees with the temporal summation, or Gildemeister effect, recently reported by Luu et al., who showed that increasing the number of pulses within a 10 kHz burst shifted the stimulus–response curve leftward, reducing motor and sensory thresholds to approximately 71% and 64% of single-pulse values, respectively[37]. This summation is mechanistically plausible at 10 kHz because the inter-pulse interval (~50 μ s) falls well below the passive membrane time constant of myelinated motor axons (~200 μ s), allowing residual depolarization from each cycle to accumulate before it fully dissipates. In contrast, our results clearly demonstrated that, at 5 kHz and 2.5 kHz, frequencies at which temporal summation might also have been anticipated, KFAC required higher stimulation intensities than the phase-matched PC conditions, indicating a threshold penalty rather than a recruitment benefit. One explanation is the interaction between inter-pulse interval and the membrane time constant. At 5 kHz (~100 μ s) and 2.5 kHz (~200 μ s), the hyperpolarizing phase of each biphasic cycle may have enough time to offset the depolarization produced by the preceding phase, partially dissipating accumulated charge before the next cycle and limiting temporal summation. This frequency-dependent penalty contrasts with findings at lower burst frequencies.

Formento et al. showed that 4–5 pulse bursts delivered at 400–600 Hz reduced sensory-axon thresholds during epidural spinal cord stimulation, supporting temporal summation well below 2.5 kHz [19]. In addition, Keeseey et al. provided computational and experimental evidence demonstrating that, during biphasic KFAC stimulation, membrane depolarization is repeatedly interrupted by the negative phase of each cycle and that this interference becomes progressively more pronounced as the inter-pulse interval approaches the membrane time constant [39]. This mechanism is consistent with the threshold penalty observed in the present study at 5 kHz and 2.5 kHz. Collectively, these findings suggest that the threshold-reducing effect attributed to temporal summation is not an inherent property of KFAC stimulation but rather may be specific to 10 kHz under single-burst transcutaneous conditions. Moreover, intermediate carrier frequencies (2.5–5 kHz) may impair recruitment efficiency relative to conventional pulsed current, supporting a non-linear relationship between carrier frequency and axonal activation threshold that warrants further mechanistic investigation. [19], [39].

Hmax amplitudes were largely comparable across waveforms, suggesting that frequency modulation did not enhance sensory axon recruitment under the tested conditions.

These findings are consistent with recent evidence from Keeseey et al. and Luu et al., who reported that kilohertz-frequency waveforms generally require higher stimulation intensities and may be less efficient than conventional pulsed stimulation for recruiting proprioceptive afferents [37], [39]. When phase duration was matched, only the 0.2 ms condition showed a significant difference, whereas 1 ms currents consistently produced greater Hmax amplitudes than shorter durations (≤ 0.2 ms). Durigan et al. [11] reported that longer phase durations (0.5–2.0 ms) generated significantly higher Hmax amplitudes than shorter phases (0.1 ms), with no significant effect of waveform type (monophasic, biphasic, or KFAC). Notably, a 0.5 ms phase duration generated H-reflexes up to ~60% larger than narrower phases, independent of current modality.

This duration-dependent recruitment phase reflects established neurophysiology: sensory axons, particularly Ia afferents mediating the H-reflex, have a longer chronaxie and lower rheobase than motor axons, requiring longer stimuli for optimal activation [7], [8]. In addition, our data showed that stimulation intensities required to elicit Hmax were similar for 1 ms monophasic and 0.5 ms pulsed current, whereas shorter durations (≤ 0.2 ms) were less effective, especially the 0.05 ms pulsed current.

Elevated H/M ratios observed with the 1 ms pulse indicate that longer phase durations preferentially enhance sensory responses relative to motor recruitment, consistent with Durigan et al. [11], who reported a main effect of phase duration on Hmax ($p < 0.001$) independent of waveform. Clinically, this selective recruitment is particularly relevant for interventions targeting spinal excitability, such as neurorehabilitation or spasticity management, where maximizing sensory input without excessive motor activation is desirable [5]. Collectively, these results establish phase duration as an important determinant of differential axonal recruitment, refuting claims of frequency-dependent advantages in KFAC. Submaximal evoked torque levels, between 5% and 50% of the maximum voluntary contraction, have been reported to be effective for strengthening for orthopedic, pulmonary, and intensive care patients [12].

Therefore, examining neural and motor responses at submaximal activation levels may provide greater clinical relevance than assessments performed exclusively under maximal stimulation conditions. Interestingly, at submaximal activation levels (3–7% and ~20% of Mmax), M-wave amplitudes did not differ between KFAC and PC, indicating that both waveforms elicit comparable motor responses. At 20% intensity, H-reflex amplitudes were similar across matched parameters, except that 1 ms currents elicited significantly larger responses than shorter durations (≤ 0.1 ms KFAC and PC), while ≥ 0.2 ms produced comparable central activation [5], [11]. At 3–7% Mmax, the 0.2 ms PC waveform produced recruitment responses comparable to those observed with the 1 ms monophasic waveform. In contrast, the 2.5 kHz condition showed reduced H-reflex recruitment despite similar Mmax amplitudes and stimulation intensities. Together with the consistent findings from maximal and submaximal H-reflex analyses, these results suggest that frequency modulation at 2.5 kHz did not provide a recruitment advantage over conventional pulsed stimulation and may have reduced afferent recruitment efficiency. As this pattern was consistent across maximal and submaximal recruitment curves for Hmax and the H/M ratio, frequency modulation appears to confer no benefit and may impair muscle performance, making the PC current preferable.

Furthermore, in both submaximal conditions (3–7% and 20% of Mmax), analysis of Hmax and H/M ratios revealed that the 1 ms current elicited significantly greater responses than shorter phase durations (≤ 0.2 ms) and did not differ from the 0.5 ms conditions for either

KFAC or PC. At 20% Mmax, the 0.05 ms/10 kHz KFAC waveform required lower stimulation intensities than the corresponding PC condition, whereas the 5 kHz and 2.5 kHz KFAC waveforms required higher intensities than their PC counterparts. This pattern partially aligns with previous reports indicating that KFAC may require higher stimulation intensities under certain conditions[12]. In contrast, the 0.5 ms PC condition required stimulation intensities similar to those of the 1 ms monophasic current, indicating that comparable activation can be achieved despite the narrow phase duration [40].

Regarding perceived sensory discomfort, no differences were observed between KFAC and PC when phase duration was matched, except when comparing the 1 ms pulse with shorter durations (≤ 0.2 ms). Interestingly, very short phase durations (0.05–0.1 ms) were perceived as more uncomfortable than the 1 ms pulse, regardless of waveform. This finding indicates that longer phase durations do not necessarily increase discomfort and may, in fact, be better tolerated under certain conditions. A likely explanation is that longer pulses achieve axonal depolarization at lower stimulation intensities, reducing the activation of high-threshold nociceptive afferents and limiting the overall sensory burden. In contrast, shorter phase durations require substantially higher intensities to overcome membrane capacitance, which may increase the recruitment of superficial pain fibers and contribute to greater discomfort.

These results contrast with previous reports suggesting increased discomfort at intermediate phase durations (0.2–0.5 ms) [12], highlighting that perceived discomfort is not determined by phase duration alone but by its interaction with stimulation intensity and recruitment patterns. Collectively, these findings emphasize the critical role of phase duration optimization in maximizing sensory and synaptic activation during comfort-constrained submaximal contractions, while also challenging the assumption that KFAC is inherently more comfortable or efficient than conventional pulsed stimulation, and highlight the importance of tailoring NMES parameters to individual tolerance levels and specific therapeutic goals.

The current study presents limitations. First, the exclusive inclusion of healthy young adults limits the generalizability of our findings to clinical populations. Second, long-term adaptations to different stimulation parameters were not assessed. Third, sensory discomfort was evaluated solely using a visual analogue scale (VAS); future studies incorporating alternative approaches, such as electrophysiological or neuroimaging measures, may provide more comprehensive insights. Finally, while this study focused on acute neuromuscular responses, additional research is needed to determine the clinical relevance of these findings for functional recovery and therapeutic applications.

1 **Conclusion**

2 The results of the current study demonstrate that phase duration, rather than waveform
3 type (KFAC and PC) or carrier frequency, is the primary determinant of neuromuscular
4 recruitment and comfort during NMES. While both KFAC and PC effectively activate motor
5 and sensory pathways, the 1-ms monophasic pulse emerged as the optimal parameter,
6 eliciting higher H/M ratios (enhanced sensory recruitment) while requiring significantly
7 lower stimulation intensities than shorter durations. Contrary to the common assumption that
8 high-frequency kilohertz currents (e.g., 10 kHz) offer superior comfort, we found no
9 difference in perceived discomfort between waveforms when phase duration was matched.
10 These findings suggest that clinicians should prioritize selecting wider phase durations (~1
11 ms) to maximize physiological efficiency and sensory–motor integration without
12 compromising patient tolerance. Future research should evaluate the functional implications
13 of these optimized parameters in clinical rehabilitation settings.
14

Practical Implications of the Findings for Society

The findings of this study have direct clinical implications for physiotherapists and other rehabilitation professionals by supporting the prescription of more efficient and comfortable NMES protocols tailored to specific therapeutic goals. Ultimately, optimizing stimulation parameters may enhance rehabilitation outcomes, improve functional recovery, and contribute to higher quality of care for patients requiring NMES. Furthermore, this work advances the understanding of the neurophysiological mechanisms underlying electrical stimulation and provides a scientific foundation for the development of future NMES clinical guidelines and rehabilitation protocols based on objective physiological evidence.

Beyond its scientific contributions, the knowledge generated during this research has been translated into educational, professional, and scientific dissemination activities. The results supported continuing education initiatives, including professional training on electrotherapy for the Physiotherapy Department of the Civil Police of the Federal District, an invited lecture on electrostimulation in oncological rehabilitation promoted by the Academic League of Physiotherapy in Oncology at the University of Brasília and a presentation at the V Brazilian and International Congress of ABRAFITO (COBRAFITO 2025), fostering scientific discussion and promoting evidence-based clinical practice among researchers and rehabilitation professionals. These knowledge translation activities broadened the impact of research beyond academia and facilitated the incorporation of current evidence into clinical practice.

References

- [1] F. V. Medeiros *et al.*, “Kilohertz and low-frequency electrical stimulation with the same pulse duration have similar efficiency for inducing isometric knee extension torque and discomfort,” *Am. J. Phys. Med. Rehabil.*, vol. 96, no. 6, 2017, doi: 10.1097/PHM.0000000000000631.
- [2] A. N. Dalrymple, C. A. Hooper, M. G. Kuriakose, M. Capogrosso, and D. J. Weber, “Using a high-frequency carrier does not improve comfort of transcutaneous spinal cord stimulation,” *J. Neural Eng.*, vol. 20, no. 1, 2023, doi: 10.1088/1741-2552/acabe8.
- [3] P. F. A. De Oliveira, J. L. Q. Durigan, K. A. G. Modesto, M. Bottaro, and N. Babault, “Neuromuscular fatigue after low- and medium-frequency electrical stimulation in healthy adults,” *Muscle Nerve*, vol. 58, no. 2, 2018, doi: 10.1002/mus.26143.
- [4] J. L. Veale, R. F. Mark, and S. Rees, “Differential sensitivity of motor and sensory fibres in human ulnar nerve,” *J. Neurol. Neurosurg. Psychiatry*, vol. 36, no. 1, 1973, doi: 10.1136/jnnp.36.1.75.
- [5] T. S. Barss *et al.*, “Utilizing Physiological Principles of Motor Unit Recruitment to Reduce Fatigability of Electrically-Evoked Contractions: A Narrative Review,” *Arch. Phys. Med. Rehabil.*, vol. 99, no. 4, pp. 779–791, Apr. 2018, doi: 10.1016/j.apmr.2017.08.478.
- [6] J. A. I. Bastos, W. R. Martins, G. C. Júnior, D. F. Collins, and J. L. Q. Durigan, “Contraction fatigue, strength adaptations, and discomfort during conventional versus wide-pulse, high-frequency, neuromuscular electrical stimulation: a systematic review,” *Applied Physiology, Nutrition, and Metabolism*, vol. 46, no. 11, pp. 1314–1321, Nov. 2021, doi: 10.1139/apnm-2021-0269.
- [7] D. Burke, M. C. Kiernan, and H. Bostock, “Excitability of human axons,” *Clinical Neurophysiology*, vol. 112, no. 9, pp. 1575–1585, Sep. 2001, doi: 10.1016/S1388-2457(01)00595-8.
- [8] M. Panizza, J. Nilsson, and M. Hallett, “Optimal stimulus duration for the H reflex,” *Muscle Nerve*, vol. 12, no. 7, 1989, doi: 10.1002/mus.880120708.
- [9] V. Z. M. da Silva, J. L. Q. Durigan, R. Arena, M. de Noronha, B. Gurney, and G. Cipriano, “Current evidence demonstrates similar effects of kilohertz-frequency and low-frequency current on quadriceps evoked torque and discomfort in healthy individuals: a systematic review with meta-analysis,” *Physiother. Theory Pract.*, vol. 31, no. 8, pp. 533–539, Nov. 2015, doi: 10.3109/09593985.2015.1064191.

- 71 [10] O. Lagerquist and D. F. Collins, "Stimulus pulse-width influences H-reflex
72 recruitment but not H max/Mmax ratio," *Muscle Nerve*, vol. 37, no. 4, 2008, doi:
73 10.1002/mus.20957.
- 74 [11] J. L. Q. Durigan, B. C. Kelly, R. R. Costa, M. Dyjak, and D. F. Collins, "Influence
75 of phase duration and waveform on the relative recruitment of motor and sensory
76 axons in a human peripheral nerve," *Applied Physiology, Nutrition and Metabolism*,
77 vol. 50, 2025, doi: 10.1139/apnm-2024-0469.
- 78 [12] N. L. Pinto Damo, K. A. Modesto, I. V. de S. Neto, M. Bottaro, N. Babault, and J. L.
79 Q. Durigan, "Effects of different electrical stimulation currents and phase durations
80 on submaximal and maximum torque, efficiency, and discomfort: a randomized
81 crossover trial," *Braz. J. Phys. Ther.*, vol. 25, no. 5, 2021, doi:
82 10.1016/j.bjpt.2021.03.001.
- 83 [13] K. A. G. Modesto, J. A. I. Bastos, M. A. Vaz, and J. L. Q. Durigan, "Effects of
84 Kilohertz Frequency, Burst Duty Cycle, and Burst Duration on Evoked Torque,
85 Perceived Discomfort and Muscle Fatigue," *Am. J. Phys. Med. Rehabil.*, vol. 102,
86 no. 2, pp. 175–183, Feb. 2023, doi: 10.1097/PHM.0000000000001982.
- 87 [14] A. R. Ward and N. Shkuratova, "Russian electrical stimulation: the early
88 experiments.," *Phys. Ther.*, vol. 82, no. 10, pp. 1019–30, Oct. 2002, [Online].
89 Available: <http://www.ncbi.nlm.nih.gov/pubmed/12350217>
- 90 [15] M. A. Vaz and V. B. Frasson, "Low-Frequency Pulsed Current Versus Kilohertz-
91 Frequency Alternating Current: A Scoping Literature Review," *Arch. Phys. Med.*
92 *Rehabil.*, vol. 99, no. 4, pp. 792–805, Apr. 2018, doi: 10.1016/j.apmr.2017.12.001.
- 93 [16] G. A. Manson, J. S. Calvert, J. Ling, B. Tychhon, A. Ali, and D. G. Sayenko, "The
94 relationship between maximum tolerance and motor activation during transcutaneous
95 spinal stimulation is unaffected by the carrier frequency or vibration," *Physiol. Rep.*,
96 vol. 8, no. 5, 2020, doi: 10.14814/phy2.14397.
- 97 [17] Y. Al'joboori *et al.*, "The Immediate and Short-Term Effects of Transcutaneous
98 Spinal Cord Stimulation and Peripheral Nerve Stimulation on Corticospinal
99 Excitability," *Front. Neurosci.*, vol. 15, 2021, doi: 10.3389/fnins.2021.749042.
- 100 [18] R. Martin, "Utility and Feasibility of Transcutaneous Spinal Cord Stimulation for
101 Patients With Incomplete SCI in Therapeutic Settings: A Review of Topic,"
102 *Frontiers in Rehabilitation Sciences*, vol. 2, Sep. 2021, doi:
103 10.3389/fresc.2021.724003.

- 104 [19] E. Formento *et al.*, “Electrical spinal cord stimulation must preserve proprioception
105 to enable locomotion in humans with spinal cord injury,” *Nat. Neurosci.*, vol. 21, no.
106 12, pp. 1728–1741, Dec. 2018, doi: 10.1038/s41593-018-0262-6.
- 107 [20] N. A. Maffiuletti, “Physiological and methodological considerations for the use of
108 neuromuscular electrical stimulation,” *Eur. J. Appl. Physiol.*, vol. 110, no. 2, pp.
109 223–234, Sep. 2010, doi: 10.1007/s00421-010-1502-y.
- 110 [21] A. J. Bergquist, J. M. Clair, O. Lagerquist, C. S. Mang, Y. Okuma, and D. F. Collins,
111 “Neuromuscular electrical stimulation: Implications of the electrically evoked
112 sensory volley,” 2011. doi: 10.1007/s00421-011-2087-9.
- 113 [22] J. G. T. Cavalcante *et al.*, “Effect of muscle length on maximum evoked torque,
114 discomfort, contraction fatigue, and strength adaptations during electrical stimulation
115 in adult populations: A systematic review,” 2024. doi:
116 10.1371/journal.pone.0304205.
- 117 [23] A. Theodosiadou, M. Henry, J. Duchateau, and S. Baudry, “Revisiting the use of
118 Hoffmann reflex in motor control research on humans,” 2023. doi: 10.1007/s00421-
119 022-05119-7.
- 120 [24] A. R. Ward and W. L. H. Chuen, “Lowering of Sensory, Motor, and Pain-Tolerance
121 Thresholds With Burst Duration Using Kilohertz-Frequency Alternating Current
122 Electric Stimulation: Part II,” *Arch. Phys. Med. Rehabil.*, vol. 90, no. 9, 2009, doi:
123 10.1016/j.apmr.2009.02.022.
- 124 [25] A. R. Ward, “Electrical stimulation using kilohertz-frequency alternating current,”
125 2009. doi: 10.2522/ptj.20080060.
- 126 [26] G. Kantor, G. Alon, and H. S. Ho, “The effects of selected stimulus waveforms on
127 pulse and phase characteristics at sensory and motor thresholds,” *Phys. Ther.*, vol.
128 74, no. 10, 1994, doi: 10.1093/ptj/74.10.951.
- 129 [27] P. H. Gorman and J. T. Mortimer, “The Effect of Stimulus Parameters on the
130 Recruitment Characteristics of Direct Nerve Stimulation,” *IEEE Trans. Biomed.*
131 *Eng.*, vol. BME-30, no. 7, 1983, doi: 10.1109/TBME.1983.325041.
- 132 [28] J. C. Dean, J. M. Clair-Augier, O. Lagerquist, and D. F. Collins, “Asynchronous
133 recruitment of low-threshold motor units during repetitive, low-current stimulation
134 of the human tibial nerve,” *Front. Hum. Neurosci.*, vol. 8, no. DEC, 2014, doi:
135 10.3389/fnhum.2014.01002.
- 136 [29] C. Walton, J. Kalmar, and E. Cafarelli, “Caffeine increases spinal excitability in
137 humans,” *Muscle Nerve*, vol. 28, no. 3, 2003, doi: 10.1002/mus.10457.

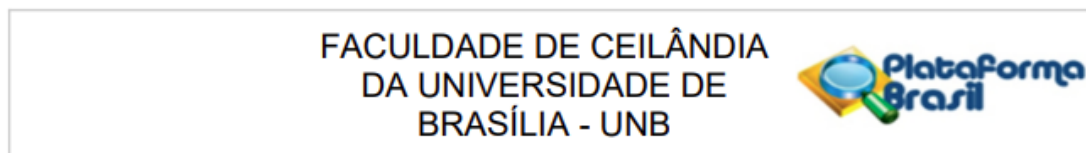
- 138 [30] S. Grosprêtre, T. Jacquet, F. Lebon, C. Papaxanthis, and A. Martin, “Neural
139 mechanisms of strength increase after one-week motor imagery training,” *Eur. J.*
140 *Sport Sci.*, vol. 18, no. 2, 2018, doi: 10.1080/17461391.2017.1415377.
- 141 [31] C. J. McNeil, J. E. Butler, J. L. Taylor, and S. C. Gandevia, “Testing the excitability
142 of human motoneurons,” *Front. Hum. Neurosci.*, vol. 7, 2013, doi:
143 10.3389/fnhum.2013.00152.
- 144 [32] J. Xu, A. J. Lopez, M. M. Hoque, M. R. Borich, and T. M. Kesar, “Temporal Profile
145 of Descending Cortical Modulation of Spinal Excitability: Group and Individual-
146 Specific Effects,” *Front. Integr. Neurosci.*, vol. 15, 2022, doi:
147 10.3389/fnint.2021.777741.
- 148 [33] D. Lakens, “Calculating and reporting effect sizes to facilitate cumulative science: A
149 practical primer for t-tests and ANOVAs,” *Front. Psychol.*, vol. 4, no. NOV, 2013,
150 doi: 10.3389/fpsyg.2013.00863.
- 151 [34] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. New York:
152 Routledge, 2013. doi: 10.4324/9780203771587.
- 153 [35] K. J. Tucker, M. Tuncer, and K. S. Türker, “A review of the H-reflex and M-wave in
154 the human triceps surae,” *Hum. Mov. Sci.*, vol. 24, no. 5–6, 2005, doi:
155 10.1016/j.humov.2005.09.010.
- 156 [36] R. M. Palmieri, C. D. Ingersoll, and M. A. Hoffman, “The hoffmann reflex:
157 methodologic considerations and applications for use in sports medicine and athletic
158 training research,” *J. Athl. Train.*, vol. 39, no. 3, pp. 268–77, Jul. 2004, [Online].
159 Available: <http://www.ncbi.nlm.nih.gov/pubmed/16558683>
- 160 [37] B. L. Luu, H. T. Finn, T. Trinh, S. C. Gandevia, M. E. Héroux, and J. E. Butler,
161 “Temporal summation in human peripheral axons when stimulated transcutaneously
162 with a 10-kHz waveform,” *Exp. Physiol.*, vol. 111, no. 3, pp. 1268–1278, Mar. 2026,
163 doi: 10.1113/EP092659.
- 164 [38] A. Delitto, M. J. Strube, A. D. Shulman, and S. D. Minor, “A study of discomfort
165 with electrical stimulation,” in *Physical Therapy*, 1992. doi: 10.1093/ptj/72.6.410.
- 166 [39] R. Keeseey *et al.*, “Fundamental limitations of kilohertz-frequency carriers in afferent
167 fibre recruitment with transcutaneous spinal cord stimulation,” *Nat. Biomed. Eng.*,
168 May 2026, doi: 10.1038/s41551-026-01684-w.
- 169 [40] I. de Almeida Paz, F. C. Sonda, M. Fröhlich, J. L. Q. Durigan, and M. A. Vaz,
170 “Kilohertz Frequency Alternating Current Induces Less Evoked Torque and Less

171 Neuromuscular Efficiency Than Pulsed Current in Healthy People: A Randomized
172 Crossover Trial,” *J. Sport Rehabil.*, vol. 32, no. 5, 2023, doi: 10.1123/jsr.2022-0159.
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175 **Appendices**

176 **Appendix 1. Ethics Committee approve**

177



PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Avaliação de diferentes tipos de correntes elétricas no recrutamento sensorial, motor e periférico

Pesquisador: DAIANE VIEIRA DE BARROS

Área Temática:

Versão: 2

CAAE: 72475623.9.0000.8093

Instituição Proponente: Programa de Pós-Graduação em Ciências da Raebilitação PPGCR

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 6.408.802

Apresentação do Projeto:

Resumo

"Introdução: A estimulação elétrica neuromuscular (EENM) é um recurso que pode ser utilizado para analisar o recrutamento máximo (onda M), que representa a ativação periférica, e o reflexo de Hoffmann (reflexo H), que determina a ativação central de acordo com a intensidade do estímulo. O reflexo H e a onda

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FACULDADE DE CEILÂNDIA
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BRASÍLIA - UNB



Continuação do Parecer: 6.408.802

Outros	LattesVictor.PDF	28/07/2023 13:50:55	DAIANE VIEIRA DE BARROS	Aceito
Outros	LattesLuis.pdf	28/07/2023 13:47:18	DAIANE VIEIRA DE BARROS	Aceito
Outros	LattesGabrielOliveira.pdf	28/07/2023 13:47:06	DAIANE VIEIRA DE BARROS	Aceito
Outros	LattesDurigan.pdf	28/07/2023 13:46:51	DAIANE VIEIRA DE BARROS	Aceito
Outros	LattesDaniloPolvina.pdf	28/07/2023 13:46:34	DAIANE VIEIRA DE BARROS	Aceito
Outros	LattesDaiane.pdf	28/07/2023 13:46:05	DAIANE VIEIRA DE BARROS	Aceito

Situação do Parecer:

Aprovado

Necessita Apreciação da CONEP:

Não

BRASILIA, 06 de Outubro de 2023

Assinado por:
José Eduardo Pandossio
(Coordenador(a))

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191 **Products Developed During the Master's Program**

192 **Product 1.**



Policlínica da Polícia Civil do DF
Núcleo de Fisioterapia



CERTIFICADO

Certificamos que a aluna Vitória dos Santos Nogueira ministrou o treinamento de equipe "Agentes Eletrofísicos Aplicados à Fisioterapia", com carga horária de 5 horas sob orientação do professor João Durigan, realizado em 9 de dezembro de 2025, na Policlínica da Polícia Civil do Distrito Federal.

Flávia de Oliveira Quintanilha
Chefe do Núcleo de Fisioterapia

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196 **Product 3.**



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- 199 **Link to the video**
200 <https://youtu.be/U85TyiuEPPs>