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Article in *Isokinetics and exercise science* · January 2013

DOI: 10.3233/IES-130495

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Comparison of peak torque, intensity and discomfort generated by neuromuscular electrical stimulation of low and medium frequency

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Received 17 May 2012

Accepted 24 January 2013

Abstract.

BACKGROUND AND PURPOSE: Neuromuscular electrical stimulation (NMES) is an important tool in clinical practice to improve the recruitment of motor units. Optimal forms of NMES, as well as the optimal frequency to achieve the highest torque with the least possible discomfort are not well established. This study was designed to compare maximum electrically-induced torque (MEIT) in the quadriceps, the maximum intensity tolerated by the subject, and the level of discomfort generated by three types of stimulation.

METHODS: Thirty subjects (mean age of 25.0 ± 3.0 years) participated in the study. Each subject was submitted to three currents: medium frequency (2500 Hz) modulated in low frequency (Russian Current), and two currents of low frequency (50 Hz), i.e. without an intrapulse interval (FES), and another with an intrapulse interval of $100 \mu\text{s}$ (VMS). The maximum voluntary isometric torque (MVIT) of the quadriceps was measured. The MEIT, the level of discomfort, and the maximum intensity reached were also measured while applying the three types of NMES. The order of the tests was randomized and the torque was normalized in relation to MVIT.

RESULTS: The results showed no significant difference between the three types of NMES in relation to the generated torque. However, the subjects were able to tolerate a significantly higher intensity with the medium frequency current, and suffered less discomfort when compared to subjects exposed to low frequency currents.

CONCLUSION: Russian Current, FES, and VMS can be used clinically in order to increase the torque of the quadriceps muscle. However, we suggest using the Russian Current in the early stages of a rehabilitation protocol because it showed better tolerance by the participants with less discomfort.

Keywords: Neuromuscular electric stimulation, arthrogenic muscle inhibition, maximal electrically induced torque, isokinetic, quadriceps muscle

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1. Introduction

The restoration of muscle function to pre-injury levels is a major focus of any rehabilitation protocol. However, a commonly observed clinical phenomena is that periarticular muscles cannot reach their full potential after articular damage in relationship to voluntary contraction [1,2]. This phenomenon is known as arthrogenic muscle inhibition (AMI) and is defined as a continuous presynaptic reflex inhibition of the muscle around a joint previously injured [3]. The AMI is a response of the body to protect the joint from further injuries, resulting in decreased reflex of the motor units. Abnormal stimulus to the articular mechanoreceptors and nociceptors may cause afferent discharge that seems to have a powerful effect on the central nervous system, influencing the excitability of several spinal and supraspinal pathways, thus leading to decreased volitional muscle activation [4].

The failure to activate voluntarily the quadriceps muscle has been indicated as a cause of persistent weakness in these muscles, commonly observed after acute [5], chronic [6], or even experimental knee joint injuries [1]. The appearance of this condition has been linked to several factors such as patellar injury [5], anterior knee pain [2], edema [1], ligament injuries or ligament surgical reconstruction [7,8], osteoarthritis [9–11], and total knee replacement (TKR) [12,13]. These factors lead to muscle inhibition which can persist a long time after the injury [4].

Clinically, the quadriceps seems to be the most affected muscular group, due to persistent weakness. Loss of muscle activation can compromise knee joint stability, leading to decreased function, increased risk of further injury, thereby, predisposing the subject to a potential risk of chronic joint degeneration [1,4]. Another important factor is the tendency of AMI to limit strength restoration, as well as to decrease the effectiveness of strengthening protocols based solely on resistance exercises [3,14].

There are some modalities in physical therapy practice aimed at minimizing AMI in order to improve the effectiveness of strengthening and neuromuscular control programs during rehabilitation. Specifically, neuromuscular electrical stimulation (NMES) is the application of low or medium frequency electrical current to promote peripheral nerve depolarization, thereby activating the skeletal muscles, which in turn, promotes muscle contraction [15,16].

Because the number of motor units recruited during voluntary contraction can be increased, the NMES

has been widely used in clinical practice to optimize resistance exercise in order to improve muscle strength and performance in rehabilitation protocols after TKR [12,16], anterior cruciate ligament (ACL) reconstruction [17], and rotator cuff repair [18].

Currently, there are a wide variety of devices that provide different waveforms and pulse settings that can generate muscle contractions for therapeutic purposes [7,19,20]. Researchers are still trying to identify the optimum stimulus in terms of discomfort [20,21] and strength generation [19]. These researchers have observed that some parameters such as intensity, frequency, pulse duration, duty cycle, waveform, and on-off time play an important role regarding these two variables, resulting in increased or decreased clinical efficacy [20,22,23].

A recent topic of analysis is low frequency alternating current versus medium frequency current modulated in cycles; however, the results are not conclusive with respect to torque generation and discomfort [19, 24,25]. It is believed that higher frequencies of stimulation suffer less tissue impedance, reaching greater penetration and, consequently, generating less discomfort. Moreover, this greater spread could activate a higher number of motor units when compared to low frequency stimulation. Thus, an analysis of the influence of different spectrums of frequency on NMES is warranted to achieve better therapeutic results.

The purpose of this study was to compare the maximum electrically-induced torque (MEIT) of the quadriceps, the maximum tolerated intensity, and the level of discomfort generated by three types of stimulation: A medium frequency current modulated in low-frequency (Russian Current), and two low frequency currents (Functional Electrical Stimulation – FES and Variable Muscle Stimulation – VMS).

We hypothesized that medium frequency NMES would be able to reach a higher level of intensity and therefore, greater quadriceps peak torque, as well as generate less discomfort when compared to other stimulations. We further hypothesized that VMS would present less discomfort when compared to FES due to the intrapulse interval.

2. Methods

2.1. Participants

Thirty healthy males (average \pm SD age, 25.0 \pm 3.0 years; height, 175 \pm 6 cm; body mass index, 24.2

± 1.7) volunteered to participate in this study. Participants were excluded if any neuromuscular disorders in the lower limbs, or any contraindications related to the NMES application such as acute muscle or tendon injury, myositis, infection, pacemaker, tumor, and others. All volunteers were informed about the study procedures, and signed informed consent forms written in accordance with National Health Council Resolution CNS-196/96. This study was approved by the ISCMSP Research Ethics Committee.

2.2. Procedures

Each subject submitted to sequential tests using three types of stimulation, all were performed in a single session. Before these tests, the subjects performed a warm-up program based on 10 minutes on a treadmill or stationary bike.

Initially, the maximum voluntary isometric torque (MVIT) was measured so as to create standard data for normalization for the three electrically-induced torques. The subjects were then positioned in an isokinetic dynamometer (Cybex[®] Norm-2000) with the backrest set at a posterior incline of 110 degrees, the dominant knee was flexed at 60 degrees [19,26,27, 29–31], and the inferior portion of the shin pad was adjusted to 5.0 cm superior to the medial malleolus. The seating system pads and belts stabilized the subject's leg, thigh, and pelvis. The lever arm fulcrum was aligned with the most inferior portion of the femoral epicondyle.

Participants were instructed (with verbal encouragement throughout the contraction) to extend the knee as forcefully as possible and hold this position for 10 seconds. In order to ensure that the maximum value was recorded, the subjects underwent three trials with a 2-minute rest period between each trial. The highest value of the three tests was used as the MVIT [27].

After determining the MVIT (interval of 5 minutes), the subjects submitted to three types of stimulation to determine the MEIT. The anterior area of the thigh of the evaluated limb was cleaned with alcohol and four self-adhesive electrodes (8.5 × 5.0 cm) were placed on the limb: one electrode on the rectus femoris, two electrodes on the proximal and distal area of the vastus lateralis, and one electrode on the vastus medialis [24] (Fig. 1). After placing the electrodes on the subject's thigh as afore mentioned, the subjects were placed in the same position used to determine the MVIT, and were instructed to inform the maximum level of tolerance.

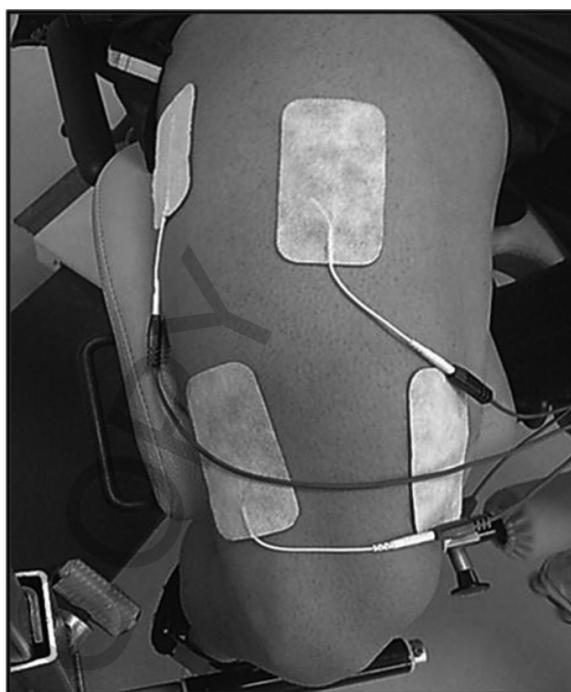


Fig. 1. Positioning of self-adhesive electrodes for neuromuscular electrical stimulation of the quadriceps.

The *Chattanooga Intellect Mobile Stim* (Chattanooga Group, Hixson, TN, USA) was used to generate electrical currents and the modulated parameters were: 1) Russian Current – medium frequency alternating current (2500 Hz), pulse frequency of 50 Hz, burst duration of 10 ms, symmetric pulses of sinusoidal form, with a pulse duration of 400 μ s and a duty cycle of 50%; 2) FES – low frequency alternating current (50 Hz) with rectangular symmetrical pulses and a pulse duration of 400 μ s; and 3) VMS – low frequency alternating current (50 Hz), with rectangular symmetrical pulses, plus a pulse duration of 400 μ s and an intrapulse interval of 100 μ s. For all of these conditions, a rise/decay ramp of 0.5 s was established (Fig. 2).

The application order of each stimulus was determined after randomization, with a rest time of 5 minutes between them. Randomization was performed using opaque envelopes containing the type of stimulation. The envelopes were randomly selected by an individual not involved in the study.

The subjects received a random electrical muscle contraction stimulation to familiarize them with the device, 10 minutes before data collection. Then a single series of electrical stimulations were administered for each waveform. The electrical stimulations were performed with increasing intensity until the maximum

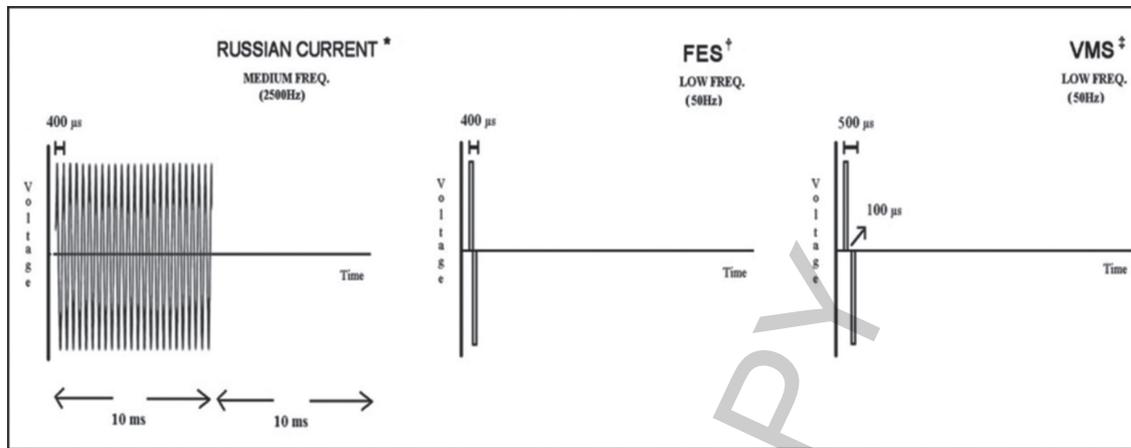


Fig. 2. Characteristics of the currents used for neuromuscular electrical stimulation of the quadriceps. *Russian Current (carrier frequency of 2500 Hz, pulse frequency of 50 Hz, duty cycle of 50%); †Functional Electrical Stimulation (frequency of 50 Hz); ‡Volitional Muscle Stim (frequency of 50 Hz, intrapulse interval of 100 μ s).

tolerance threshold was reached for each subject. They were instructed not to participate in muscular contractions, and they were asked to tell the evaluator when the electrical stimulation intensity level became intolerable.

Data collection was performed by two therapists. The first therapist was responsible for the modulation of parameters and the second therapist, who was blinded to the treatment, was responsible for increasing the equipment intensity. An opaque cover was placed on the equipment during the application process to maintain the blinding procedure (except for the intensity parameter). When the subjects indicated to the second therapist, their maximum discomfort level, he recorded their maximum intensity and the MEIT, followed by a decrease in the intensity to zero. After each contraction, the subjects were asked to express their perceived discomfort on a Visual Analogue Scale (VAS) 10 cm long labeled on the extreme left side as “no discomfort” and on the extreme right side as “intolerable” [28].

2.3. Data analysis

The torque was normalized in relation to the percentage of MVIT: $[(\text{torque produced}/\text{MVIT}) \times 100]$. The Anderson-Darling test was used to verify the homogeneity of the sample. Therefore, a non-parametric analysis to repeated measures was employed by Friedman’s test, with post hoc using the Wilcoxon Signed Ranks test to comparisons between the three types of stimulation in relation to the normalized torque, as well as the level of discomfort by the VAS, and the maxi-

imum intensity tolerated. It was considered the significance of $P < 0.05$. The data are presented as median (Md) and 25–75% interquartile interval.

3. Results

In the analysis of the normalized torque (% MIVT) produced by the Russian Current (Md = 38.3, 24.2–82.7), FES (Md = 54.5, 31.1–82.1), and VMS (Md = 50.5, 43.0–75.8), there was no significant difference ($P > 0.08$). However, when analyzing the maximum intensity (mA) achieved by the device, the Russian Current presented a significantly higher subject tolerance (Md = 71.0, 63.0–87.7) when compared to FES (Md = 57.0, 50.0–68.0) and VMS (Md = 56.0, 48.7–69.0) ($P < 0.0001$).

Finally, the analysis of discomfort by VAS of the intensity parameter showed a significant difference ($P < 0.0001$) when compared to the medium frequency current (Md = 7, 6–8) to FES (Md = 8, 7–9.6) and to VMS (Md = 8, 8–9). The comparison between the intensity tolerance and the discomfort level of the two low frequency currents was not significant ($P > 0.05$) (Table 1).

4. Discussion

This was a randomized study utilizing an evaluator blinded to the treatment procedures for the purpose of comparing the electrically-induced peak torque in the quadriceps, the maximum intensity reached in

Table 1
Outcome measures of the three types of stimulation

| | VMS [‡] | FES [‡] | RC [‡] | Chi-Square | df | P-value | Between-group difference in change score | | |
|----------------|---------------------------------|---------------------------------|---------------------------------|------------|----|----------|--|-----------------------------|------------------------|
| | | | | | | | RC – VMS [†] | RC – FES [†] | VMS – FES [†] |
| % MVIT | 60.2 ± 25.2 50.5 [43.0–75.8] | 59.5 ± 28.7 54.5 [31.1–82.1] | 54.2 ± 36.9 38.3 [24.2–82.7] | 5.0 | 2 | 0.08 | (–) 6.0 (–) 22.4, 10.4 | (–) 5.3 (–) 22.4, 11.8 | 0.7 (–) 13.3, 14.7 |
| Intensity (mA) | 60.3 ± 15.0 56.0 [48.7–69.0] | 59.7 ± 10.9 57.0 [50.0–68.0] | 74.7 ± 14.5 71.0 [63.0–87.7] | 31.2 | 2 | 0.0001* | 14.4 6.8, 22.0 | 15 8.4, 21.63 | 0.6 (–) 6.2, 7.4 |
| VAS (0–10) | 8.4 ± 1.0 8 [8–9] | 8.2 ± 1.5 8 [7–9.6] | 6.8 ± 1.6 7 [6–8] | 16.4 | 2 | 0.0001** | (–) 1.6 (–) 2.3, (–) 0.9 | (–) 1.4 (–) 2.2, (–) 0.6 | 0.2 (–) 0.5, 0.9 |

% MVIT (percentage of the maximum volitional isometric torque); RC (Russian current), df (degrees of freedom).

[‡]Values are mean ± SD, median [25–75%]; *Russian Current showed a significant higher value when compared to FES and VMS; **Russian Current showed a significant lesser value when compared to FES and VMS; [†]Values are mean (95% confidence interval).

the device, and the discomfort level conveyed by the subjects when exposed to the three types of electrical stimulation commonly used in clinical practice. We applied a medium frequency current modulated in low frequency (Russian Current) and two low-frequency currents (FES and VMS). The VMS-type stimulus presents an intrapulse interval of 100 μ s. Based on our results we observed that the three types of neuromuscular electrical stimulation – NMES are equivalent to the generation of passive isometric torque, despite the fact that the Russian Current reached greater intensity with less discomfort.

It is known that after surgery or acute trauma, there is an inhibition of the periarticular muscles, resulting in a voluntary contraction deficit [12,14]. The quadriceps is the most affected muscle when knee compromise is concerned, demonstrating a decline in performance. We also chose this musculature due to easy access to the anterior thigh for data collection.

Although many studies have compared the effect of NMES associated with active exercise to generate isometric and isotonic torque [20,22,23,33–37], the present study was designed to evaluate the maximum torque generated by electrically-induced muscle contraction. We tried to observe the isolated benefit of NMES in a situation similar to the AMI, thereby generating torque in the musculature without voluntary contractions, as occurs in patients with pathological conditions.

Our results demonstrate that NMES alone is capable of generating approximately 60% of maximum isometric torque in a healthy subject. Although these data cannot be extrapolated to patients with muscle activation deficit, these findings are important in helping us to understand the importance of NMES in a rehabilitation program.

Considering this deficit in muscular activation, our efforts were directed toward early force generation improvement and quadriceps function. Many studies have

tried to find the most effective type of stimulation with less discomfort [19,20,22–25,27,32,34,38]. However, the results are still inconsistent and ideal equipment parameters are not well known by physical therapists in clinical practice. Thus, we need to analyze the spectrum of different frequencies, waveforms, and intensity in order to obtain the optimal stimulation dose with higher torque and less discomfort.

We hypothesized that a medium frequency current could generate a higher torque due to lower skin impedance and greater tissue penetration. This hypothesis was not confirmed because there was no significant difference between generated torque by Russian Current, FES, and VMS. However, there was greater intensity tolerance and less discomfort when utilizing medium frequency currents when compared to low frequency currents. Another hypothesis was that the VMS would be more comfortable when compared to FES due to the intra-pulse interval which generates a break in the total pulse amplitude, thus allowing higher intensity with greater generated torque. This was not confirmed because there was no significant difference in all evaluations of both low frequency currents.

Although some studies have shown that lower carrier and pulse frequencies probably generate higher torque [23,24], we believe that by allowing a significant increase in intensity, the Russian Current would allow greater recruitment of motor units. Such procedures ensure equity in the generation of torque, because all applied currents in the present study had the same pulse duration.

Some studies compared the generated torque of low and medium frequency stimulation [19,27,32]. Our results corroborate the findings of Snyder-Mackler et al. (1989) [19], who found no significant difference in the MEIT generated by the Russian Current modulated at 50 Hz and the VMS with the same frequency at 50 Hz.

On the other hand, Laufer et al. [27] indicated higher MEIT generated by a biphasic current with a frequency

of 50 Hz when compared to a monophasic current with the same frequency as well as the Russian Current modulated at 50 Hz with a duty cycle of 50%. Because the low frequency stimulation reached 150 mA of intensity versus 100 mA in the medium frequency stimulator their results may have been influenced.

In addition to the torque, the level of discomfort found in the NMES is also questionable. Laufer and Elboim [25] and Lyons et al. [30] found no significant difference when comparing the discomfort caused by the Russian Current and FES. In contrast, studies conducted by Ward et al. [23,24] showed that the low frequency currents are more uncomfortable than the medium frequency. As we observed, there are still contradictions in the literature regarding the optimal parameters of stimulation needed to obtain the best clinical outcomes.

A limitation of this study was the evaluation of passive torque generated by electrical stimulation, since some studies have shown greater efficacy of NMES associated with active exercises [32,33]. However, we observed that isolated NMES can simulate muscles with severe impairment of voluntary contractions in cases of arthrogenic inhibition; this is a common condition after recent surgery or acute knee trauma. We performed a maximal voluntary isometric torque for normalizing the electrically induced torque. However, the participants did not perform a familiarization to this maximal contraction, only a 10-minutes warming-up on a treadmill or stationary bike.

This study supports the idea that Russian Current is less uncomfortable than low frequency current, but there is no difference in generated torque. A suggested treatment approach can be the application of medium frequency current stimulation in the initial phase of rehabilitation protocols. Future studies should be performed with other frequency spectrums, stimulation parameters, and associated voluntary contractions. These studies should also be conducted with musculoskeletal injury patients.

5. Conclusion

Based on these findings, we conclude that there is no difference in maximum electrically-induced torque when applying Russian Current, FES, and VMS. However, there is greater subject tolerance to higher intensities of Russian Current as well as less discomfort when compared to low frequency currents. There were no differences in all evaluations between the VMS and FES, despite an intrapulse interval.

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