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Low-frequency electrical stimulation with variable intensity preserves torque

Joni A. Mettler[a,*], Dillon M. Magee[a], Barbara M. Doucet[b]

[a] Dept. of Health and Human Performance, Texas State University, San Marcos, TX, USA
[b] Dept. of Occupational Therapy, Louisiana State University Health Sciences Center, New Orleans, LA, USA

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ABSTRACT

The neuromuscular electrical stimulation (NMES) parameters that optimally modulate torque output during prolonged stimulation protocols are not well-established. The purpose of this study was to compare torque output between low-frequency and high-frequency NMES protocols while increasing stimulation intensity. Eleven healthy young individuals received a repetitive, intermittent low-frequency (20 Hz) and high-frequency (60 Hz) NMES over the quadriceps muscles. Stimulation intensity was increased throughout the protocol to achieve a submaximal target torque output. Mean torque, peak torque and torque-time integral (TTI) were measured. The 20 Hz protocol produced a higher mean torque ($P = 0.001$) and TTI ($P = 0.008$) compared to the 60 Hz protocol. The stimulation intensity required to achieve target torque during NMES was not different between frequencies ($P > 0.0001$). When the goal is to optimize torque output during prolonged submaximal NMES, such as during functional electrical stimulation, low-frequency stimulation may be preferred.

1. Introduction

Muscular fatigue, the inability to maintain force output, occurs rapidly during neuromuscular electrical stimulation (NMES) (Doucet and Griffin, 2008; Downey et al., 2011; Thomas et al., 2003). Fatigue is often the primary limiting factor during clinical applications where repetitive contractions of longer duration are induced by electrical stimulation. In skeletal muscle of paralyzed and hemiplegic patients, the ability of an electrical stimulation protocol to facilitate and maintain high torque output for periods of ∼10 s or longer is critical for important activities of daily living, such as standing, postural control, grasping items (e.g., a fork, a glass, or a comb), raising and holding arms overhead during dressing activities, and holding a partial squat position during care-giver assisted transfers (Jacobs and Mahoney, 2002; Jacobs et al., 2003). Additionally, maintenance of force for prolonged periods of time is critical to continue a productive exercise program (Decker et al., 2010; Donaldson et al., 2000; Doucet and Mettler, 2018; Mahoney et al., 2005). When treatment time is reduced, the intended physiological and functional therapeutic benefits of muscle strengthening, muscle endurance, aerobic capacity, energy balance and or glucose regulation that can be augmented through use of this treatment are also compromised (Decker et al., 2010; Kjaer et al., 1996; Mahoney et al., 2005; Petrofsky and Stacy, 1992). During typical NMES delivery, habituation occurs creating a decreased responsiveness to the repetitive pulses, and resulting in a progressive decline in force output over the duration of the program. Therefore, stimulation protocols that extend the duration of torque output will potentially produce the most successful outcomes; however, optimal NMES treatment parameters including frequency, pulse width, and intensity for specified applications have not been fully elucidated. In this study, we investigated torque maintenance in the quadriceps muscle during a high-frequency (HF, 60 Hz) and a low-frequency (LF, 20 Hz) 60-minute stimulation program, while stimulation intensity was increased at regular intervals to consistently achieve a target torque level.

During voluntary muscle contraction, the central nervous system regulates force output through motor unit recruitment and modulation of motor unit firing rates; however, during electrically induced muscle contraction, these two physiological factors are controlled via the stimulation intensity and the stimulation frequency parameters, respectively. Stimulation frequency and intensity work in conjunction to regulate electrically elicited force output. Stimulation frequency refers to the number of electrical pulses elicited each second, which simulates a physiological motor unit firing rate during electrically induced muscle contraction. Motor unit activation rate modulates torque output (Adrian and Bronk, 1929). During constant voltage stimulation, intensity refers to the current (amperes) delivered to the muscle and is

* Corresponding author at: Texas State University, Department of Health and Human Performance, Division of Exercise and Sport Science, 601 University Drive, San Marcos, TX 78666-4684, USA.
E-mail address: jam388@txstate.edu (J.A. Mettler).

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responsible for recruitment or depolarization of the muscle fibers. As intensity increases, more muscle fibers are depolarized and contribute to augmentation of the torque output.

Electrical stimulation protocols often deliver a constant submaximal intensity level throughout the duration of a program; (Bickel et al., 2012; Binder-Macleod et al., 1998; Eser et al., 2003; Matsunaga et al., 1999) however, when using this approach, no additional motor unit recruitment occurs and only those active at the onset of contraction will contribute to the torque output. For clinicians, stimulation intensity can be easily increased during NMES treatment and can offset some of the fatigue experienced during NMES treatment. When using this method of torque preservation, it is still unclear if higher or lower stimulation frequency would be more effective for force maintenance. For instance, during constant intensity stimulation, several previous studies have reported greater torque output during low-frequency compared to high-frequency stimulation (Bickel et al., 2012; Binder-Macleod et al., 1995; Gorgey et al., 2009, 2007), while others have found that high frequency was able to better maintain torque (Eser et al., 2003; Matsunaga et al., 1999). The inconsistent fatigue effects during constant intensity stimulation are likely dependent on frequency, pulse width, duty cycle, and treatment duration. *Selection of Stimulation Parameters:* We chose to use a pulse width of 200 μs as this is the longest pulse duration that is approved by the Food and Drug Administration (FDA) for the stimulation device that was used in this study (Digitimer DS7AH, MEPs-LLC, Fort Lauderdale, FL). We chose to use 200 μs over a shorter pulse duration as larger pulse widths have been shown to optimize motor unit recruitment that can potentially offset fatigue (Bochkezanian et al., 2017), generate stronger contractions (Lagerquist and Collins, 2010), and penetrate deeper into the tissue (Bracciano, 2000). The stimulation was delivered for 60 min as the typical application time in clinical use ranges from 30 min daily to hourly or more three times per day (Doucet et al., 2012). We selected an on-off time of 10 s on and 15 s off as longer contraction times that elicit maintained torque are needed for many activities of daily living as stated earlier. In addition, when force development is interrupted with silent or rest periods such as in intermittent stimulation, muscle tissue is able to recover more effectively than when constant patterns are used (Boom et al., 1993). This becomes critically important in paralyzed populations where overall muscle output and activity may be severely limited. In paralyzed populations, off times that are longer than on times have been shown to preserve muscle force (Matheson et al., 1997; Packman-Braun, 1988) thus we chose a longer off time to preserve force output, while at the same time, keeping the muscle in an activated steady state to facilitate repetitive contractions. Larger electrodes (3 × 5 in) were used to cover more surface area of the quadriceps muscles compared to smaller electrodes. Additionally, larger electrodes disperse current over a larger area, decreasing current density and thereby reducing the discomfort that can be experienced with smaller electrode application. Because NMES has to penetrate subcutaneous tissue, larger electrodes have been found to optimize current delivery as well as reduce discomfort (Doheny et al., 2010).

We hypothesized that low-frequency (20 Hz) NMES would maintain torque output to a greater degree than high-frequency (60 Hz) NMES when stimulation intensity is adjusted and then increased to attain a target torque output throughout the protocol. We chose a low-frequency (20 Hz) protocol and a high-frequency (60 Hz) protocol that both resulted in fused torque, but 60 Hz delivers three times as many pulses and therefore, three times the number of muscle contractions. In terms of muscle efficiency, 20 Hz provided sufficient temporal summation for producing tetanic torque, while 60 Hz may require extra energy and overtax calcium kinetics without added benefit for torque production.

The purpose of this study was (1) to compare torque parameters during a low-frequency (20 Hz) and a high-frequency (60 Hz) NMES protocol while increasing submaximal stimulation intensity to achieve a target torque output and (2) to compare the submaximal stimulation intensity required to achieve the target torque output throughout both high-frequency and low-frequency NMES protocols. In this study, peak torque, mean torque, and torque-time integral (TTI) have been measured to clearly depict torque output parameters during the 60-min NMES protocols. Peak torque was measured because torque produced by NMES is variable during each contraction, especially at the onset of a series of contractions when force potentiation is in play. Measuring peak torque obtained during each contraction during the first 5 min (without adjustments in stimulation intensity) allowed us to monitor the initial contractions until these stabilized and variability of force output was reduced, observe the participant's force response to the stimulation as intensity was increased throughout the protocol, and examine any decrements of force that would warrant intensity adjustment. Measurement of mean torque during each contraction allowed for determination of changes in the average torque output that was produced and how it changed over the course of the 60-min protocol even when stimulation intensity was increased every 5 min to reach the 15% MVC target torque. Lastly, from a clinical and functional standpoint, the ability to maintain force over time [torque-time integral (TTI)] in muscles is critically deficient in paralyzed populations. This ability is needed for maintaining postural control, which directly impacts functional limb use, and for extended or repetitive periods of standing, bending, reaching, and moving, which are foundational for performance of daily living tasks.

2. Methods

Participants. Eleven healthy adults participated in the study [age: 24.6 ± 1.1 years; male (n = 6) and female (n = 5)]. Participants were not enrolled in the study if any of the following exclusion criteria were present: (1) contraindicating conditions for electrical stimulation were present (i.e., swollen, infected, or painful areas on the lower limbs, implanted pacemaker, implanted electronics, or surgical hardware in the lower limbs); (2) they participated in a resistance training program or physical rehabilitation involving the lower extremity within 6 months of the study; (3) they had a current injury to the lower limb or current knee pain. A healthy history phone screen was conducted to determine if interested volunteers meet the participation criteria. Participants were recruited through advertisements on the Texas State University campus and in the San Marcos/Austin, Texas area. All subjects provided written informed consent and all procedures were approved by the Texas State University Institutional Review Board (IRB).

2.1. Study procedures

A pre-test – post-test quasi-experimental crossover design was used for this study in which each participant received a single application of both the HF- (60 Hz) and the LF- (20 Hz) NMES protocol.

Maximal voluntary contraction (MVC) testing. On the first visit to the Translational Neuromuscular Physiology Laboratory participants were familiarized with the isokinetic dynamometer and practiced performing submaximal and maximal intensity knee extension contractions with both legs (Biodex, Systems-4, Shirley, NY). Dynamometry MVC testing was then performed with the subject seated upright with hip flexion at 85° and knee flexion at 60°. A 15-min rest period followed the familiarization. MVC testing consisted 3, 4 s isometric knee extension MVCs to test maximal strength. Subjects were instructed to contract as fast and forcefully as possible during each MVC and verbal encouragement was provided. If torque continued to increase through the third MVC, a fourth MVC was performed to ensure that maximal torque output had been achieved. Right and left legs were tested in random order as determined by a randomization software program (Urbaniac and Plous, 2015). Participants were seated on the isokinetic dynamometer in the same position for all three test days. Participants were also asked to refrain from caffeine consumption on all tests days and were asked to avoid exercise for at least 72 h prior to testing.