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Effects of current amplitude and pulse duration modulation on neuromuscular fatigue during repetitive electrical stimulation

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Effects of current amplitude and pulse duration modulation on neuromuscular fatigue during repetitive electrical stimulation

by

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Abstract

Effects of current amplitude and pulse duration modulation on neuromuscular fatigue during repetitive electrical stimulation

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The University of Texas at Austin, 2015

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Introduction: Functional electrical stimulation (FES) has been used to enhance function and prevent muscle atrophy in people with spinal cord injury (SCI). In this study, we examined the effect of two different stimulation parameter sets on FES-induced muscle fatigue in 10 healthy individuals**. Methods**: 3 FES protocols were applied to the knee extensor muscle group of participants. The experimental protocols were as follows: practice session, test session 1 and test session 2. Subjects were trained to perform the MVIC test, and their MVIC was measured in the practice session. A long pulse duration (1000 μs) and a current amplitude set to evoke 25% MVIC at 30 Hz was applied on subject's thigh for 2 minutes in test session 1. The protocol for test session 2 was identical to the test session 1 with the exception of a different pulse shape. A short pulse duration (200 μs) and a current amplitude set to evoke 25% MVIC was used in test session 2. The percentage decline in peak force, the recovery rate during rest-periods, and self-reported pain were compared between the two FES parameter sets in both test sessions. **Results**: Percent muscle fatigue was significantly lower for the parameter set with long pulse duration (1000 μs) and low current amplitude (LL) than for the stimulation parameter set with short pulse duration (200 μs) and high current amplitude (SH). The reduction of peak force between the first and last peaks was significantly lower in the LL condition than in the SH condition. Pain scores were significantly lower for the LL than for the SH. **Conclusion**: The use of LL reduced the occurrence of muscle fatigue and pain compared to the use of SH. These results suggest that stimulation with LL may help reduce muscle fatigue during FES application.

List of Acronyms

FES – functional electrical stimulation

EMS – electrical muscle stimulation

MVIC – maximal voluntary isometric contraction

LL – parameter set with longer pulse duration (1000 μs) and lower current amplitude

SH – parameter set with shorter pulse duration (200 μs) and higher current amplitude

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CHAPTER 1

INTRODUCTION

1.1 Background

In North America, 400,000 people currently live with a spinal cord injury (SCI) and approximately 11,000 new cases occur each year (Canadian Paraplegic Association, 2006). SCI's are caused by mechanical trauma that damages the neurological tissues of the spinal cord. Most of the damage from SCI's is irreversible and results in partial or total loss of motor and sensory function. Improving motor function in individuals with a SCI can increase quality of life. The most commonly used technique for improving motor function in patients with SCI is functional electrical stimulation (FES). This intervention has been widely applied for the rehabilitation of individuals with limited ability to generate functional movement (Popovic et al. 1992). Muscle force production during repeated electrical stimulation is dependent on FES parameters settings including current amplitude, pulse frequency, and pulse duration. Increasing the pulse duration or current amplitude during muscle stimulation can increase the muscle's production of torque through the recruitment of more muscle fibers (Gorgey et al. 2006). Gorgey et al. (2006) found that reducing the current amplitude from 75% to 45% of maximal voluntary isometric contraction (MVIC) and shortening the pulse duration from 450 µs to 150 µs decreased torque. There has, however, been contrasting evidence about which stimulus parameters are more effective in maintaining force production over time. Collins and his colleagues suggested that longer pulse durations produced larger isometric contractions with a relatively greater central contribution than when short pulse durations were used. The stimulation pattern used in this study was using electrical stimulation at a frequency of 20 Hz for a duration of 2 seconds followed by use of an electrical stimulation at a frequency of 100 Hz for a duration of 2 seconds and ending with electrical stimulation using a frequency of 20 Hz for a duration of 3 seconds, with electrical stimulation lasting a total of 7 seconds. The stimulus intensity was adjusted to evoke a M-wave of 5% M_{max}, and the M-wave and H-reflex were measured at different pulse widths. This study found that the delivery of 3 seconds of neuromuscular electrical stimulation (NMES) at 20Hz (post-100Hz) increased the H-reflex amplitude and torque significantly in the wider pulse widths (200 μs, 500 μs, and 1000 μs) but not in the shorter pulse width (50 μs) (Collins and Largerquist 2010). Kesar and Binder-Macleod (2006) found that when the frequency and pulse duration were held constant throughout repetitive stimulation, long pulse duration (600μs) with a low frequency (11.5 ± 1.2 Hz) maximized isometric performance by minimizing muscle fatigue compared to short pulse duration (131 ± 24μs) with high frequency (60 Hz). However, a study of the gastrocnemius muscle of a rat during a single bout of NMES showed that the use of low frequency with long pulse width (20 Hz and 5 ms) during 40 isometric contractions lasting 5 seconds did not minimize the occurrence of fatigue compared to the use of high frequency with short pulse duration (100 Hz and 1 ms). Instead, it allowed for metabolic changes, such as decreases in phosphocreatine [PCr] concentration, pH, and ATP concentration, which can induce muscle fatigue when the average stimulation intensity, average total charge, initial peak torque, contraction duration, and torque-time integral are controlled (Julien et al. 2009).

1.2 Statement of purpose

The primary goal of this study was to compare the degree of muscle fatigue, during isometric contractions, when two different combinations of current amplitude and pulse duration are used. Another goal of this study was to compare the pain response of participants to electrical stimulation using the different combinations of current and pulse duration condition.

1.3 Hypotheses

We hypothesized that the parameter set with shorter pulse durations and higher current amplitudes would induce the muscle fatigue more quickly compared to the set with longer pulse durations and lower current amplitudes because lower amplitude prevents antidromic transmission, which blocks orthodromically transmitted signals, in motor axons, allowing the central recruitment of motor units, and a longer pulse width recruits a greater number of motor units simultaneously compared to a shorter pulse width, which can activate only a few fibers in a localized region. We also hypothesized that the parameter set with shorter pulse durations and higher current amplitudes would also induce more pain because using a low current amplitude has a greater effect on preventing the depolarization of Aδ and C sensory afferents than when a shorter pulse width is used.

CHAPTER 2

REVIEW OF LITERATURE

2.1 FES treatment

Functional electrical stimulation (FES) is a technique that uses electrical currents to generate functional movements in patients with motor neuron paresis. It has been used in various medical areas such as rehabilitation, geriatrics, and cardiovascular medicine. In particular, this method is used in the rehabilitation of patients with paralysis from a spinal cord injury (SCI), cerebral palsy or stroke (Liberson et al. 1961).

Electrical current from FES functions similar to action potentials from the brain to the somatic motor neurons that innervate muscle fibers. The electrical signals from the brain do not function naturally after an accident resulting from a fall, sports injury, or motor vehicle accident. Rehabilitation of motor function after a serious accident is often challenging due to the decrease in synaptic transmission, which inhibits the nerve's ability to produce the voluntary muscle forces needed to create joint movement during functional tasks (Kathleen et al. 2010).

There are various types of medical treatments that use functional electrical stimulation for promoting muscle movement in paralyzed patients. For instance, it can be embedded within a complex apparatus to facilitate multi-joint movement or it can be utilized by itself. In this respect, the potential of using FES in clinical areas is invaluable, and it is a promising tool for patients with paralysis or SCI (Ashley Erin Clark 2012). FES can improve a patient’s range of motion (ROM) by increasing the patient’s movement performance in tasks such as grasping, walking and sit-to-stand transitions during postural rehabilitation therapy. In addition, FES rehabilitation systems have also been developed for restoring function in the upper extremities, lower extremities, bladder, bowel, and respiratory system (Hunter and Peckham 2005).

2.2 Muscle fatigue and pain in FES treatment

Since the basic purpose of FES treatment is to allow the weakened muscles to regenerate sufficient force, it is commonly used to facilitate fundamental functions. However, the major barrier to the effective use of FES for functional activities is muscle fatigue, which is defined as a reduction in the peak force and the torque time integral following repeated stimulation (Dejan and Laszlo 1997).

The problem of muscle fatigue is exaggerated in patients with spinal cord injury (SCI). Remarkable atrophy is typically seen on paralyzed muscle due to the loss of contractile proteins following SCI. There are fiber type changes as well, with a transition from type 1, slow-twitch, fatigue-resistant fibers to type 2b, fast twitch, non fatigue-resistant fibers. Consequently, the decreased fatigue resistance of paralyzed muscles can make it difficult to apply effective FES treatment (Scott et al. 2006, Bickel et al. 2004).

In addition, during FES, motor unit recruitment is different from the Henneman's size principle. As the tension in a muscle is increased, starting from the relaxed state, motor units containing a small number of muscle fibers are the first to be recruited; larger motor units are recruited later. Thus, when there is little activity in the pool of motor neurons controlling a muscle and the tension in the muscle is low, small motor units are recruited to produce an increase in tension. This ensures that the added increments of tension are small and prevents large jerky increases in tension when the tension is small (Roger and Douglas 1984). To sum it up, the natural muscle contraction follows Henneman's size principle, which minimizes the amount of muscle fatigue by using fatigue resistant muscle fibers first and only using fatigable fibers when high force is absolutely necessary. On the contrary, the motor unit recruitment pattern caused by FES is nonselective, spatially fixed, and synchronous (Gregory and Bickel 2005). Muscle recruitment during FES occurs in a random order that is dependent on the position of the stimulating electrodes. Therefore, the motor units are recruited in a synchronous and repeated manner, and this pattern of motor unit activation causes muscle fatigue relatively faster than those of natural motor unit activation (Joseph 1997, Adams 1993). Therefore, when a patient receives the FES treatments for rehabilitation, strategies aimed at attenuating muscle fatigue are necessary because of the limitations imposed by muscle fatigue.

2.3 Parameters of electrical simulation

When a stimulating current is applied to the electrodes, which are placed on the skin's surface, an electrical field is created between two electrodes (the anode and cathode). The ionic flow across the somatic nerve evokes a trans-membrane potential, and this electrical potential acts as an action potential from the brain (Rushton 1997).

2.3.1 Pulse shape

FES can create a series of rectangular, monophasic or biphasic (symmetrical or asymmetrical) electric pulses, which are composed of the following parameters: current amplitude, pulse duration and pulse frequency. Geometric shapes represent the waveform patterns of electric pulse, and these shapes characterize electrical currents that rise above the baseline (0 mV) or below the baseline. In monophasic electric pulses, the pulse shape is determined from positive phases only. On the contrary, biphasic electric pulses are the combination of pulse shape from both positive and negative phases (McLoda and Carmack 2000). Periodic monophasic and unidirectional pulses are commonly used in most cases of FES application while biphasic and bidirectional pulses can be used for preventing galvanic processes that cause slight tissue (epidermal) damage (Tadej and Marko 2010).

Force production and muscle fatigue during FES depend on the waveform of the pulse width. Specifically, Laufer and colleagues found that monophasic and biphasic waveforms have an advantage over poly-phasic waveforms when applied on the quadriceps muscles to produce torque (Laufer et, al. 2001).

2.3.2 Pulse frequency

Pulse frequency is the number of pulses produced per second during electrical stimulation. Hertz is the unit used to measure frequency (Hz, e.g., 30 Hz = 30 pulses per second) and to describe the consistent wave frequency of the electromagnetic signal. It is commonly acknowledged that the higher the stimulation frequency, the greater the muscle fatigue (Johns et al. 1979), and greater muscle fatigue is associated with a larger metabolic cost of contraction (Bergstrom and Hultman 1988). For instance, one study showed that stimulation at a frequency of 80 Hz with a 300 ms pulse caused more muscle fatigue when compared to a frequency of 20 Hz with a 1200 ms pulse (Russ et al. 2002). They found that the metabolic cost associated with brief stimulation trains, which ranged from 0.3 to 1.8 sec, was higher when stimulation was delivered at 80 Hz in comparison to those evoked at 20 Hz.

Since increasing the frequency of pulses has been shown to promote muscle fatigue, choosing proper pulse settings (pulse frequency) can reduce or postpone muscle fatigue and promote nerve cell adaptation, allowing for FES-induced contractions to be maintained for a longer duration. Most clinical FES systems use the lowest pulse frequency that can generate a fused tetanic contraction and vary the intensity to produce the desired force (Talor et al. 1999; Weber et al. 2005). These tendencies are based on the premise that higher frequencies cause greater muscle fatigue than when lower frequencies are used in FES (Garland et al. 1988). However, another study showed that muscle fatigue was significantly greater at a low frequency (20Hz) than during intermittent high frequency (100Hz) stimulation, suggesting that intermittent high frequency stimulation is valuable in the development of FES application (Matsunaga et al. 1999). Thus, previous literature does not provide conclusive evidence about the isolated effect of stimulation frequency on muscle fatigue.

2.3.3 Pulse width / Duration

Pulse width, also known as pulse duration, is the time span of a single pulse. Generally, pulse duration ranging from 50 μs to over 600 μs is preferred. For instance, dynamic quadriceps extensions, similar to those used in FES cycling tests, use a pulse width between 300 μs - 600 μs. (Janssen et al. 2004).

Short pulse width can be used for neural stimulation when maximal selectivity of discrete groups of nerve fibers is required. Experimental measurement of joint torque generated by peripheral nerve stimulation demonstrated that short pulse duration generates larger torques and creates a larger dynamic range of currents, allowing for more spatially selective stimulation of nerve fibers (Warren et al. 1996). Peter and Thomas showed that short pulse duration, which was fixed at a value less than 100 μs, increased the threshold difference between nerve fibers with different diameters lying at the same distance from the electrodes (Peter and Thomas 1983). Since the difference in threshold between nerve fibers of different diameters allows for more gradual recruitment of nerve fibers, the choice of a shorter pulse width provides better control of electrically activated muscles.

On the contrary, some studies showed that FES delivered using long pulse durations generated larger contractions and produced stronger isometric torque with a relatively greater central pathway contribution than when using short pulse durations. Collins and Largerquist showed that using longer pulse durations could produce relatively stronger isometric contractions than shorter pulse durations. In this study, the soleus EMG and the isometric plantar-flexion torque was compared after FES was delivered to the tibial nerve using 50, 200, 500, and 1000 μs pulse widths. This study found that delivery of 2 seconds of NMES at 100 Hz increased the H-reflex amplitude and torque in the longer pulse durations (200 μs, 500 μs, and 1000 μs) but not in the shorter pulse duration (50 μs). The increased torque and H-reflex amplitude with long pulse durations demonstrated that shorter pulse durations are not as effective for recruiting motor neurons through spinal reflex pathways (Collins and Largerquist 2010).

When it comes to the effects of pulse duration on muscle fatigue, Kesar and Binder-Macleod recently reported that the combination of long pulse duration and low frequency stimulation can minimize fatigue of the motor unit population recruited by the stimulation protocol (Kesar and Binder 2006). On the contrary, another study reported that the use of low frequency stimulation and long pulse duration did not minimize muscle fatigue or affect the corresponding stimulation-induced metabolic changes, such as PCr, pHi, and ATP, when the average stimulation intensity and total charge were carefully controlled (Julien et al. 2009).

2.3.4 Duty Cycle

Intermittent stimulation is needed to preserve force development since muscle tissue is able to recover during the periods when it is not being stimulated ("off" time). This would allow the patients to feel more comfort during their FES treatment (Boom et, al. 1993).

Duty cycle is a ratio of the time of electrical stimulation ("on" time) to the total treatment time (sum of "on" time and "off" time) and is expressed as a percentage. Namely, 70% duty cycle means the electrical signal is on 70% of the time but off 30% of the time (Baker et, al. 2000). In general, clinical application use a 1:3 duty cycle as a standard, but this ratio can be modified to accommodate the needs of the patient and the goals of the treatment (Bracciano 2008).

2.3.5 Current amplitude

The current amplitude of FES is another parameter that will contribute to torque production and muscle fatigue. Current amplitude is the strength of the electrical current and it is measured in milliamperes (mA). Previous studies have clearly established that increasing current amplitude leads to increased torque production, which is caused by the activation of additional motor units (Gorgey et al. 2006). Increasing current amplitude also affects conduction velocity. Mesin et al found that increasing the current amplitude increases the conduction velocity of stimulation and motor units closer to the stimulation electrodes are recruited first regardless of their unique excitation thresholds (Mesin et al. 2010). Binder-Macleod et al demonstrated that although increased current amplitude led to a rapid increase in M-wave amplitude, further increases of current amplitude produced an increase in the exerted force, without substantial changes in the M-wave amplitude (Binder et al. 1995).

Although higher current amplitudes can activate a large number of muscle fibers, a recent study has suggested that lower current amplitudes can induce more central nervous system input than higher current amplitudes. When the electrical stimuli is large enough to elicit an action potential in the nerve fiber situated within mixed nerve, the action potential volley travels in both the ‘normal’ orthodromic direction and in the ‘opposite’ antidromic direction. The antidromic action potential volley in type 1a afferents has little effect, whereas in the motor nerve, the antidromic volley can collide with the oncoming orthodromic type 1a afferent volley and reduce the maximal H reflex magnitude obtained. Thus, antidromic transmission reduces sensory impulses from the spinal motor pool, resulting in less central nervous system activation (Bergquis et al. 2011).

Current amplitude also affects the patient’s pain during FES treatment. The larger the FES amplitude is, the stronger the muscle contraction is. However, if the current amplitude is too high, the onset of muscle fatigue is earlier and the pain felt by the patient is stronger. If high current amplitude is used for a long duration of time, the stimulated muscle can become damaged. On the other hand, low current amplitudes can cause weak contractions. Thus, an appropriate current amplitude needs to be applied to FES treatments to prevent pain and early muscle fatigue (Manabu et al. 2009).

2.4 Rehabilitation benefits of FES

A wide range of FES systems exist for patients with SCI, which include grasping, standing, stationary rowing, cycling as well as systems for improving gait patterns during walking (Thrasher et al. 2006). Electrical stimulation combined with fast isotonic training can increase maximal concentric movement. One study found that significant increases in muscle and fiber cross-sectional area, isokinetic peak torque, maximal isometric and dynamic strength, and improvements in motor performance skills have occurred as a result of percutaneous electrical stimulation (PES) during training. The research team demonstrated that the PES training method is complementary to voluntary training because the application of the PES induces a spatial recruitment of motor units, which entails the preferential recruitment of the fast-twitch fibers (Sanchez et al. 2005).

Sabut and colleagues recently showed that FES therapy combined with conventional therapy treatments, which was made for the purpose of improving in gait parameters, greatly improves walking ability and recovery of motor units when compared to conventional therapy alone. They found that the FES group showed 26.3% improvement in walking speed, which was measured with a 10 m walkway, whereas the improvement in walking speed in the control group was only 11.5%. The FES group also demonstrated greater improvements, compared to control group, in other gait parameters, such as cadence, step length and ankle range of motion (Sabut et al. 2010).

Interferential therapy is a form of FES treatment that uses two slightly different frequencies, which interfere with each other in the tissues. A low frequency current generated through interferential therapy can be used to block pain signals. A study about the restoration of blinking in facial paralysis patients demonstrated that interferential stimulation provided an effective means of recruiting broader areas of the orbicularis oculi muscle (OOM) without substantial activation of cutaneous pain receptors in the eyelid. This study suggested that interferential stimulation using FES is more effective at evoking pain-free blinking because stimulation from FES can be more widely distributed across the paretic OOM (Daniel and Shane 2009).

2.5 Limitations of FES application

2.5.1 Problems with electrodes

Electrodes of FES can damage the skin in the contact area if they are handled improperly. The area of skin underneath the anode electrodes can typically be burned when using identical surface electrodes. Another problem is in properly and precisely positioning electrodes along a muscle. Finding a specific nerve fiber, which is supposed to be stimulated by surface electrodes, is difficult because the distance from the nerve is not constant. Moreover, even a displacement of a few millimeters of the electrodes can change the muscle response completely because a slight change of location can excite pain receptors in the skin. This explains why the movement caused by electrical stimulation cannot be consistently repeated. In addition, small muscles cannot be activated selectively and deep muscle cannot be stimulated without prior activation of superficial muscles (Bajd and Munih. 2010).

2.5.2 Muscle fatigue during FES treatment

Another limitation of FES treatment is that stimulated muscles tend to fatigue very rapidly, which limits the role of FES in rehabilitation of skills such as standing and walking (Adam Thrasher et al. 2005). Muscle fatigue during FES is caused by the differences in motor unit recruitment order and a higher activation frequency compared to volitional contraction (Peckham and Knutson 2005). For this reason, tetanic contractions with FES stimulation require a much higher pulse frequency (20 – 50 Hz) than the frequency needed to induce tetanic contractions with asynchronous recruitment, which is performed by the central nervous system (6 – 8 Hz). This unnaturally high stimulation frequency is the main cause for the increased rate of muscle fatigue compared to muscle contractions initiated by the CNS (Mortimer 1981).

In addition, the opposite natural muscle-fiber recruitment order occurs during FES stimulation. The fast twitch fibers, which are less fatigue resistant than slow twitch fibers, are recruited first during FES (30 Hz – 100 Hz) because the fast twitch fibers are innervated by axons with a larger diameter, while the slow twitch fibers are composed of axons with a smaller diameter (Morita et al. 1995). When it comes to the thickness of axons, axons with a larger diameter have a greater chance to be affected by the electric field than axons with a smaller diameter (Ruff and R L 1992). Thus, fast-twitch fibers respond first during FES stimulation at lower levels of pulse frequency than slow-twitch fibers, and this non-physiological recruitment of muscle fibers increases the rate of muscle fatigue.

2.6 New stimulation techniques to prevent fatigue

To deal with FES stimulation problems, which recruit motor units in a synchronous manner, a new stimulation technique has been proposed for minimizing fatigue in practical FES applications by simply modifying the stimulation patterns.

Zi-Ping and Thomas found that the use of shape of quasi-trapezodial pulses and a tri-polar cuff electrode made selective activation of small motor axons possible, achieving physiological recruitment order of small-to-large motor units in electrically activated muscles (Zi-Ping and Thomas 1991). These results indicated that slow twitch fibers (fatigue resistant motor units) could be activated before the fast twitch fibers (fatigable muscle) were recruited by the new stimulation method.

In addition, Zoher and his colleagues demonstrated that using optimized N-let (double let or triplet) stimulation greatly increases the ability of a stimulated muscle to sustain force during isometric contraction compared to the traditional singlet stimulation (Zoher et al. 1995). They found that doublet stimulation with a pulse interval of about 5 ms produced the maximum torque time integral, and this resulted in a 36% increase in isometric torque compared to single pulse trains of conventional FES. Thus, this study suggested that N-let stimulation is an effective way to reduce muscle fatigue in FES applications and can be exploited beneficially in other FES applications that use intramuscular or nerve cuff electrodes.

Several selective nerve-blocking techniques that aim to provide stimulation analogous to natural motor unit stimulation are available. One study demonstrated that normal size-order recruitment could be achieved through tri-polar nerve cuff electrode (Richard et al. 1989). They found that using single tri-polar electrodes allows recruitment of motor units, according to their independent size, and changes their firing rate similar to that of voluntary muscle contraction.

CHAPTER 3

METHODS

3.1 Subjects

Ten healthy subjects, comprised of 8 males and 2 females 24 ± 1 (mean $\pm$ S.E.) years old, participated in this study. Volunteers did not have any medical problems or previous surgery to the right lower extremity. All participants were requested to refrain from strenuous exercise for at least 48 hours before participating in the study. Prior to participating in this study, all individuals signed an informed consent form. All procedures were approved by the University of Texas at Austin Institutional Review Board and were in accord with the Helsinki Declaration of 1975.

3.2 Experimental Setup

Participants were seated in a chair with an ankle cuff placed around their right leg (See Figure 1). The ankle cuff was attached to a strain-gauged transducer (Entran Sensors & Electronics, Fairfield, NJ). Their backs were supported with their hips flexed at approximately 80 degrees. Their knees were flexed at 90 degrees. Velcro straps were used to stabilize the participants' upper trunk and waist. Electrical stimulation was delivered via two self-adhesive surface electrodes (5 cm × 10 cm, Axelgaard PALS, Platinum Self Adhesive Stimulation Electrodes). The area of the skin where the electrodes were to be placed was cleaned with a 70% isopropyl alcohol swab prior to and after shaving the area with a disposable razor. During stimulation, the electrodes were placed on the skin over the right rectus femoris.

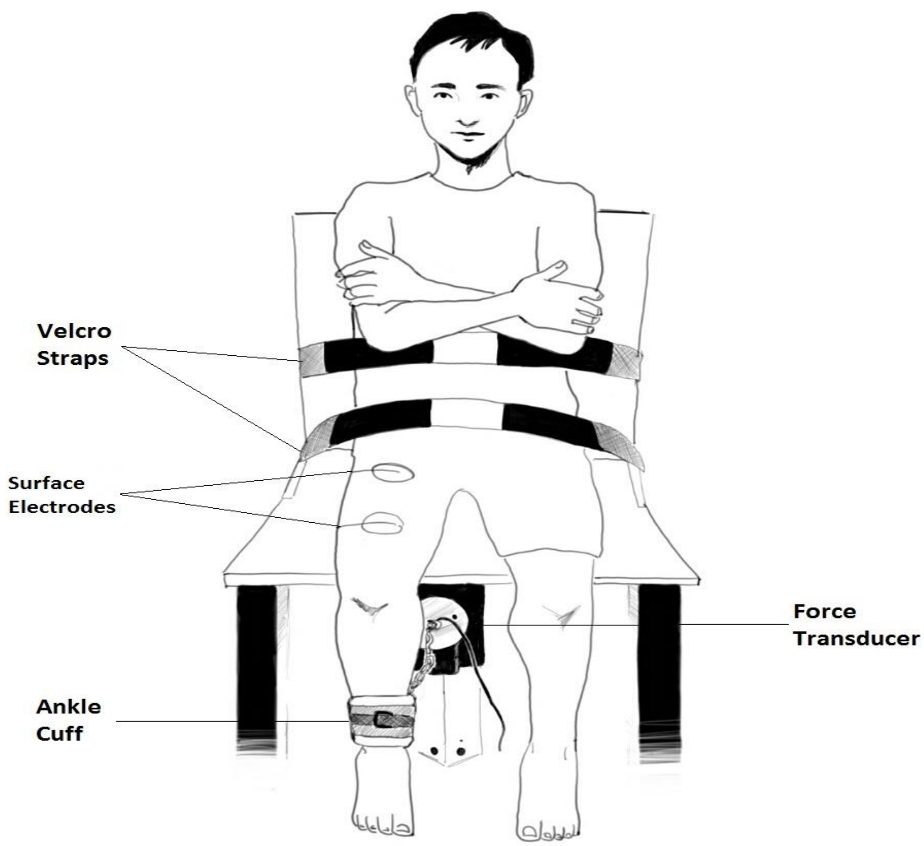

Figure 1. The experimental set up used for testing on participants.

3.3 Electrical Stimulation

A constant-current stimulator (Digitimer DS7A) was used to deliver the electrical stimulation. The force was digitized at 2,000 Hz using the SPIKE2 program (version 7.09, Cambridge Electronic Design, Cambridge, England). The stimulation intensity was set to produce 25% MVIC force during a 300 ms pulse train of 30 Hz.

The pulse frequency remained constant at 30Hz using a modified Bulke fatigue protocol (Burke et al. 1973) and the protocol lasted for a total of 2 minutes. Each cycle was composed of 10 trains and each train consisted of 10 constant pulses lasting 300 ms with 700 ms of rest time following each train. Each train thus lasted 1000 ms with each cycle lasting 10 s (See Figure 2). Five seconds resting time was given between each cycle due to the pain caused by continuous electrical stimulation. After the fatigue task, the participants were asked to rate their pain during the stimulation on a scale of 0 to 10, with a rating of 0 corresponding to “no pain.” and a rating of 10 corresponding “to the worst possible pain”.

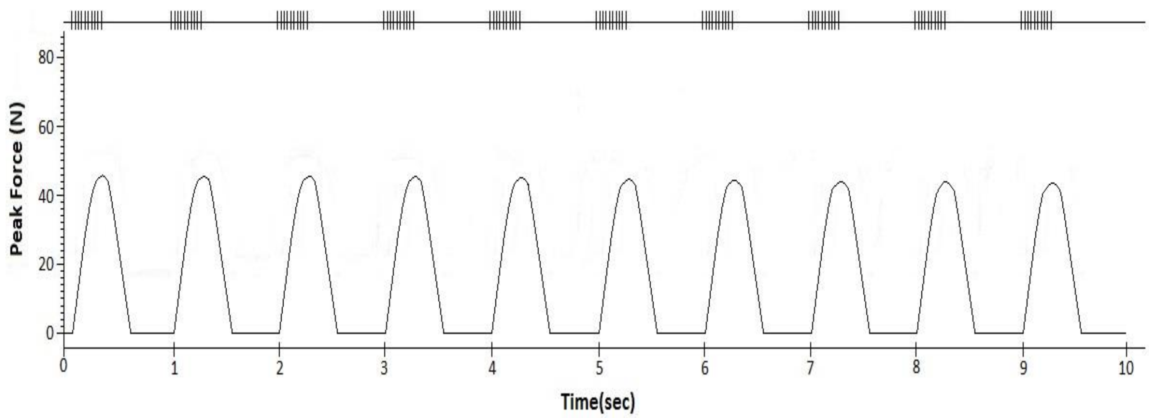

Figure 2. One cycle of FES and the peak forces produced. Each cycle was composed of 10 pulse trains. Each train was 10 square-wave pulses, lasting 300 ms at 30 Hz. 700 ms of rest time was followed each train. Five-second rest-periods were given prior to the beginning of each new cycle.

3.4 Experimental Protocol

All individuals participated in three experimental sessions separated by at least 48 hours.

Day 1

At the start of the practice session, participants received an overview of the entire testing protocol. After volunteers agreed to participate in this study, they were asked to sign the informed consent form and completed the physical activity questionnaire regarding their general health. They were also questioned about their medication usage in order to determine if the medications the subject was currently taking affected the subject's ability to exercise. Then they participated in a 15-minute practice session to acquaint themselves with the FES protocols and were trained to perform the knee extension MVIC test. During the practice session, each participant was asked to perform between three to seven trials of MVIC. The average of the three highest MVICs was used to set the stimulation intensity for the two stimulation protocols.

Day 2

In one test session, a parameter set with a long pulse duration and low current amplitude was used. Continuous electrical stimulation, composed of a long pulse duration (1,000μs) and a current amplitude set to evoke 25% MVIC during a 300 ms time interval, was applied on the participants' thigh for 2 minutes. 5 seconds of resting time was given between each cycle. Each cycle consisted of 10 trains with each train being composed of 10 constant pulses. Each train lasted 300ms, and 700ms of rest time was given after each train. The stimulation frequency was set at 30 Hz to elicit electrically evoked contractions. Participants were given the visual analog scale (VAS) immediately after stimulation was finished and were asked to rate their pain on a scale of 0 to 10 (See Figure 8).

Day 3

In another test session, the protocol was identical with the exception that a different pulse shape was used. A short pulse duration and high current amplitude was used. A short pulse duration (200μs) and current amplitude, set to evoke 25% MVIC during a time interval of 300ms, elicited electrically evoked contractions at a stimulation frequency of 30 Hz.

3.5 Data Analysis

Maximal Voluntary Isometric Contraction Force

During the practice session, each participant was asked to perform between three to seven trials of MVIC of the knee extensors until three consistent maximal contractions, with no more than 5% variability, were achieved. The average maximal torque during the largest of the three contractions was measured and used as individual MVIC value. Participants were provided with visual feedback of their torque production via use of a computer monitor and verbal encouragement was provided.

Muscle fatigue

The percentage decline in peak force was calculated for each EMS test session. The difference between the torque of the initial contraction and the torque of the final contraction of each FES protocol was divided by the torque of the initial contraction in order to determine the percent muscle fatigue, as shown in the equation below:

$$\text{Percent muscle fatigue} = \frac{(Torque\ of\ the\ 1st\ contraction - Torque\ of\ the\ last\ contraction)}{Torque\ of\ the\ 1st\ contraction} \times 100$$

The recovery rate during periods of rest

The rate of increase in peak force during the 5 seconds rest periods was calculated as the difference between the peak forces of consecutive trains (the last train of the pre-cycle and the first train of the post-cycle) divided by the 5 seconds window between cycles, as shown by the equation below:

The recovery rate during periods of rest (N/5sec)

$$= \frac{|Peak\ Force\ of\ the\ last\ train\ of\ the\ pre{-}cycle - Peak\ Force\ of\ the\ first\ train\ of\ the\ post{-}cycle|}{5\ sec}$$

3.6 Statistical Analysis

A repeated-measure analysis of variance (ANOVA) was used to determine any differences between two different pulse width conditions. The percentage decline of muscle force during the fatigue protocols, the recovery rate during periods of rest, and self-report pain level were compared using a one-way repeated measures ANOVA analysis with SPSS software. Statistically significant difference (the α level) was set at $p \leq 0.05$, and is presented as means ±S.E.

CHAPTER 4

RESULTS

4.1 Muscle Fatigue.

Figure 3 shows the mean value of the initial and the final peak forces of the two different parameter sets.

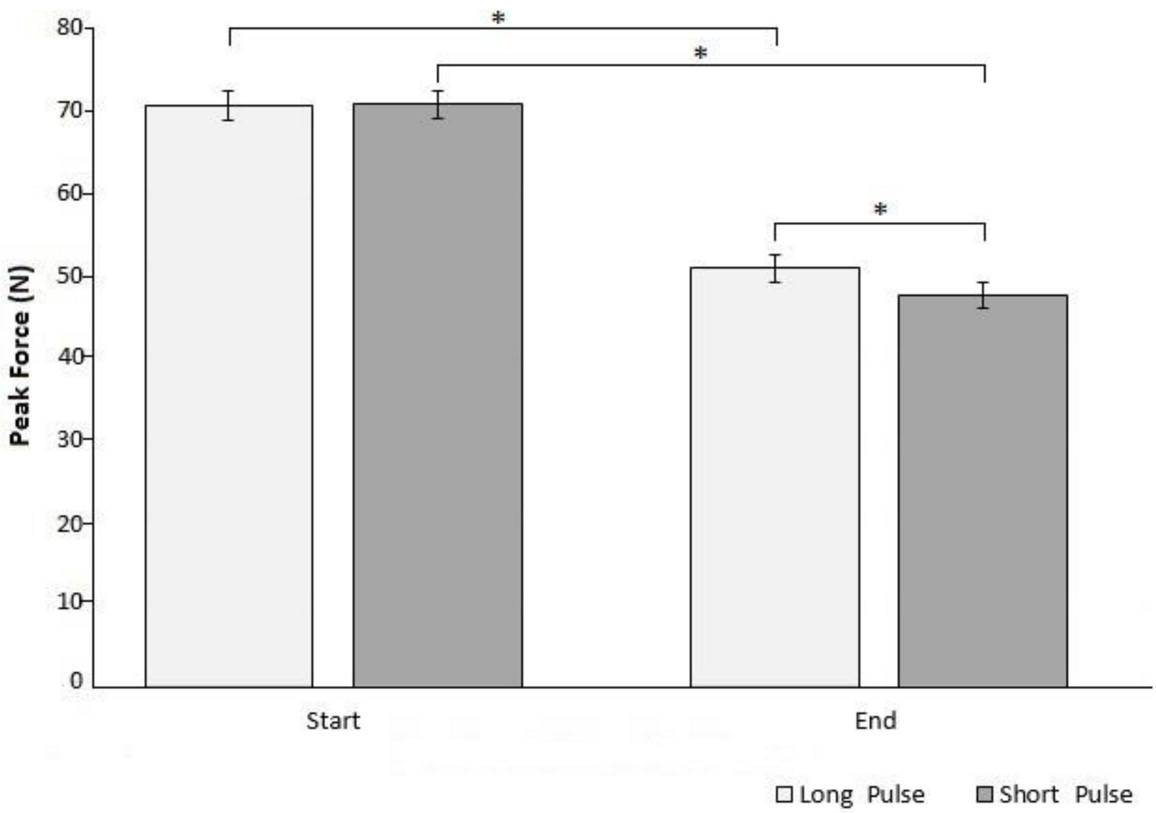

Figure 3. The subjects' mean value of the initial and final peak forces in the different pulse durations (± standard error). An asterisk (*) represents the peak force difference between LL and SH.

In terms of the two different parameter sets, the LL condition was composed of a pulse duration of 1000 μs and current amplitude of 34.20 mA ± 4.15 (Mean ± S.E.) and the SH condition was composed of 200 μs and current amplitude of 72.98 mA ± 5.15 (Mean ± S.E.) (See Figure 4).

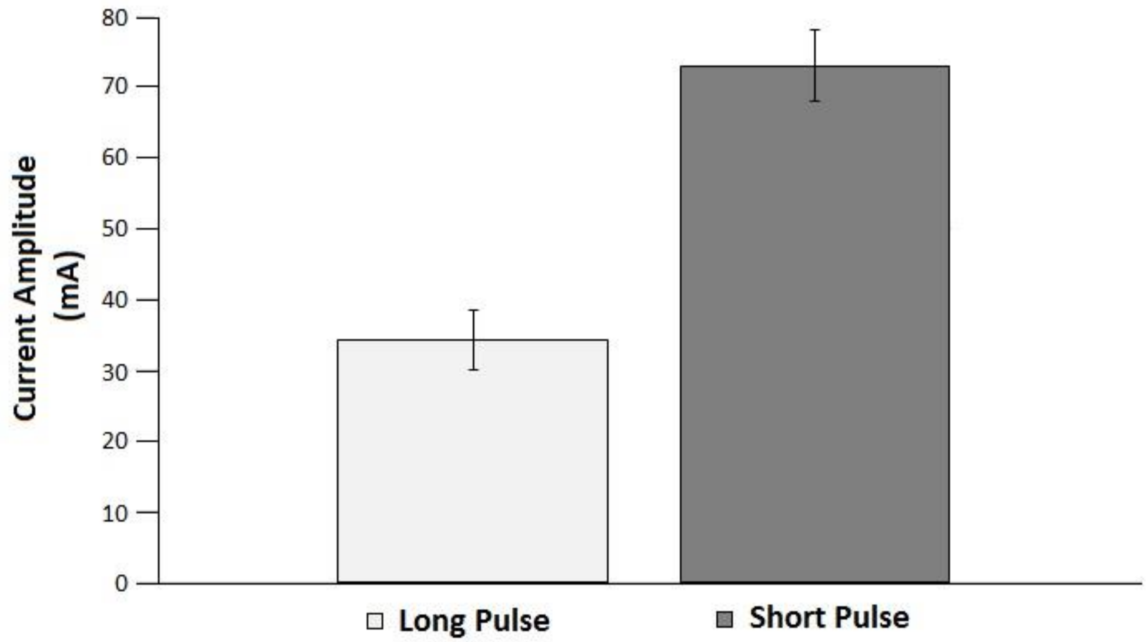

Figure 4. The Mean difference of current amplitude between two pulse conditions (25% of MVIC)

We found that the mean values of the final peak force in the LL condition (Mean ± S.E. 50.56 ± 1.65) were different from the final peak force in the SH condition (Mean ± S.E. 47.27 ± 1.54), ($p=0.006$).

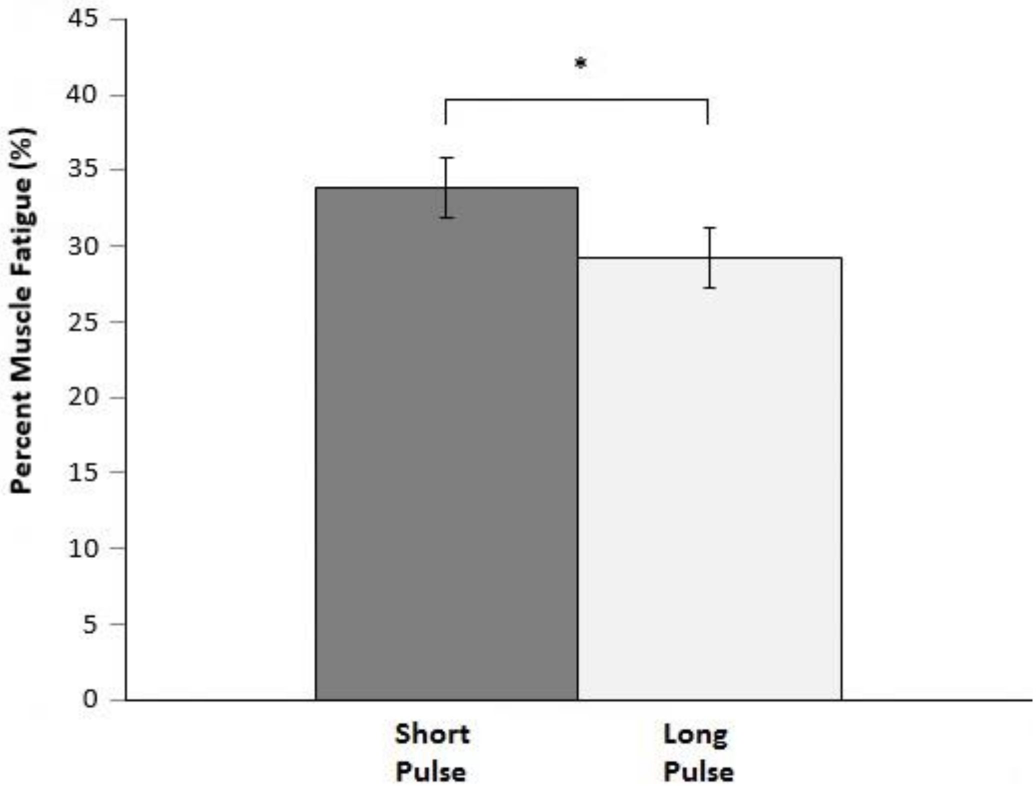

Figure 5. The use of different pulse durations and their effect on percent muscle fatigue (± standard error). An asterisk (*) represents the percent muscle fatigue difference between the two different FES conditions (LL and SH).

In terms of percent muscle fatigue, Figure 5 shows the percentage decline in peak force between the torque of the initial and the final contractions of each FES protocol. Percent muscle fatigue of LL (Mean ± S.E. percent fatigue, 29.20 ±2.12) was significantly lower than for SH (Mean ± S.E. percent fatigue 33.89 ±2.01), ($p = 0.002$).

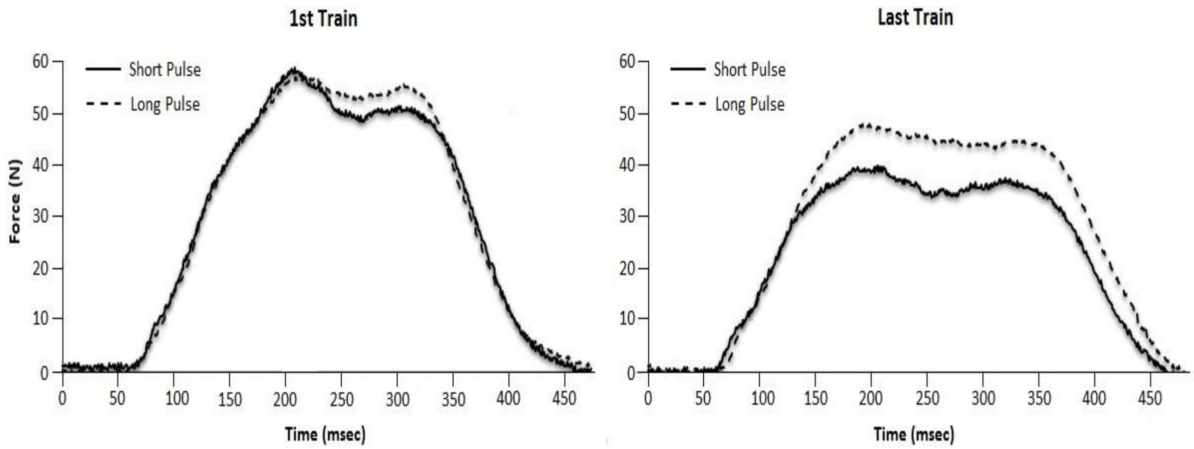

Figure 6. Initial and final peak forces during contractions in the two different FES conditions in one participant.

Figure 6 compares the reduction of peak force between the initial and final peak from pulse train in one subject. The peak force significantly decreased more during the SH condition in comparison with the LL condition (the mean of force reduction: Mean ± S.E. 16.60N± 0.17 at SH, 9.80N ± 0.09 at LL, $p < 0.001$).

4.2 Recovery rate during periods of rest.

There was some force recovery during the 5-second rest periods. The force recovery rate increased over time throughout from the first rest-period to the 6^{th} rest-period (See Figure 7). It, however, did not increase during the last rest-period, and the force recovery rate was significantly different between the two parameter sets (LL: Mean ± S.E. 0.75 ±0.06 N/5s SH: 0.53±0.07 N/5s, F=10.104, P=0.019). Specifically, the recovery rate from the first rest-period to the 3^{rd} rest-period was significantly higher for LL than for SH [F=19.692, P = 0.047].

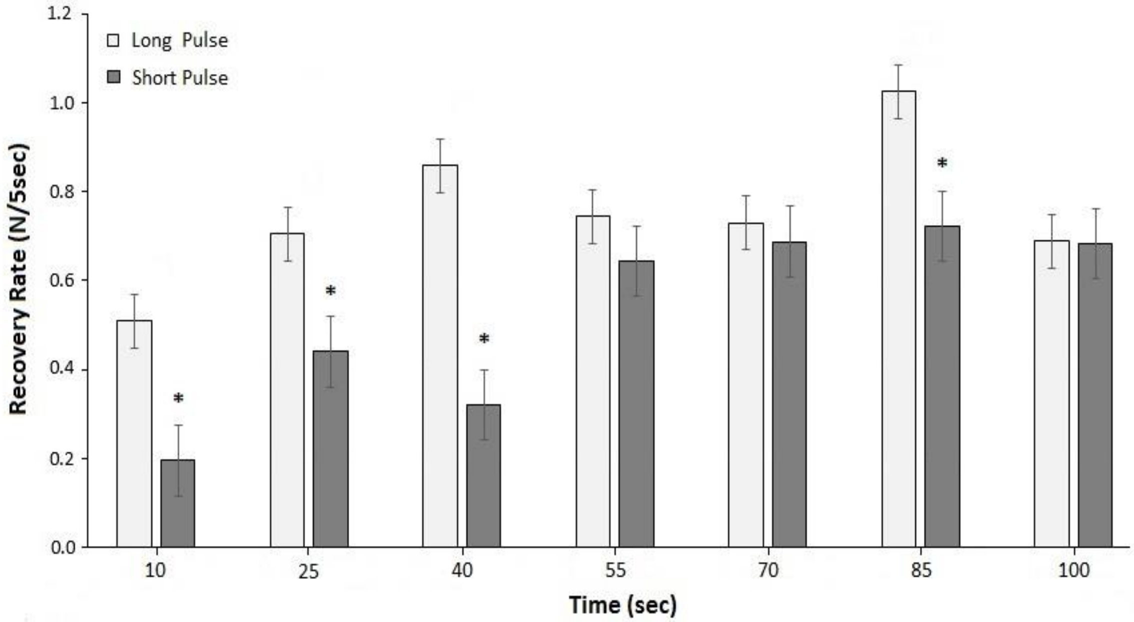

Figure 7. Differences in recovery rate between the two different FES conditions (LL and SH) during each rest-period. Asterisks (*) represent significant differences between the two FES conditions.

4.3 Pain

Self-reported pain associated with the application of FES was evaluated according to visual analog scale (VAS) (See figure 8) and it was significantly lower for the LL condition than for the SH condition ($p = 0.033$, 95% CI range for LL: 2.264-6.236; 95% CI range for SH: 4.589-6.911). The mean score of self-reported pain was 5.75 ± 0.49 (Mean $\pm$ S.E.) for SH and 4.38 ± 0.83 for LL.

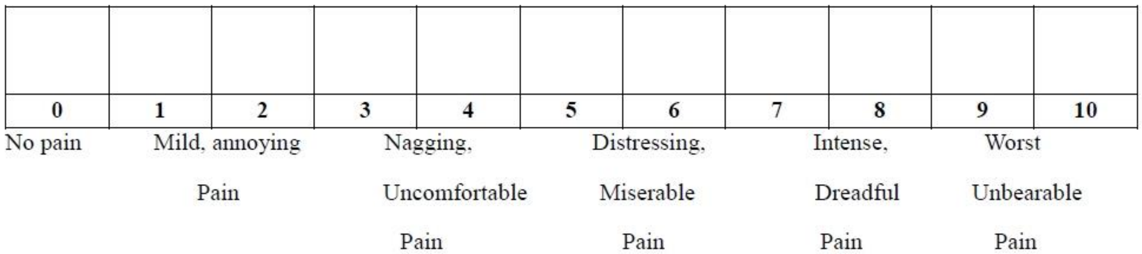

Figure 8. Visual analog pain scale used during FES.

CHAPTER 5

DISCUSSION

The main finding of this study was that the parameter set with longer pulse duration and lower current amplitude reduced the muscle fatigue compared to the parameter set with shorter pulse duration and higher current amplitude when FES was delivered at 30 Hz to elicit 25% of the MVIC using identical initial peak force, duty cycle, and concentration duration. Our results also suggest that the recovery rate from muscle fatigue is higher for a long pulse duration with low current amplitude parameter set than for a short pulse duration with high current amplitude, and that most subjects felt more discomfort from the short pulse duration with high current amplitude parameter set than from the long pulse duration with low current amplitude parameter set.

5.1 Percent Muscle Fatigue

Pulse amplitude

When FES is applied to the muscle belly, this electrical stimulation depolarizes the motor axon and sensory axon (type I_a or type $II_{b)}$ beneath the stimulating electrodes. A M-wave is an early muscle activation response that occurs in 3 to 6 msec through α-motor neuron axons after FES. A H-reflex activation response begins in the sensory axons, and these sensory axons synapse with a α-motor neurons in the spinal cord (central pathway), leading to muscle activation after about 35-40 msec. In other words, 25% MVIC produced by FES is generated by a combination of peripheral recruitment (caused by activation of motor axons underneath the stimulating electrodes, which is indicated by the M-wave), and central recruitment (originating with an electrically evoked sensory volley, such as type I_a and type II_b, which is indicated by the H-reflex) of muscle fiber activation.

Generating contractions through the central pathway is an efficient way to reduce muscle fatigue because stimulation through the central pathway, to recruit motor units, follows the Henneman size principle, allowing smaller motor units and fatigue-resistant motor units to be recruited first.

When FES is applied, action potentials (AP) can travel in both directions (orthodromic and antidromic). Because the diameter of type I_a and type II_b is larger than that of α-motor neuron, antidromic volley in type I_a and type II_b afferent neurons has little effect on the collision between two volleys (orthodromic and antidromic). However, because of the relatively small diameter of the α-motor neuron, the antidromic volley in α-motor neuron can collide with the oncoming sensory afferent orthodromic volley. Thus, as the current amplitude of FES is increased, the central recruitment of motor units is decreased. This correlates with the findings obtained when comparing percentage muscle fatigue evoked by quadriceps stimulation. We found that the percentage decline in peak force when FES is delivered using the parameter set with low current amplitude and long pulse duration (1000 μs) was significantly lower than FES made by high current amplitude and short pulse duration (200 μs). Thus, these results strongly suggest that delivering FES at low current amplitude with long pulse duration can maximize the contribution of the recruitment of motor units through the central pathway. In line with this finding, the relatively less time taken to reach the highest force peak in the SH condition compared to the LL condition (Figure 5) supports the position that more motor units are recruited through the peripheral pathway, which has a relatively short distance to activate motor axons, in the parameter set with high current amplitude and short pulse duration (200 μs).

Pulse duration

The use of longer pulse duration during FES is associated with greater motor unit recruitment through the central pathway. Specifically, the use of longer pulse durations activates more sensory axons than motor axons (Kiernan et al. 1996). Lagerqusit and Collins showed that pulse durations of 200 μs, 500 μs, and 1000 μs (relatively longer pulse width) generated larger H-reflexes and greater torque than shorter pulse durations (50 μs). This support is consistent with our results in the different percentage declines in peak force between the two different FES conditions. At the beginning of the first contraction, we used two different FES conditions: long pulse width (1000 μs) with a low current amplitude (34.20 mA $\pm$ 4.15, Mean $\pm$ S.E.) adjusted to evoke 25% MVIC and short pulse width (200 μs) with a high current amplitude (72.98 mA $\pm$ 5.15, Mean $\pm$ S.E.) adjusted to evoke 25% MVIC. Although the percent fatigue increased in both conditions as time passed, the average rate of increase rate in percent fatigue was significantly lower at long pulse durations (1000 μs) with low current amplitude than short pulse durations (200 μs) with high current amplitude (See Figure 9).

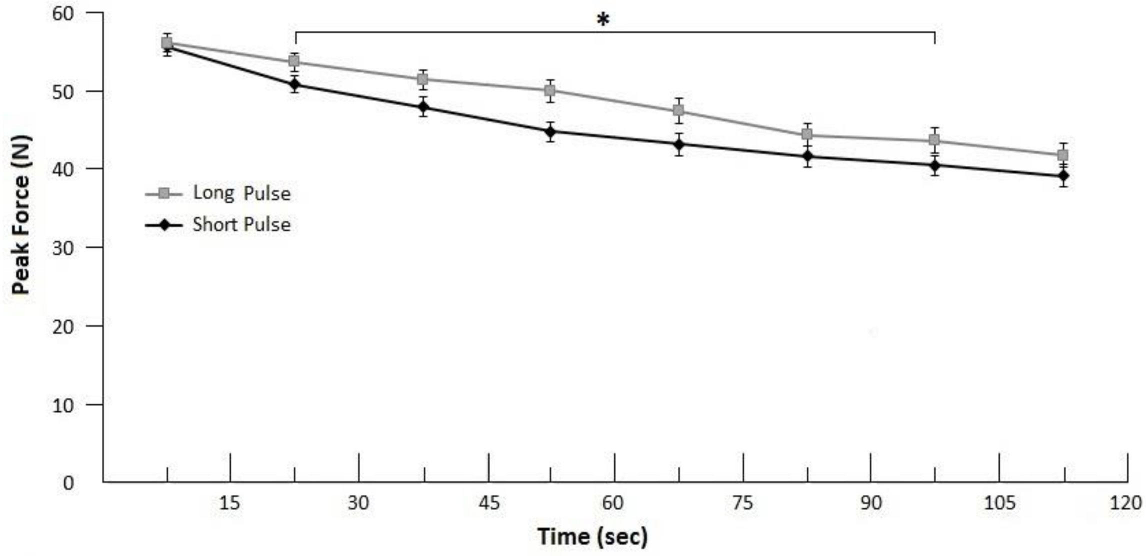

Figure 9. Decline in peak force throughout each cycle. Asterisks (*) represent significant peak force differences in each cycle.

The percentage decline in peak force was always lower in the long pulse width condition (1000μs) than in the short pulse width (200μs) condition. This result strongly suggests that the use of longer pulse duration recruits more sensory axons than motor axons to contract muscle and it allows increased motor unit recruitment though the central pathway, reducing peripheral muscle fatigue.

Neuromuscular transmission failure is a major factor of peripheral muscle fatigue, and it is indicated by changes in the M-wave. Interference with the transition state of the actin-myosin cross bridges from weakly bound, low-force states to strongly bound, high-force states that occur during contraction may develop as products such as calcium, hydrogen ions, inorganic phosphate, and reactive oxygen change during contraction. In addition, the relationship between force and calcium concentration results in fatiguing muscles requiring more calcium to maintain a certain force. However, the rate of change in calcium concentration decreases for a number of reasons: The action potential could be attenuated because of potassium accumulation in the transverse tubules (T-tubules), the rise in magnesium interrupts the opening of calcium channels, and inorganic phosphate enters the sarcoplasmic reticulum and precipitates with the calcium (Allen et al. 2008a, 2008b).

Another important effect of pulse width is related to the spatial selectivity of neural stimulation. For instance, a shorter pulse width provides greater selectivity between nerve fascicles than a long pulse width, because the threshold difference between the nerve fibers of varying diameters increases with decreasing pulse width (Gorman P.H. and Mortimer J.T 1983) In other words, a longer pulse width activates a greater number of motor units to be recruited simultaneously compared to a shorter pulse width that activates only a few fibers in a localized region. Warren and his colleague found that shorter pulse widths (100µs, 50µs, 10µs) provided more spatially selective activation of nerve fibers than longer pulse width(500µs) and generated larger torques when stimulus parameters were applied using controlled current amplitude at 0.5 Hz (Warren et al. 1996). Thus, this indicates that longer pulse durations promote the spread of stimulation to adjacent nerve fascicles, and this can distribute muscle fatigue to relatively larger numbers of motor units than when shorter pulse durations are applied.

5.2 Recovery rate.

As mentioned earlier, the properties of motor neuron recruitment by FES are different from those elicited by normal physiological mechanisms. In normal physiological mechanisms, the smallest diameter neurons are recruited prior to recruitment of larger diameter nerve fibers, and the Henneman size principle supports this progressive size-dependent recruitment of motor units. The nerve fiber recruitment pattern resulting from FES, however, is different from the normal physiological mechanisms. When applying electrical stimulation, larger diameter nerve fibers, which innervate larger motor units with more fast-twitch muscle fibers (non-fatigue resistant fiber), are recruited prior to smaller diameter nerve fibers, which activate muscle fibers capable of longer contractile activity without muscle fatigue. Thus, we can assume that the relatively high recovery rate with lower intensity stimulation is related to ideal combinations of FES parameters, which allow for preferential stimulation of fatigue resistant type 1 muscle fibers (slow-twitch fibers).

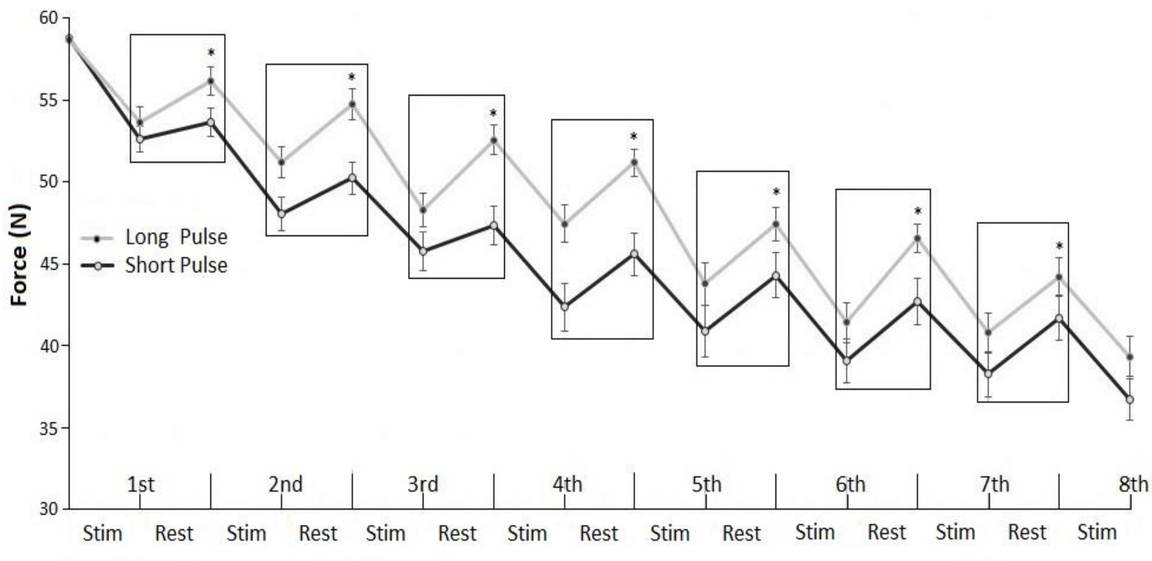

Figure 10. Force recovery differences during rest-periods in two different FES conditions (LL and SH). Asterisks (*) represent the significant differences in 1st peak force of each cycle between the two FES conditions after each rest-period.

In our experiment, FES at low current amplitude with long pulse duration (1000μs) allows the asynchronous and orderly motor unit recruitment to a greater extent than stimulation at high current amplitude with short pulse duration (200μs), increasing the recovery rate. Consequently, the recovery rate was affected by which type of muscle fiber was stimulated constantly. Since the combinations of low current amplitude and long pulse width activate more sensory axons, this contributes to the evoking contractions through the central pathway, recruiting relatively more "fatigue resistant" muscle fibers.

5.3 Discomfort

Nociceoptors (pain receptors) activate sensory neurons that respond to potentially damaging stimuli by sending pain signals to the brain. They are found in any area of the body that can sense “noxious stimuli”. A noxious stimulus is defined as "an actual or potential tissue damaging event" caused by mechanical (e.g. pinching or other tissue deformation), chemical (e.g. exposure to acid or irritants), or thermal (e.g. high or low temperatures) disturbances, which trigger the nociceoptors (Loeser JD and Treede RD 2008).

Nociceoptors have two different types of axons: Aδ fiber axons and C fiber axons. The Aδ fiber axons are myelinated and allow an action potential to travel at a rate of about 20 meters/second towards the CNS, whereas C fiber axons conduct much more slowly due to the axons being unmyelinated (speed of around 2 m/s). As a result, in the first phase, Aδ fibers are activated for fast conduction, which is associated with the initial pain, and C fibers respond to a more prolonged and slightly less intense pain in the second phase (Fields HL et al. 1998).

When electrical current is applied to the two electrodes placed on the skin overlying sensory nerve fibers, an electric field is established between the two electrodes, and the ionic flow across the nerves in the tissue generates an action potential. If this electrical energy reaches a threshold value of nociceptors, this leads to the conscious awareness of pain through the central pathway, which contain Aδ and C sensory afferents.

When the pulse width parameter is fixed, increasing the current amplitude of FES produces a stronger depolarizing drive that can depolarize more Aδ and C sensory afferent and send more sensory volleys into the central pathway, increasing sensitivity to pain. Also when the pulse amplitude is fixed, a longer pulse width increases the spread of electrical stimulation to a greater number of sensory afferent so that more Aδ and C fibers are depolarized, increasing the intensity of pain and reducing subject tolerance to pain. In other words, using shorter pulse widths is more efficient to prevent pain because shorter pulse widths provide greater selectivity between nerve fibers, localizing the region for the recruitment of nerve fibers and minimizing the time required for irreversible electrochemical reactions, such as oxygen reduction, hydrolysis of water, and neural damage caused by electrical charge (Warren and J. Thomas 1996). Thus, in terms of reducing pain during FES, using both a low current amplitude and shorter pulse duration is the most ideal way to prevent feelings of discomfort.

The results of our experiment show that self-reported discomfort was significantly lower for the parameter set with longer pulse durations (1000 μs) and lower current amplitudes than for the shorter pulse durations (200 μs) and higher current amplitudes. Therefore, this suggests that if the stimulus parameters are increased, increasing of the current amplitude has a greater effect on evoked pain than increasing pulse duration, when other parameters are fixed at constant values.

CHAPTER 6

CONCLUSION

In conclusion, our results demonstrate that when the frequency is kept constant at 30 Hz throughout repetitive FES to evoke 25% of MVIC, long pulse duration (1000 μs) with low current amplitude induces a greater recruitment of motor units through the central pathways, contributing to the recruitment of more fatigue-resistant motor units. In terms of the discomfort associated with FES application, although a narrow pulse width is more effective in preventing the occurrence of pain, subjects' discomfort can also be diminished by using a long pulse duration (1000 μs) with a low current amplitude because using a low current amplitude has a greater effect on preventing the depolarization of Aδ and C sensory afferents than when a shorter pulse width is used.

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