Effects Of Frequency And Pulse Duration On Skeletal Muscle Fatigue During Repetitive Electrical Stimulation

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Abstract

Both stimulation intensity and frequency can be modulated to compensate for any decline in force generating ability of the muscle due to fatigue during functional electrical stimulation (FES). However, most current FES systems only vary the intensity to control muscle force. This study compared the fatigue produced during repetitive stimulation using 5 different protocols. Three of the 5 protocols consisted of stimulation with trains of a constant frequency and pulse duration (PD) throughout the protocol (no-modulation protocols). The 3 no-modulation protocols used 3 different combinations of frequency and PD: (1) low-frequency, long-PD, (2) medium-frequency, medium-PD, and (3) high-frequency, short-PD. Two of the 5 protocols involved a stepwise increase of either frequency (frequency-modulation) or PD (PD-modulation). All 5 fatigue protocols were made to produce the same initial peak force by varying either the frequency or the PD. The dependant variable was the percent decline in force during each fatigue protocol. The results showed that frequency-modulation produced the least decline in force, followed by PD-modulation. Also, the no-modulation protocol consisting of trains of relatively high-frequency and short-PD produced the greatest decline in force. Although frequency-modulation is not commonly used during clinical FES, it appears that clinicians should consider this strategy to optimize muscle performance.

1. INTRODUCTION

The central nervous system (CNS) uses both recruitment and rate coding to achieve a precise control of muscle force. During FES, modulation of stimulation intensity is analogous to recruitment and modulation of stimulation frequency is analogous to rate-coding.

However, most current FES systems only use modulation of stimulation intensity to control skeletal muscle force [1,2].

1.1. Effects of Frequency and Intensity on Muscle Fatigue

Fatigue is defined as a decline in the force generating ability of skeletal muscle. Rapid fatigue may prevent the generation of sufficient force and impede effective task performance during FES applications.

Different combinations of stimulation frequency and intensity can be delivered to generate the force required during FES. It has been suggested that using a relatively low frequency and high stimulation intensity may minimize fatigue during repetitive electrical stimulation [3,4]. However, no previous studies have systematically investigated the effect of different combinations of frequency and intensity on the fatigue produced during repetitive activation. Both stimulus pulse duration (PD) and pulse amplitude can be used to vary the intensity. In this study, we kept the amplitude constant, and controlled stimulation intensity by varying PD.

The **first aim** of this study was to compare the fatigue produced during repetitive activation with protocols that produced the same initial force but used different combinations of stimulation PD and frequency.

1.2. Effects of 'Modulation' of Frequency or PD on Muscle Fatigue

As fatigue occurs during repetitive stimulation, the muscle may not be able to generate the force required for an FES task. Stimulation frequency or PD can be increased to maintain the required force for longer durations.

Previous studies on animal muscles showed improved control of muscle force using simultaneous modulation of stimulation PD and frequency [5]. However, there are no studies to suggest whether frequency-modulation or PD-modulation will produce lesser fatigue during repetitive electrical stimulation.

Our **second aim** was to investigate the effects of stepwise increase of frequency (frequency-modulation) or PD (PD-modulation) on force production during repetitive stimulation.

2. METHODS

2.1. Subjects

The quadriceps femoris muscles of eleven healthy subjects were electrically stimulated via surface electrodes.

2.2. Apparatus

An electromechanical dynamometer (KINCOM, Chattanooga Corp., Chattanooga, TN) was used to measure knee joint torques. A Grass Model S8800 stimulator (Grass Instrument Company, Quincy, MA) was used to deliver electrical stimulation. A custom written LabVIEW software was used to control the timing of the pulses (stimulus frequency) and the PD of each pulse.

2.3. Testing Sessions

Each subject participated in 6 testing sessions. During the 1st session, the subject's maximal voluntary isometric contraction (MVIC) force was recorded using the burst superimposition technique. In addition, a series of stimulation trains (frequencies 10 to 100-Hz, PD 100 to 600-μs) were delivered to obtain data for plotting the force-frequency and force-PD curves.

The subsequent 5 sessions were used to test the 5 fatigue protocols (3 no-modulation + 2 modulation) in random order. Two consecutive fatigue sessions were separated by at least 48 hours.

During each of the 5 subsequent testing sessions, 300-ms long stimulation trains were used for stimulation. In the beginning, the stimulation amplitude (V) was set to produce 50% of the subject's MVIC force using a 60-Hz, 600-μs PD train. Next, the stimulation train parameters were fixed at either 600-μs PD, 30-Hz, or 60-Hz, and the PD or the frequency was adjusted to generate 20% MVIC force. The fatigue protocols consisted of 176 trains delivered at the rate of 1 train every second.

2.4. Fatigue Protocols

The 5 fatigue protocols tested were as follows:

No-Modulation Protocols:
(1) 600-μs PD, Low-Frequency
(2) 30-Hz Frequency, Medium PD
(3) 60-Hz frequency, Short PD
Modulation Protocols:
(4) Frequency-Modulation:
PD constant at 600-μs, frequency increased stepwise every 16 contractions
(5) PD-Modulation:
Frequency constant at 60-Hz, PD increased stepwise every 16 contractions.

The percentage decline in peak forces and force-time integrals were calculated for each of the 5 fatigue protocols tested.

3. RESULTS

3.1. No-Modulation Protocols

Analysis of the averaged percent decline in peak force (N=11) showed that no-modulation protocol #1, consisting of stimulation trains with the low-frequency, long-PD produced the least decline in peak force (29.5%) (Figs.1 and 2).

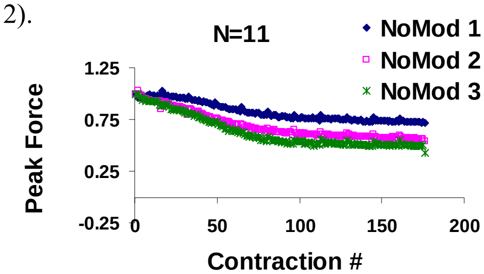

Figure 1: Peak forces produced in response to each stimulation train (contraction #) during the three no-modulation protocols (N=11).

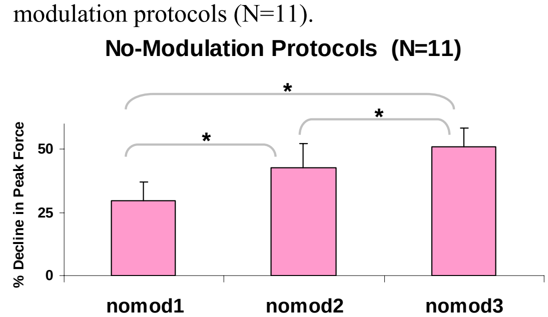

Figure 2 – The percent decline in peak force between the first and last trains (N=11) for the 3 no-modulation protocols (One-way repeated measures ANOVA, F=32.7, p=0.00, *p≤0.01 for planned pairwise comparisons).

3.2. Modulation Protocols

Interestingly, the frequency-modulation protocol demonstrated a 17.9% increase in peak force between the first and the last train, while the PD-modulation protocol showed a 3.6% increase in peak force (N=11) (Figs. 3 and 4).

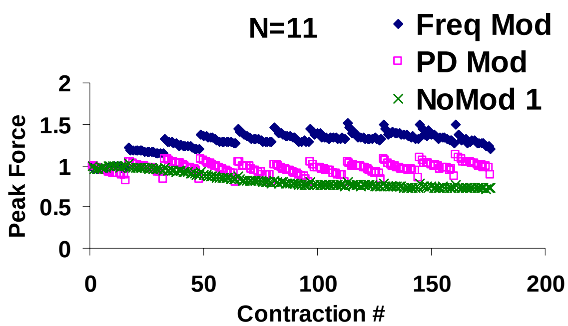

Figure 3– The peak forces (N=11) produced in response to each stimulation train during the frequency-modulation and PD-modulation protocols. The no-modulation protocol (1) is shown for comparison.

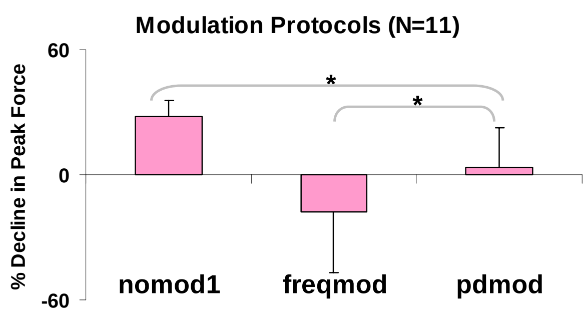

Figure 2 – The percent decline in peak force between the first and last trains (N=11) for the modulation protocols. The no-modulation protocol (1) was used for comparison (Repeated measures ANOVA F=28.25, p=0.00, *****$p \leq 0.01$ for pair-wise comparisons).

The averaged force-time integrals showed similar trends to the peak forces.

4. DISCUSSION AND CONCLUSIONS

In this study, frequency-modulation produced greater forces at the end of the fatigue protocol than PD-modulation. This is important because most current systems modulate PD to control force. Perhaps using a high-PD throughout the frequency-modulation protocol allowed the metabolic effects of fatigue to be shared among greater number of motor units, and, therefore, produced lesser decline in force due to fatigue. A similar rationale can help to explain the lesser decline in force due to fatigue produced during the no-modulation protocol consisting of relatively low frequency and long PD.

Frequency-modulation may help to minimize the decline in muscle force due to fatigue during FES applications involving repetitive activation. An understanding of the effects of frequency and PD on the fatigue produced during electrical stimulation can help to design stimulation strategies that improve muscle performance during FES-elicited movements. Concurrent studies in our lab are testing stimulation strategies involving simultaneous modulation of both frequency and PD during repetitive activation.

References

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Acknowledgements

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