Changes in the relationship between stimulation pulse duration and force output with fatigue for human quadriceps muscles

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Abstract

Functional movements often require repetitive activation of muscles. Muscle fatigue causes the decline in force output and may result in inability of the muscle to produce sufficient forces to allow continued performance. Clinically, stimulation intensity is increased to overcome the decline in force due to muscle fatigue during FES. The precise control of muscle force is needed to maximize performance and minimize fatigue during FES; however, changes in the human skeletal muscle force-intensity relationship with fatigue have not been previously reported. The purpose of this study is to investigate the changes in the force-intensity relationship with fatigue. Right quadriceps muscles of 9 healthy adults were tested isometrically. Pre- and post-fatigue force responses to 60-Hz stimulation trains at different pulse durations were recorded and analyzed. Our results showed an exponential relationship between force output and stimulation pulse duration and that the normalized force-intensity relationship did not change with fatigue. Thus, although the force-intensity relationship is dynamic, the fact that the normalized force-intensity relationship did not change with fatigue can help clinicians identify appropriate stimulation intensity to precisely control muscle force during the application of FES.

1. INTRODUCTION

Motor units are activated synchronously and the recruitment order does not follow Henneman’s size principle [1] during electrically elicited contractions [2, 3]. Thus, rapid muscle fatigue is often observed, which limits the application of electrical stimulation [4].

One way to overcome the decline in force due to muscle fatigue is to increase the stimulation intensity. Researchers have examined the force – intensity relationship for non-fatigued animal and human muscles [5, 6]. The precise control of muscle force is needed to maximize performance and minimize fatigue during FES; however, this relationship has not been investigated during muscle fatigue. To better understand the changes in the force-intensity relationship as a consequence of muscle fatigue, human quadriceps muscle force responses to stimulation trains at different pulse durations before and after a modified Burke’s fatigue protocol [7] were investigated in the present study.

2. METHODS

2.1. Experimental setup

Right quadriceps muscles of 9 healthy adults were tested isometrically at 90° knee flexion using a Grass S8800 stimulator with an SIU8T stimulus isolation unit (Grass Instrument Co., Quincy, MA) with two, 7.6 × 12.7-cm, self-adhesive electrodes (Versa-stim, Conmed Corp., Utica, NY). A customized program (LabView 6.0) on a PC controlled the timing parameters of each stimulation train and recorded force data at 200Hz.

2.2. Experimental procedures

Each subject was tested on 2 different days. During the first session, maximal voluntary isometric contraction (MVIC) was determined using the burst superimposition technique [8]. Next, quadriceps muscles were potentiated using 15, 300-ms, 14-Hz trains (pulse duration 600 µs) before setting the stimulation amplitude. The stimulation amplitude was determined by using 600-µs pulses and gradually increased the pulse amplitude until the quadriceps muscles reached maximum twitch force. The stimulation amplitude was then unchanged for the remainder of that session. Stimulation pulses ranging from 100 to 600 µs with 50-µs increments were delivered...
to quadriceps muscles every 10 seconds to obtain twitch responses at different stimulation intensity.

During the second session, quadriceps muscles were first potentiated using the same 14-Hz trains used in the first session. Stimulation amplitude was then determined using 300-ms, 60-Hz trains (pulse duration 600 µs). The stimulation amplitude was gradually increased until the muscle force reached 20% of the subject’s MVIC. The stimulation amplitude was then unchanged for the remainder of that session. Next, each subject received a testing protocol consisted of a pre-fatigue portion, a fatiguing portion, and a post-fatigue portion. The pre-fatigue portion, containing twenty-two, 60-Hz testing trains (300 ms in duration) with different pulse durations, were delivered to the quadriceps muscles to examine the force responses to different stimulation intensities before the muscles were fatigued. The rest time between each testing trains was set at 10 seconds to avoid fatigue. Eleven pulse durations, ranging from 100 to 600 µs with 50-µs increment were selected for testing. The sequence of these pre-fatigue testing trains was randomly determined for each subject. Each pulse duration was tested twice, and the force responses to each pulse duration were averaged for later analysis. Forty-Hz, 300-ms trains (pulse duration 600 µs) were delivered to the muscle once every second for a total of 180 trains to fatigue the quadriceps. The post-fatigue portion was delivered to subject’s quadriceps muscle immediately after the fatigue portion. Stimulation trains in this portion were delivered at a rate of 1 per second. Post-fatigue portion consisted of the same random sequence of 60-Hz testing trains as that used in the pre-fatigue portion, but each of the testing trains was separated by two fatiguing trains (e.g., 40-Hz, 300-ms train with pulse duration at 600µs) to maintain a steady state of fatigue.

2.3. Data management and analysis

Time to peak twitch and one-half relaxation time were measured and compared across different pulse durations using One-way analysis of variance (ANOVA) with repeated measures. Time to peak twitch force was the time from the onset of the force to the peak of the twitch; one-half relaxation time was the time to return to half of the twitch force from the peak twitch.

Pre- and post-fatigue peak force responses to each of the 60-Hz testing trains were measured to generate the force-intensity relationship, and were normalized to the peak force responses at 600-µs pulse duration. A two-way ANOVA with repeated measures was used to identify changes in the force-intensity relationship with fatigue. Pairwise comparison with a Bonferroni correction was performed if a significant main effect was observed. A similar analysis was performed for normalized data. Intraclass correlation coefficient (ICC) was calculated to measure the normalized relationship between pre- and post-fatigue peak force responses to 60-Hz testing trains at different pulse durations.

An exponential function

\[ F = A \left(1 - e^{-\frac{(PD-PD_0)}{\tau}}\right) \]  

was used to fit the pre- and post-fatigue data, where parameter \( A \) is the scaling factor for the force \( F \), \( PD \) represents the actual stimulation pulse duration. \( PD_0 \) represents the threshold pulse duration (above which there will be a measurable force). \( \tau \) is the time constant controlling the rise of the force with increasing pulse duration. Paired t-tests were used to compare differences in parameters \( A \), \( PD_0 \) and \( \tau \) in the pre- versus post-fatigue force-intensity relationships. Statistical significance was accepted at \( P \leq 0.05 \).

3. RESULTS

3.1. Twitch data

Peak twitch forces increased with an increase in the stimulation pulse duration (Fig. 1). Neither time to peak twitch nor one-half relaxation time changed with the increase of pulse duration (\( P > 0.05 \)).

Fig 1. Superimposed quadriceps muscle group twitch responses to stimulation pulses at different pulse durations. The peak twitch force increased from 55 to 111 N with the increase of stimulation intensity.
pulse duration from 100 to 600 µs (from bottom to top; only 6 pulse durations were shown for clarity). Numbers shown on the graph are the values for time to peak twitch and one-half relaxation time.

3.2. Force-intensity relationship

Two-way ANOVA of the non-normalized force-intensity data showed a significant difference between pre- and post-fatigue force responses and among stimulation intensities (F = 64.30 and 101.07, respectively; both P < 0.01); however, no difference was found between normalized pre- and post-fatigue force-intensity relationships. ICC was 0.99 for the normalized pre- versus post-fatigue force-intensity relationships, indicating a very high correlation (Fig. 2).

Fig 2. Raw (left) and normalized (right) force-intensity relationship. Pre- (triangle) and post-fatigue (circle) peak force responses (Mean ± SE) to 60-Hz stimulation trains at pulse duration from 100 to 600 µs were plotted.

4. DISCUSSION AND CONCLUSIONS

This is the first study to investigate the changes of force-intensity relationship with fatigue for human skeletal muscles. Our findings of a consistent twitch contractile speeds with increasing stimulation intensity suggested that motor units were not recruited in an orderly manner with respect to their contractile speed. In addition, the shape of the force-intensity relationship is determined by the recruitment order with respect to motor unit force. Previous studies have shown that motor unit force is negatively correlated with fatigability [9, 10], if recruitment was orderly with respect to the force and hence fatigability of the motor units, we should have observed a shift in the force-intensity relationship after the muscles were fatigued. Because no shift in the force-intensity relationship was observed, we can conclude that recruitment was also not orderly with respect to force or fatigability of the motor units. Thus, our results support previous studies that have suggested that motor unit recruitment during transcutaneous electrical stimulation is less orderly for human skeletal muscles [11, 12, 13].

References


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