Effect of Random Modulation of FES Parameters on Muscle Fatigue

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Abstract

Muscle contractions induced by functional electrical stimulation (FES) tend to result in rapid muscle fatigue, which greatly limits activities such as FES-assisted walking. It was hypothesized that muscle fatigue caused by FES could be reduced by randomly modulating parameters of the electrical stimulus. Seven paraplegic subjects participated in this study. While subjects were seated, FES was applied to quadriceps and tibialis anterior muscles bilaterally using surface electrodes. The isometric force was measured, and the time for the force to drop by 3 dB (fatigue time) was determined. As well, the force-time integral during this interval was determined. Four trials were performed for each muscle – one with constant stimulation, and three in which one of the following FES parameters were randomly modulated in a range of +/- 15%: frequency, current amplitude, and pulse width. A uniform probability distribution was used in the trials with randomization. There was no significant difference observed between the fatigue time measurements for the four modes of stimulation. There was also no significant difference in the FTI measurements. Therefore, we conclude that random modulation of the stimulation frequency, current amplitude and pulse width have no effect on muscle fatigue.

1 Introduction

A major limitation of FES, particularly surface stimulation modalities, is that muscle fatigue tends to occur far more rapidly than when muscles are undergoing voluntary contraction [1], which limits the role of FES in applications that involve high energy expenditure such as standing and walking. There have been several attempts to reduce the rapid fatigue effects of FES to date. Researchers have introduced techniques aimed at fatigue reduction such as pulse doublets [2,3,4], chronic FES training (muscle conditioning) [5], sequential stimulation of multiple motor points [6], and intermittent high frequency stimulation [7]. Graupe et al. provided some evidence that randomized frequency could reduce muscle fatigue, however this was only demonstrated on a single subject [8]. The present study was designed to build upon this result.

Our goal was to reduce the rate of muscle fatigue by randomly modulating the three main FES parameters: frequency, current amplitude and pulse width. We hypothesized that by randomly modulating these parameters, muscle fatigue would be reduced, because the firing rate and level of recruitment of individual motor units, or groups of motor units, would vary over time. A constantly changing firing rate and level of recruitment could increase the total number of motor units activated, allow motor units brief periods of rest, thus increasing the fatigue resistance during isometric contractions.

2 Methods

Table 1: Subject data

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (yrs)</th>
<th>Level of injury</th>
<th>Injury duration (yrs)</th>
</tr>
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<tr>
<td>1</td>
<td>M</td>
<td>26</td>
<td>T2</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
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<tr>
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<td>M</td>
<td>24</td>
<td>C6</td>
<td>8</td>
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<tr>
<td>4</td>
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<td>M</td>
<td>39</td>
<td>T8</td>
<td>10</td>
</tr>
</tbody>
</table>

Seven subjects participated in this study. Their data is summarized in Table 1. All subjects had spinal cord injuries and no voluntary motor function below the level of injury (class A or B on the ASIA neurological scale). Four of the
subjects were first time FES users, while three of them (1, 5 and 6) had at least three months of previous FES training. All participants signed a consent form approved by the Toronto Rehabilitation Institute Research Ethics Board.

Each subject sat in a neutral position on an apparatus that consisted of a chair and footrest with broad straps to immobilize the pelvis and thighs. Isometric muscle force was measured using a stain gage based, tension/compression pancake load cell (Honeywell Sensotec, Columbus, Ohio, USA – fig. 2D) with a range of -1100 to 1100 N. The load cell was mounted on the base of the apparatus in one of two positions. When knee extension moment was being measured, the load cell was mounted anterior to the subject’s ankle, and a strap connected in series to the load cell was fixed to the ankle. In the second configuration, the load cell was mounted below the foot rest, and the strap was attached to the foot over the metatarsus. The strap was inelastic, and the load cell was thus used to measure isometric knee extension and isometric dorsiflexion moments.

Biphasic, bipolar, current controlled stimulation pulses were administered using a programmable stimulator and self-adhesive surface electrodes (Compex Motion SA, Switzerland). A mean pulse width of 250 µs, and a mean frequency of 40 Hz were used. The current amplitude was set between 34 and 110 mA, depending on each subject and muscle group. Stochastic modulation of the amplitude, frequency and pulse width was achieved using a uniform probability distribution between -15 and +15%. Values for pulse amplitude, width, and frequency were updated every 100 ms.

Each subject performed a total of 16 trials. The muscle groups tested were the left and right quadriceps, and the left and right tibialis anterior muscles. Each muscle was stimulated using four modes: (1) constant stimulation parameters, (2) randomized current amplitude, (3) randomized frequency, and (4) randomized pulse-width. When one parameter was randomized, all others were held constant. The order of trials was randomly determined for each subject. Each muscle was given a ten minute rest between trials, which was considered to be adequate for repeatable results [3][4][9]. The isometric muscle force, frequently used as an indicator of fatigue in previous studies [2][3][9], was measured and recorded during each test over a time period of no more than 90 seconds. The quadriceps and tibialis anterior muscles were selected as the target muscles since they are convenient to stimulate with surface electrodes and easy to measure for force output using a load cell.

Two main indices of muscle fatigue were used in this study: fatigue time and force-time integral (FTI). Fatigue time was defined as the total time from the onset of stimulation until the force decreased to below 70.8% of the maximum force for that trial, equivalent to a drop of 3dB. According to control theory, when the system’s output decreases below -3dB, the system’s performance is severely altered and it cannot be used for practical applications. FTI was defined as the summation of force measurements over the interval in which fatigue time is defined, i.e. from stimulation onset until -3dB time. In this case, larger forces sustained over a longer period of time resulted in a larger FTI value, which has been regarded by others to be the most suitable measure of sustained muscle power and therefore a good measure of resistance to muscular fatigue [3,9].

Since the force-time curves exhibited a great deal of variability, a 22nd order polynomial was fitted to each curve using a least squares algorithm. The polynomial was used to determine the fatigue time and the FTI. To approximate how much the stimulation order biased the results, the stimulation order for each muscle was compared to the order in the magnitude of maximum force, fatigue time, and FTI for each test. Our hypothesis that there will be differences between the four modes of stimulation was tested using a two-factor ANOVA with replication on both outcome measures.

3 Results

![Figure 1: A typical force versus time curve (subject 3’s right tibialis anterior muscle with randomized amplitude stimulation).](image)

Data was collected for all subjects. An example of the type of force-time curves that were
collected is given in Figure 1. There was no significant difference observed between the fatigue time measurements for the four modes of stimulation. There was also no significant difference in the FTI measurements. The mean values yielded from the four different modes of stimulation are shown in Figure 2 (fatigue time) and Figure 3 (FTI).

**Figure 2:** Average fatigue time results for each stimulation mode. No significant difference between modes of stimulation was observed ($p > 0.05$).

**Figure 3:** Average fatigue time interval for each stimulation mode. No significant difference between modes of stimulation was observed ($p > 0.05$).

A post hoc analysis of data revealed that subjects who had previous FES training demonstrated much greater fatigue resistance in the order of about 100% ($p < 0.05$).

### 4 Discussion and Conclusions

None of the randomized stimulation modes resulted in a significant increase in fatigue time or FTI compared to the stimulation with no randomization. Graupe et al. [2] demonstrated similar results.

Isometric muscle force is a critical factor in many FES applications, such as standing and walking, and therefore effort is justified in trying to reduce isometric fatigue. A limitation of isometric force as an index for fatigue is that it cannot be directly compared to dynamic fatigue indexes such as the number of achievable leg lifts. Nor can results from this study be extrapolated to conditions where dynamic muscle force is the most important factor, such as the swing phase of walking. FES induced muscle contractions have been shown to be more prone to fatigue under dynamic conditions than under isometric conditions [30], so there are clear differences in the two mechanisms of fatigue.

### References


### Acknowledgements

This study was funded in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada, and the Canadian Paraplegic Association Ontario (CPA Ontario).