Short-duration FES-induced leg cycling dynamics at different stimulation intensities and flywheel resistances

Faghri PD and **Trumbower RD**

University of Connecticut, Storrs CT

Pouran.Faghri@uconn.edu

Abstract

This study investigated the peak crank power output production during different flywheel resistances and stimulation intensities and their relationship to fatigue rate during short duration functional electrical stimulation leg cycle ergometry (FES-LCE). Six healthy individuals with spinal cord injury (SCI) participated in this study. Subjects pedalled at different maximum allowable stimulation intensities of 70, 105, and 140mA and flywheel resistances of 0/8th, 1/8th, and 2/8th kilopond. The results showed that peak power production was significantly different between three stimulation intensities for each flywheel resistances ($p<0.05$). Mean cycling cadences were also significantly different between three stimulation intensities and flywheel resistances ($p<0.05$). A fatigue index was formulated based on changes in peak crank power output levels during cycling and compared between testing conditions. The level of fatigue was strongly related to flywheel resistance and stimulation intensity ($p<0.01$). The higher fatigue indexes were noted at higher flywheel resistance and during lower stimulation intensities. These finding suggest that to minimize fatigue rate and to optimize power output during steady-state cycling,, increases in stimulation intensity is required. However the current maximum stimulation intensity of 140mA may not be essential in maintaining constant pedalling speed at higher flywheel resistances.

1. INTRODUCTION

Functional electrical stimulation-induced semi-reclined leg cycling (FES-LCE), have been used for cardiovascular exercise in individuals with spinal cord injury (SCI). Although studies have shown improvements in cardiovascular fitness and muscle strength for individual users [1, 2] still the number of individuals using the system is limited. Studies have reported mechanical inefficiencies related to seat configuration as well as inappropriate muscle stimulation timing and duration during cycling as some of the shortcomings for the system.[3, 4]optimization techniques to maximize power output while minimizing muscle stimulation intensity (mechanical efficiency) across a range of cycling cadences have also been reported [5] as a way of increasing user acceptance and performance. However, it is unclear how stimulation patterns and intensities will affect cycling coordination patterns and performance. Identifying a stimulation pattern that provide a balance between the strength required and the muscles recruited is very important in any future improvements of FES-LCE systems.

The purposes of this investigation were to establish a torque profile for FES-induced cycling and examine the effects of different maximal stimulation intensities and flywheel resistance levels on power output and fatigue rate during short-duration (anaerobic) cycling exercise.

2. METHODS

Subjects: Six healthy male individuals with SCI (4 with ASIA score ‘A’ and 2 with ASIA score ‘C’) of 32±12 years of age, 1.75±0.04 m body height, and 79±11 kg body weight participated in the study. All subjects were regular users of FES-LCE (having used the system for least 3 months) and were required to sign an informed consent approved by the University’s Institutional Review Board prior to participation.

Instrumentation: A two-dimensional video-based motion capture system (Peak Performance Technologies Inc., Centennial, CO USA) recorded pedal and crank positions using retro-reflective markers.

A piezoelectric force sensor (Piezoelectronics Inc., USA) was mounted on the bike pedal of an FES-LCE to measure orthogonal (normal and tangent to pedal) pedal forces in the sagittal plane. The out-of-plane force was assumed to be negligible as was found to be the case during upright leg cycling [6] and was therefore not considered.

Protocol: Each subject was fitted with the FES-LCE (ERGYS®, Therapeutic Alliances Inc, Fairborn OH, USA) and seat configuration was adjusted based on anthropometry.

Flywheel resistance of 0/8th, 1/8th, and 2/8th kilopounds (KP) were applied using an internal magnetic brake within the FES-LCE system. Maximum stimulation intensity levels were set at 70mA, 104mA, or 140mA and referred to the highest level of stimulation allowed by the controller during cycling. The FES-LCE feedback controller's target cadence was set at 50rpm for all tests. Levels of flywheel resistance and maximum stimulation intensity were randomly assigned prior to testing. Initially subjects were provided a warm-up of active-assisted FES-induced leg cycling at 50rpm. Following the warm-up, subjects pedalled for 2 minutes at a maximum stimulation level setting of 70mA, 104mA, or 140mA and flywheel resistance of 0/8th, 1/8th, or 2/8th KP. During the 2-minute cycling period, kinematic and kinetic data were collected for 30 seconds. After recording, subjects were given a two-minute cycling cool-down followed by 5 minutes of rest. The test was repeated for each combination of flywheel resistance and maximum stimulation level.

Data Analysis: Crank and pedal displacement as well as velocity were calculated for each crank period. All data recorded at a defined cycling cadence and were expressed as a function of crank arm angle as it rotated in the forward direction from the highest pedal position corresponding to 0º crank position or top-dead-center (TDC) to the lowest pedal position corresponding to 180º or bottom-dead-center (BDC) and back to TDC to complete a full crank cycle.

Pedal force measurements were acquired with a LabVIEW® DAQ board (National Instruments Inc, USA) at a sampling rate of 180samples*s^{-1}. Tangential pedal force and normal pedal force were measured relative to the pedal and then calculated relative to crank orientation. [7] Kinematic and kinetic data were passed through a 5th order, zero lag, Butterworth lowpass digital filter at 10Hz which corresponds to the maximum frequency of normal human movement.

Instantaneous power developed by the crank was calculated as $P = \tau * \dot{\vartheta}$ where τ is the instantaneous crank torque and $\dot{\vartheta}$ is the instantaneous crank velocity. The instantaneous crank torque is related to the measured pedal forces by $\tau = \left(F_x \cos\varphi + F_y \sin\varphi\right) * \ell_{cr}$ where the quantity in parentheses is the component of the pedal force vector normal to the crank and ℓ_{cr} is the crank arm length. Peak power (W) and crank torque (Nm) were calculated for every crank revolution and averaged across subjects.

A fatigue index (FI) similar in form to [8] was used to quantify the extent of decline in power during short-duration leg cycling

$$\text{fatigue index} = \frac{\overline{P}_{initial} - \overline{P}_{final}}{\overline{P}_{initial}} * 100$$

where $\overline{P}_{initial}$ was the average of the first 2 peak power values, which represented the initial observed peak power and $\overline{P}_{final}$ was the average of the last 2 peak power values, which represented the final observed peak power. A positive fatigue index corresponded to decline in average peak crank power.

Statistical analyses were performed using MATLAB® (Mathworks Inc., MA USA). An MANOVA was administered to determine differences in the effects of stimulation intensities on average cycling cadence across flywheel resistance levels. The p-value was set at 0.05. Post-hoc comparisons using Bonferroni corrections were calculated to determine mean pair significance. A non-parametric chi-square analysis was used to determine whether cycling fatigue was influenced by the three maximum stimulation levels and flywheel resistances.

3. RESULTS

Cycling Cadence: The average cycling cadence was computed for each testing conditions. The average cadence for stimulation levels of 70mA, 105mA, and 140mA was 30±3rpm, 44±2rpm, and 48±0.8rpm respectively. Significant differences were found between cycling cadences at 0/8th KP and maximum stimulation levels of 70mA and 105mA ($p<0.01$) and 70mA and 140mA ($p<0.01$). Similar differences were found at 1/8th KP. At 2/8th KP, a significant different was found between 70mA and 140mA ($p<0.05$), but not between 70mA and 105mA.

Peak Power: Peak power increased with increased maximum stimulation levels (133±12W at 70mA, 257±37W at 105mA, and

275±17W at 140mA). Significant differences were found between 70mA and 140mA at 0/8th KP resistance ($p<0.04$). Significant differences were also found between 70mA and 140mA and 70mA and 105mA at 1/8th KP.

Fatigue Index: The number of subjects that presented with increased positive fatigue index values increased with increased maximum stimulation level and flywheel resistance (i.e., 100% of subjects fatigued at 70mA and 2/8th KP). The relationship between cycling fatigue, maximum stimulation level, and flywheel resistance is shown in Figure 1.

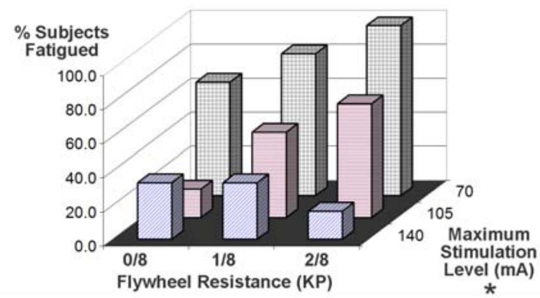

Figure 1. Percentage of subjects that fatigued (positive fatigue index) at different maximum stimulation levels (70mA, 105mA, and 140mA) and flywheel resistances (0/8th, 1/8th, and 2/8th KP). *Chi-square test with aysmptotic singificance at $p < 0.05$.

4. DISCUSSION

The results of this study indicated that peak crank power, average cycling cadence, and fatigue index values were influenced by maximum stimulation level and to a lesser extent flywheel resistance. Maximum stimulation level of 70mA showed the lowest average cycling cadence and largest numbers of fatigue. Over 83% of subjects at 70mA maximum stimulation across all flywheel resistance levels experienced fatigue. It is suspected that at a maximum stimulation of 70mA, the work requirement was compromised by the limited number of muscle fibers recruited as compared with 105mA and 140mA. Although many subjects at the higher stimulation intensities did not utilize the full amount of stimulation offered, their average stimulation level was still greater than 70mA (mean stimulation level = 87mA) with comparable average cadences.

The stimulation pattern that minimizes muscle strength and maximizes the amount of power the muscles can transfer to the crank in a given cycle is considered optimal. An optimal pattern may also increase the total time of stimulation at the lower stimulation amplitude. The results of our study indicated that while relative increases in stimulation intensity contributed to higher muscle force and cycling cadence, the mean stimulation intensity for all combinations was lower than the maximum allowable stimulation intensity used (i.e., 140mA).

Although this study evaluated the effects different stimulation intensities have on short-duration FES-LCE, possible over-stimulation of upper leg muscles and its potential impact on increased fatigue and low performance should be investigated. The high rate of fatigue that occurs during longer duration cycling may contribute to a user's non-compliance and utilization of the system. It is important to determine stimulation patterns that provide balance between the muscle strength required and the muscles recruited. Given that individuals with SCI differ vastly in how they respond to FES, computing user-specific stimulation schemes should be considered in any future development of this system.

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