Relationship between isometric pedal force generation and stimulation intensity of individual leg muscles involved in FES-induced leg cycling

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Abstract

Optimizing power transfer from stimulated muscles during functional electrical stimulation leg cycle ergometry (FES-LCE) and maximizing forward acceleration of the crank during cycling may increase the efficiency of this system for exercise. A better understanding of individual muscles' force generation and their relationship to the intensity of stimulation would help with this optimization. This study evaluated the orthogonal pedal force generations of quadriceps, hamstrings, gluteus, gastrocnemius, and tibialis muscles during three different stimulation intensities (70mA, 105mA, and 140mA) at eight fixed crank positions of an FES-LCE. Seven healthy male individuals with spinal cord injury participated. Significant differences in pedal forces were found between stimulation intensities and crank positions (p<0.05). Pedal forces for each muscle were significantly different between FES intensities of 70mA and 140mA with no differences at 105mA and 140mA. There was a high correlation (r=.936) in the direction and force generated for gastrocnemius and tibialis, as well as hamstrings and gastrocnemius (r=.895) across all crank positions. In conclusion, lowering the stimulation intensity during cycling and sequencing the activation of thigh and leg muscles within a closed-loop system may improve pedal effectiveness and reduce fatigue possibly due to over stimulation.

1. INTRODUCTION

Functional electrical stimulation (FES) leg cycle ergometry (FES-LCE) provides therapeutic exercise for individuals with spinal cord injury (SCI). Although studies have reported the system's physiological benefits,[1, 2] there are also reports of its inefficiency in providing full cardiovascular benefits to individual users.[3, 4]

The FES-LCE uses a closed-loop feedback control that adjusts stimulation amplitude to the quadriceps (QUAD), hamstrings (HAM), and gluteus (GLUT) muscles based on cycling speed.[5] FES amplitude proportionally increases as the cadence decreases up to certain cadence level (35RPM) at which time the system considers the person fatigued and stops stimulation and cycling. Stimulation timing is mainly a function of crank position and consists of stimulation of the QUAD from 308 degrees to 23 degrees, GLUT from 5 degrees to 73 degrees, and HAM from 112 degrees to 171 degrees. Only small adjustments in the stimulation pattern occur as a function of cycling cadence.

Our previous research on able-bodied individuals riding the FES-LCE (with no FES to the muscles) using electromyographical and kinematic evaluations reported the timing and sequencing of activation of thigh and leg leg muscles.[6, 7] The data showed that muscle activation during crank rotation is different than activation of these muscles used with FES-LCE and that lower leg muscles (GAST, TA) are major contributors to cycling. Presently lower leg muscles are not utilized with FES-LCE. However these data did not distinguish individual pedal force contributions of these muscles. Understanding the force production of each muscle and their overall contribution to forward cycling using FES is important to improve the system's efficiency. Therefore, the purpose of this study was to evaluate the individual pedal force contributions of the QUAD, HAM, GLUT, GAST, and TA muscles at different FES intensities along fixed crank positions on an FES-LCE in a group of SCI individuals.

2. METHODS

2.1. Subjects

Seven healthy male individuals with SCI (5 with ASIA score 'A' and 2 with ASIA score 'C') participated in this study (mean age 32±12 years). They were all regular users of FES-LCE (having used the system for least 3 months). All subjects signed an informed consent approved by the University's Institutional Review Board prior to participation.

2.2. Instrumentation

FES was supplied by an external unit (SpectraSTIM 2000, Therapeutic Alliances Inc., Fairborn, OH USA) with a sinusoidal, biphasic waveform, frequency 50Hz, pulse duration 500µs, and phase duration 1000µs. Stimulation amplitudes were 70mA, 105mA, and 140mA (values corresponding to 50, 75, and 100% of maximal stimulation available on the ERGYS bike (Therapeutic Alliances Inc., Fairborn OH USA). Stimulation timing consisted of 2-second ramp-up, 1-second hold, and 2-second ramp-down followed by 10-second rest period. 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 [8] and was therefore not considered.

2.3. Protocol

Each subject was fitted with the FES-LCE (ERGYS) and seat configuration was adjusted based on anthropometry. Surface electrodes were placed superficial to the QUAD, HAM, GLUT, TA, and GAST muscles. The crank position was mechanically locked at 0°, corresponding to the top-dead-center. Stimulation intensity was set at 70mA and pedal forces recorded. The stimulation was then increased to 105mA then 140mA at that same crank location and repeated for each muscle. The increase in stimulation provided acclimation for the muscle that occurs during FES cycling. Muscle testing was randomised to control for order effect. A one-minute rest was provided for each muscle between stimulation intensities. After all muscles were tested, the crank was repositioned clockwise to 45° and testing repeated. Crank repositioning continued at 45° increments to complete a full crank rotation.

2.4. Data Analysis

Normal and tangential pedal force measurements were acquired with a LabVIEW® DAQ board (National Instruments Inc, USA) at a sampling rate of 180 samples*s^{-1}. Data was passed through a 5th order, zero lag, Butterworth lowpass filter at 10Hz which corresponds to the maximum frequency of normal human movement.[9]

A two-way MANOVA was used to examine differences in the effects of stimulation intensities for each muscle on normal and tangential peak forces (F_p) and time to peak forces (T_p) at the eight crank positions. The p-value was set at 0.05. Statistical analyses were performed using MATLAB® (Mathworks Inc., MA USA). Post-hoc comparisons using Bonferroni corrections were calculated to determine mean pair significance. Pearson's correlation analysis evaluated the relationship between muscles groups' pedal forces generated (magnitude and direction) for all stimulation intensities and crank positions.

3. RESULTS

The MANOVA exhibited a significant two-way interaction for normal and tangential pedal forces by stimulation intensity and crank position. Significant differences were found for tangential and normal forces corresponding to 70mA and 140mA of stimulation for all muscle groups. However no significance difference was found between 105mA and 140mA. Overall, the QUAD generated the highest normal and tangential pedal force when compared with other muscle groups (Figures 1 and 2). The strongest correlation occurred between the GAST and TA for normal (r = .936) and tangential (r =.819) pedal force. Strong correlations were also found between the GAST and HAM (r = .818) for tangential and (r = .895) normal pedal forces (Tables 1 and 2).

Table 1. Normal Pedal Force Correlation Matrix

	QUAD	GLUT	TIB	GAST
HAM	-.571	-.336	.811*	.818*
QUAD		.797*	-.583	-.757*
GLUT			-.338	-.507
TA				.936*

*p<0.05

Table 2. Tangential Pedal Force Correlation Matrix

	QUAD	GLUT	TIB	GAST
HAM	-.833*	-.494	.696*	.895*
QUAD		.686*	-.539	-.804*
GLUT			-.536	-.535
TA				.819*

*p<0.05

4. DISCUSSION

The results of this study show significant differences between the magnitudes of pedal forces produced for thigh and leg muscles. The QUAD produced the greatest pedal forces whereas the GAST and TA produced the lowest pedal forces.

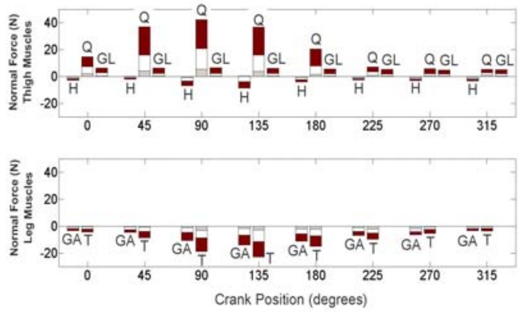

Figure 1. Normal pedal forces during 70mA (grey bar), 105mA (white bar), and 140mA (black bar) stimulation of thigh muscles (Q - QUAD, H - HAM, GL - GLUT) and leg muscles (GA – GAST, T – TA) at eight crank positions.

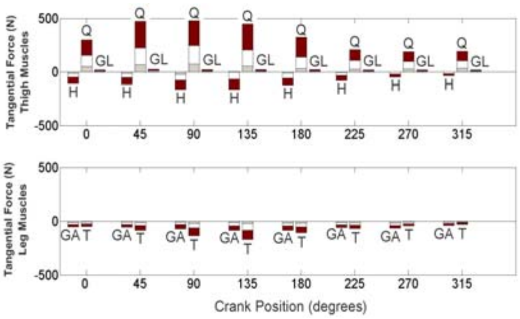

Figure 2. Tangential pedal forces during 70mA (grey bar), 105mA (white bar), and 140mA (black bar) stimulation of thigh muscles (Q - QUAD, H - HAM, GL - GLUT) and leg muscles (GA – GAST, T – TA) at eight crank positions.

No significant difference between 105mA and 140mA was found for the HAM, GLUT, TA, and GAST suggesting that the average maximal strength of these muscles occurred below the maximal stimulation intensity supplied by the FES-LCE. Since the design of the closed-loop feedback control supplies equal stimulation gain to all muscles it is inferred that gains above 105mA for these muscles may provide little or no performance benefit.

A strong correlation between the GAST and HAM suggests that they have synergistic pedal force actions. With this in mind, incorporation of the GAST may be easily done by providing similar stimulation timing as the HAM during FES cycling. Although the magnitude of force produced by the GAST was lower than the HAM, the simultaneous stimulation of these muscles may provide an alternative stimulation scheme that may allow for reduction in stimulation intensities to these muscles and thus reduce the individual muscle workloads while achieving comparable pedaling power.

It should be noted that effective pedal force generation is dependent on the direction of the force that contributes to the forward cycling movement. Thus not all of these muscles should be activated at all times. Based on the correlations found in the magnitude and direction of pedal forces of the thigh and leg muscles, sequencing and timing of stimulation of these muscles is a necessary component of any improvement to a new and effective cycling system. Therefore protocols could be developed and incorporated into the closed-loop system to induce proper activation of the thigh and leg muscles simultaneously. The additional muscles may help in forward power generation and improve the efficacy of the system allowing more people to take advantage of this system.

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