Lower leg joint power output during progressive resistance cycling in SCI subjects: the influence of stimulation intensity

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Abstract

The purpose of this study was to investigate the potential influence of stimulation intensity on joint power output during progressive resistance ergometer cycling. Six spinal cord injured subjects between the ages of twenty and fifty years old, with a complete or incomplete spinal cord injury at or below the fourth cervical vertebra participated in this study. Subjects performed a progressive resistance cycling protocol where resistance was increased by 1/8\(^\text{th}\) kp (6.25W) every two minutes. Kinematic data from the hip, knee and ankle joints, cadence, stimulation intensity and pedal forces were recorded after each resistance adjustment. Ankle, knee and hip power outputs were calculated. The strongest correlation was between stimulation intensity and knee power output. Moderate correlations were observed between 1) stimulation intensity and resistance, 2) stimulation intensity and ankle power output and 3) cadence and stimulation intensity. An observed decrease in ankle power output was attributed to the absence of lower leg stimulation. The increase in stimulation intensity and subsequent decrease in knee power output suggest that the quadriceps and/or hamstrings were experiencing fatigue by 1/8\(^\text{th}\) kp, 3.5 minutes into cycling, consistent with previous findings. Decreased knee power output may be a direct result of the one-size-fits-all stimulation paradigm used.

1 Introduction

Functional electrical stimulation-leg cycle ergometry (FES-LCE) has been considered an effective therapy for spinal cord injured (SCI) individuals. One of the primary objectives for improving FES-LCE is to maximize the subject’s riding time while minimizing the effort needed to pedal. An increased cycling time allows the rider to receive a more effective cardiovascular workout and increase stamina. To do so, it is important to develop protocols that delay the onset of fatigue during FES-LCE in order to maintain pedalling efficiency. Stimulation protocols presently used in FES-LCE may accelerate the onset of fatigue due to their “one size fits all” paradigms. The purpose of this study was to investigate the potential influence of stimulation intensity on joint power output during a progressive cycle ergometry protocol. It was hypothesized that stimulation intensity is associated with premature muscle fatigue and inversely correlates with joint power output.

2 Methods

Six male spinal cord injured subjects (complete and incomplete) with injury at or below the fourth cervical vertebrae and between the ages of twenty and fifty years old participated in this study. The ERGYS I ™ (Therapeutic Alliances®, Inc., Fairborn, OH) semi-reclined cycle ergometer was used. Adhesive reflective markers were placed at the shoulder, hip, knee, ankle, toe, heal, crank tip, tip of the pedal spindle, side of the pedal force transducer and center of the ergometer as a reference for collection of kinematic data. A piezoelectric force transducer (PCB Piezotronics, Inc., NY) was mounted underneath the boot of the right ergometer pedal to record pedal forces in normal and tangential directions with respect to the sagittal plane. Electrical stimulation was applied to the quadriceps, hamstrings and gluteus muscle groups through a feedback loop which aimed to maintain cadence at 50 rpm. Maximum stimulation intensity was 140 mA. Subjects performed a progressive resistance cycling protocol. They were passively pedalled through a 2 minute warm-up, followed by 2 minutes of active cycling at 0/8\(^\text{th}\) kp. Resistance was then increased by 1/8\(^\text{th}\) kp (6.25W) every two minutes. The cycling concluded with 2 minutes of cool down. Kinematic data were recorded continuously
throughout the cycling session and were digitally synchronized with the collected pedal forces. Pedal forces were recorded for 30 seconds, 90 seconds into each resistance adjustment. Blood pressure, pulse oxygen concentration and heart rate were monitored to ensure that the subjects maintained normal metabolic behaviours. Ankle, knee and hip instantaneous joint power output was calculated using the following equation: 

\[ P = M \times \omega \]

where \( P \) is instantaneous power, \( M \) is joint moment and \( \omega \) is joint flexion/extension angular velocity. All calculations were averaged over the last 10 revolutions completed at each resistance level to represent the steady-state values of each parameter of interest. Ergometer cadence and stimulation intensity were also recorded. A Pearson product moment correlation was used to find the association between stimulation intensity, joint power outputs, and cadence. A one-way analysis of variance (ANOVA) was performed in order to evaluate the difference in group means of cadence, stimulation intensity, and joint power outputs with increasing resistance for the subject group as a whole.

### 3 Results

Five of the six participating subjects completed progressive cycling through 2/8\( ^{th} \) kp. Their data were included in the statistical analyses. There were significant negative correlations (\( p<0.05 \)) between stimulation intensity and knee power output (\( r= -0.84 \)), stimulation intensity and resistance (\( r= -0.70 \)), stimulation intensity and ankle power output (\( r= -0.66 \)) and stimulation intensity and cadence (\( r= -0.55 \)). Stimulation intensity and hip power output both increased significantly with increased resistance (\( p<0.01 \)). Mean cadence decreased with increasing resistance. Changes in ankle and knee power outputs were noted with increased resistance. Ankle power output decreased by 2% from 0/8\( ^{th} \) to 1/8\( ^{th} \) kp and 35% from 1/8\( ^{th} \) to 2/8\( ^{th} \) kp. Knee power output decreased by 20% between 0/8\( ^{th} \) to 1/8\( ^{th} \) kp and decreased another 59% between 1/8\( ^{th} \) and 2/8\( ^{th} \) kp. However, these changes were not significant.

### 4 Discussion and Conclusions

The observed decrease in ankle power output with increase resistance may be attributed to the absence of lower leg muscle stimulation. The lack of muscle force generation proximal to the ankle prevents sufficient force production with increased resistance to move the pedal in a forward direction and maintain constant cadence. The increase in stimulation intensity and subsequent decrease in knee power output with increased resistance suggests that the quadriceps and/or hamstrings were possibly experiencing fatigue. This observation is consistent with previous findings [1-3]. The present FES-LCE protocol uses the same timing, duration, and intensity of stimulation for all muscle groups irrespective of their anthropometrics and muscle size (one-size-fits-all stimulation paradigm) in order to maintain cadence during cycling. This protocol may cause muscles to be either under stimulated or over stimulated and therefore may cause premature fatigue.

It should also be noted that during FES-LCE the ankle joints are fixed in boot pedals and the knee joints are constrained by harnesses. Therefore, the leg position during cycling is determined by the crank angle during its rotation. This constraint for ankle and knee joint motion as well as absence of active contraction of the lower limb musculature may cause the low power output in these joints during higher level of resistance.

Another possible explanation for premature fatigue could be due to the reverse stimulation characteristic of FES during FES-LCE cycling in which larger and more proximal muscle fibres are stimulated first. These fibres tend to be more prone to fatigue. As a result, excessive stimulation of these fibres may cause the reduction in joint power production and cadence. [1-4] Studies have found that modulating stimulation patterns and frequencies achieved a higher number of successful isometric contractions at a target force than when constant pulse width-, constant frequency-stimulation was applied. [5-9] The use of higher frequency stimulations has also produced slower fatigue rates in both able-bodied and SCI subjects. [4,10]

In conclusion, to improve cycling performance and prevent premature fatigue, the following options are presented: 1) implementing...
individual stimulation parameters (timing, duration, intensity) for each muscle group, and 2) stimulating lower limb musculature with less constraint of joints motion. However, in releasing the joint constraints the bike has to be modified to allow for uncontrolled leg movement and more complex stimulation patterns.

References


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