Oxygen Cost of Different Stimulation Patterns for FES Cycling

Ferrario C 1, Stone B 1, Hunt KJ 1,3, Ward SA 2, Mclean AN 3, Fraser MH 3

1 Centre for Rehabilitation Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland
2 School of Sport and Exercise Sciences, University of Leeds, Leeds LS2 9JT
3 Queen Elizabeth National Spinal Injuries Unit, Southern General Hospital, Glasgow G51 4TF

Email: c.ferrario@mech.gla.ac.uk
Website: http://fesnet.eng.gla.ac.uk/CRE

Abstract

The aim of this study was to examine the effect of different muscle stimulation paradigms on the oxygen cost of FES cycling. One complete-lesion paraplegic subject participated in the study. A motorised recumbent tricycle was used which was instrumented to provide feedback control of stimulated leg-power output and cycle cadence. Oxygen uptake during constant-power cycling with different stimulation patterns was obtained using realtime breath-by-breath measurement. Significant differences in the oxygen cost of cycling with different patterns were detected, suggesting that oxygen cost measurements may allow discrimination between the efficacy of different muscle activation patterns.

1 Introduction

Lower limb FES-cycling is a well established means of exercise for people with spinal cord injury (SCI), and is associated with a range of physiological benefits [1]. Considerable potential exists for optimisation of stimulation parameters such as muscle-group activation angles, stimulation frequency [2] or inter-pulse intervals. We focus here on selection of activation range, i.e. the parts of the 360 deg crank cycle over which each muscle group is switched on.

Previous studies have attempted to base muscle activation angles for SCI subjects on electromyographic (EMG) data from normal subjects during cycling [3]. Such approaches are limited, however, as normal volitional cycling uses a large number of muscles whose activity is coordinated through central neural control, while FES cycling activates a very limited set of muscle groups which are recruited in a non-physiological manner.

Other groups have attempted to numerically optimise activation angles by maximising a cost function which captures mechanical output forces [4,8]. This approach is based upon a dynamic simulation model of lower-limb cycling, and thus far has not been experimentally verified.

In the present work we experimentally study selection of muscle activation angles using pulmonary oxygen uptake ($V O_2$) as a measure of the oxygen “cost” of exercise. In particular, we set out to determine whether oxygen cost measurements are sensitive enough to allow discrimination between the efficacy of different muscle activation patterns.

2 Methods

Study design is a single-subject case study to determine feasibility of the proposed approach.

2.1 Subjects

One complete-lesion paraplegic subject (ASIA A, level T10) participated in the study. At the time of the study he was 59 years old and 5 years post injury. He had been participating in an FES cycle training programme (up to one hour, once per week) for more than two years before joining this study. All procedures were approved by the Southern General Hospital ethics committee, and the subject provided informed consent prior to participation.

2.2 Apparatus

We utilised a recumbent tricycle, adapted for paraplegic FES-cycling and arranged for static ergometry using an electronically-controlled load. The tricycle is equipped with an electric motor, connected through gearing to the rear drive wheel, and coupled to the cranks at the front of the tricycle. A shaft encoder provides continuous measurement of crank angle and cadence, while a sensor integrated in the crank measures the subject’s stimulation-induced leg power. The system is interfaced to a PC which provides realtime feedback control of cycling.
cadence (via the motor) and of leg power (via automatic adjustment of stimulation intensity). Technical details are described fully in [5].

2.3 Stimulation parameters

Pairs of surface electrodes are attached to the quadriceps, hamstring and gluteal muscle groups. The current for each channel is individually adjusted (in 10 mA increments, up to a maximum of 120 mA) and then fixed during cycling sessions. Stimulation frequency is 20 Hz, while the stimulation pulsewidth is automatically varied by feedback during cycling (range 0 – 700 µs) in order to achieve a pre-specified exercise workrate (i.e. leg power output).

2.4 Evaluation protocol

Each muscle group is automatically activated during the 360 deg crank cycle using the continuous crank angle measurement (schematically illustrated in figure 1). Thus, the “on” angles for the Quadriceps and Hamstring muscles in P2 were each extended by 30 deg with respect to P1.

Figure 1: Stimulation patterns: QR – Quadriceps right, HR - Hamstring right; GR - Gluteus right. Zero degrees position is the horizontal position of the crank, with the foot close to the body.

Table 1: Stimulation patterns for the three groups of muscles.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Quadriceps</th>
<th>Hamstring</th>
<th>Gluteus</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>55°-155°</td>
<td>168°-245°</td>
<td>90°-180°</td>
</tr>
<tr>
<td>P2</td>
<td>40°-170°</td>
<td>153°-260°</td>
<td>90°-180°</td>
</tr>
</tbody>
</table>

Table 2: VO2 values averaged over the last minute of each interval (l/min).

<table>
<thead>
<tr>
<th>Order</th>
<th>1-2-1-2</th>
<th>1-2-1-2</th>
<th>2-1-2-1</th>
<th>2-1-2-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>0.27</td>
<td>0.28</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>Passive</td>
<td>0.24</td>
<td>0.28</td>
<td>0.23</td>
<td>0.30</td>
</tr>
<tr>
<td>0W</td>
<td>0.33(P1)</td>
<td>0.41(P1)</td>
<td>0.34(P2)</td>
<td>0.52(P2)</td>
</tr>
<tr>
<td>Stage1</td>
<td>0.57(P1)</td>
<td>0.55(P1)</td>
<td>0.57(P2)</td>
<td>0.65(P2)</td>
</tr>
<tr>
<td>Stage2</td>
<td>0.65(P2)</td>
<td>0.59(P2)</td>
<td>0.54(P1)</td>
<td>0.58(P1)</td>
</tr>
<tr>
<td>Stage 3</td>
<td>0.63(P1)</td>
<td>0.55(P1)</td>
<td>0.56(P2)</td>
<td>0.56(P2)</td>
</tr>
<tr>
<td>Stage 4</td>
<td>0.61(P2)</td>
<td>0.53(P1)</td>
<td>0.55(P1)</td>
<td></td>
</tr>
</tbody>
</table>

Mean values for the eight presentations of P1 and seven presentations of P2 were 0.56 +/- 0.03 and 0.60 +/- 0.04 (l/min, mean +/- sd), respectively.
After removal of resting baselines, the oxygen cost of P1 is 0.28 +/- 0.04 and that of P2 is 0.31 +/- 0.05. The absolute and relative cost values for P1 and P2 are plotted in figure 2. The mean values for P2 were found to be significantly greater than those for P1, with p<0.05.

4 Discussion and Conclusions

Our preliminary observations suggest that oxygen cost of constant-power FES cycling can be appreciably influenced by the muscle stimulation paradigm employed and that oxygen cost measurements may provide sufficient discriminatory power to allow assessment of different muscle stimulation patterns during FES-cycling exercise.

However, a limitation of these experiments is the overall length of time required for evaluation. It is known that SCI subjects typically have prolonged VO₂ kinetics [6]. Ideally, therefore, we would have wished to have continued each phase until a true steady state had been attained, i.e. likely more than 6 min. We elected to approximate the steady state as the shorter phase periods allowed us to introduce a greater number of repetitions within a given 24-min period.

The requirement for test repetition is dictated by the relatively high levels of noise which characterise breath-by-breath gas exchange measurements. Repeat tests are required to obtain response averages for improved signal-to-noise ratio and therefore improved discriminability of response differences.

The responses reported here suggest that exercise with pattern P2 is significantly less efficient than with P1. This might be a result of P2 having much wider stimulation angles, and therefore larger areas of the crank cycle where muscle force is less effectively translated into work-producing torque (i.e. due to a reduced moment arm). Differences in efficiency may also, in part, reflect differences in muscle-type recruitment profile; i.e. exercise with P2 may rely on a greater contribution of fast-twitch Type II muscle fibres with lower aerobic efficiency [7].

In summary, these results raise the possibility that oxygen cost measurements may allow discrimination between the efficacy of different muscle activation patterns. However, further work is required to determine if the findings are typical for the SCI population, and whether the oxygen cost of exercise can be correlated with more easily determined indices of cycling efficiency, such as the cost in terms of the applied rate of stimulation charge (and therefore the overall intensity of muscle activation).

References


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