Abstract

Functional electrical stimulation (FES) rowing is a form of hybrid physical exercise for individuals with spinal cord injury (SCI). In the present implementation, a modified Concept 2 indoor rowing ergometer has been instrumented to record biomechanical data. FES is manually controlled using a momentary action switch mounted onto the handle.

Preliminary results are presented for an expert paraplegic FES rower who has since 2004 competed successfully in major indoor rowing championships.

The kinematics of FES rowing reveal a faster stroke rate and shorter stroke length than normal. This is associated with restricted trunk motion, which is probably less efficient than normal rowing. The temporal pattern of control switch operation indicates a honed motor skill in which the rower continuously predict the system dynamics and muscle responses and switches with a surprisingly high consistency typically within +/- 30ms. This suggests that the control of FES rowing, once learned, is performed with minimal cortical load.

1 Introduction

The ability to redirect or switch our attention between competing inputs is a key component of cognitive functioning. The study of human ability to engage in more than one activity at the same time always has been of great interest for human-machine interface design [1].

Functional electrical stimulation (FES), when combined with locomotive assistive apparatus, is gaining significance in rehabilitation therapy aimed at reducing the risks of secondary conditions in neurological disorders.

FES rowing was originally proposed as an alternative form of total body exercise for paraplegics to increase fitness and reduce the risks of cardiovascular disease and diabetes [2]. It has since been developed to a stage where teams of paraplegic and quadriplegic SCI rowers regularly compete in national and international indoor competitions. FES indoor rowing may also have a role in the cross-training of elite paraplegic athletes.

http://news.bbc.co.uk/sport1/hi/other_sports/disability_sport/7068019.stm  FES sculling on-water has also been successfully demonstrated [3]. FES rowing potentially offers a unique high intensity cardiovascular exercise with low impact on the upper limbs where evidence for its effectiveness is emerging [4, 5].

Rowing is dependent on strength, endurance and technique. The latter represents a highly sophisticated learned motor skill, involving multiple factors interacting simultaneously. Achieving consistency in co-ordinating the upper limb voluntary movements with the electrically induced motion of the paralyzed lower limbs is dependent on the learned knowledge of process. The phases of a complete FES-rowing cycle are described in [6].

FES rowers are initially instructed in the basic actions by an investigator/coach. Those who compete have increased their performance largely by themselves, developing individual styles through practice spurred on by competition. Presently, there is only scant, mainly intuitive, knowledge on which to base principles for coaching the elite FES rower. In particular there is little experimental biomechanical data. In this paper we present preliminary data related to the control strategy adopted by one elite FES rower.

2 Methods

The subject is RG who presently holds the record in the British Indoor Rowing Championships for the FES 2,000 since 2004 www.FESrowing.org. RG is a male paraplegic (age = 52yr, bodyweight = 70kg, injury level = T4/ASIA A, time since injury = 6yr, total FES rowing raining = 4yr).

Figure 1: Paraplegic rower, RG, is getting a full-body workout on the FES-rowing machine.
A modified Concept 2 model D indoor rowing machine was used (Figure 2). Trunk motion was prevented using a rigid seat back and shoulder straps. Leg motion was constrained to the sagittal plane by a telescopic mechanism. Compression spring shock absorbers were fitted to the track to limit seat movement, dampen impact and protect knee joint against hyperextension injury, and to assist in energy transfer from one phase to another [4, 6].

A manually operated, momentary action, push switch, mounted on the handle grip, was used to control 4-channels of electrical stimulation. The latter was applied to the rower’s leg muscles using surface electrodes (Pals+, Axelgaard Inc. USA). The stimulus current pulses were monophasic, charge balanced, current up to 100mA and delivered to quadriceps and hamstrings muscles.

When the control switch is pressed, during the “Drive” phase, the stimulator bi-laterally activates the quadriceps causing leg extension. Similarly, when the control switch is released, to enter the “Recovery” phase, stimulation is applied to the hamstrings and removed from quadriceps causing both legs to flex.

String type potentiometer sensors were used to provide seat and handle position data. A National Instruments (type NI USB-6008 12) bit data acquisition unit, in conjunction with a PC running custom software developed in LabVIEW, simultaneously records seat and handle data together with the state of the control switch. Seat and handle velocity and acceleration values were estimated from position data using a Savitzky-Golay differentiating filter.

3 Results and Discussion

Phase plots of fore and aft velocity-displacement for the handle and seat respectively over 10 complete rowing cycles are shown in Figures 3 and 5.

In figure 4 and 5 it can be seen that the rower anticipates the inertial system dynamics and the delays in muscle force build-up. For example, the quadriceps stimulation begins during the recovery phase before the “Catch” position has been reached, and ends before the “Finish” position is reached. RG is shown on his adapted rower in figure 1. This has been a learned skill. Initially in 2003, when RG started FES rowing, the investigators suggested to him to start quadriceps stimulation immediately following catch and switch over at finish. This was based on intuition, however, after only a few initial training sessions the rower was free to develop his own style, illustrated in figures 4 & 5, with much improved performance. This illustrates the ability of the rower to self-adapt and optimise the limited control possibilities.

In figure 4 the seat acceleration against seat position has shown the system is experiencing a maximum of 400 cm/sec^2 catch braking acceleration which is progressively decreasing during drive reaching a peak minimum of -800 cm/sec^2 whilst reversing its movement’s direction.
Figure 5: Seat velocity against seat position.

Table 1: Mean time taken and standard deviation of rowing phases.

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<tr>
<th>Phase</th>
<th>Mean Time</th>
<th>Standard Deviation</th>
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<tbody>
<tr>
<td>Drive</td>
<td>0.811 sec</td>
<td>0.0301</td>
</tr>
<tr>
<td>Recovery</td>
<td>0.481 sec</td>
<td>0.0296</td>
</tr>
</tbody>
</table>

It can be seen that the rower switches at regular points on the cycle with surprisingly high precision of approximately +/- 30ms. This suggests a sub-cortical control. Anecdotally the rower indicates that he no longer thinks about pressing and releasing the switch, whereas in the beginning he had to concentrate hard to get a smooth rowing motion. The velocity curves are smooth with no sudden zeros.

It can be seen from figure 3 that the stroke length, max – min handle position, is approximately 83cm. This is somewhat shorter than normal (typically 1.4). From table 1 the stroke rate is approximately 46 per minute which is faster than normal (typically 18-36). The high rate and short stroke we associate with the fact that the trunk does not move.

4 Summary /Conclusions

The subject appears to use anticipatory control, a learned skill in which the subject continuously predicts the system dynamics and state of fatigue of the stimulated muscle. This appears to be a sub-cortical activity. The legs extend under load applied via the handle. In each stroke the rower loads the legs through the handle force to control the speed of the drive. If too much handle force is applied against the stimulated quadriceps the motion will be sluggish or may stall. As the quadriceps strengthens with use, the rower will impose increasing levels of handle force to regulate the motion. Thus the quadriceps always works under maximal loading. Furthermore, FES activation of quadriceps during late “recovery” will first cause an eccentric contraction (where the quadriceps are lengthening whilst contracting and act like springs) to decelerate the forward motion, then concentric contraction during “drive”. Eccentric force actions will generally involve greater force actions than concentric contractions for the same FES stimulus intensity. This pattern of loading may have implications in training the quadriceps muscle properties and may explain long term changes (>1 yr) we have observed.

Further developments aimed at normalizing the fast stroke rate and short stroke length are underway that may offer further gains in performance.

Acknowledgement

The authors gratefully acknowledge the support of: The Henry Smith Charity UK and The EPSRC UK.

References