MANUAL CONTROL OF 4ch FES ROWING

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Abstract

FES rowing is a new form of high-intensity, whole body, physical exercise for individuals with spinal cord injury. Preliminary results are presented for RG, co-author and trained paraplegic FES rower. RG has regularly used FES rowing since 2003 and has competed successfully in major international indoor rowing championships, including.

The kinematic analysis reveals a faster stroke rate and shorter stroke length than normal. This is associated with the absence of sagittal trunk motion due to the method of trunk stabilization used in this simple configuration. The temporal pattern of the handle control switch indicates a well-honed motor skill in which the rower is continuously predicting the system dynamics and muscle responses. The control switching points occur with surprisingly high synchronization with the rowing cycle, typically within +/- 30ms. This suggests that the control of FES rowing, once learned, can be performed with minimal cortical load.

Switching for drive begins during recovery, thus the quadriceps are eccentrically active and highly loaded during the early drive phase. Handle forces exceeded 350N and may result in significant joint loading. For example, RG has had a 14.7% increase in BMD associated with FES rowing.

Introduction

FES rowing has been proposed as an alternative form of whole-body physical exercise for paraplegics to increase fitness [1].

http://news.bbc.co.uk/sport1/hi/other_sports/disability_sport/7068019.stm FES sculling on-water has been demonstrated [2] and evidence for its effectiveness is emerging [3, 4].

Rowing is a 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 the FES-rowing cycle are described in [5].

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 experienced FES rower (RG).

Methods

RG has rowed competitively and holds Gold and Silver medals from the British Indoor Rowing Championships for the FES 2,000m www.FESrowing.org RG (male, age = 53yr, bodyweight = 74kg, injury level = T4 ASIA(A), time since injury = 6yr, FES rowing training + 4yr).

Fig. 1: RG, using the FES-rowing machine.

A Concept2 model D indoor rowing ergometer was adapted as shown in Fig. 2. Motion of the trunk was prevented using a fixed seat back with padded shoulder straps. Leg motion was constrained to the sagittal plane by a telescopic mechanism attached to the legs with Velcro straps. Compression spring shock absorbers/stops were attached to the monorail 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, 5].

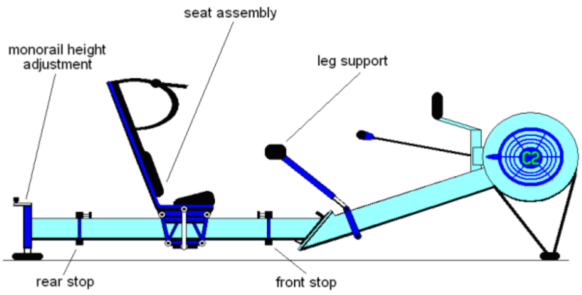

Fig 2: Schematic of the adapted Concept2 ergometer

A thumb operated momentary action, push switch, mounted on the handle grip, and was used to control a 4-channel electrical stimulator Odstock Medical

www.odstockmedical.com/products/odstock-4-channel-stimulator-kit Surface electrodes (Pals+, Axelgaard Inc. USA). The stimulus current pulses were monophasic, charge balanced, current up to 100mA 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 digital differentiating filter.

Results and Discussion

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

In figures 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 handle force against handle position has shown the rower is able to apply a maximum of 340N pulling force to the handle (typically 400-600N for normal individuals) which is progressively decreasing onward reaching a peak minimum of 20N whilst reversing its movement's direction.

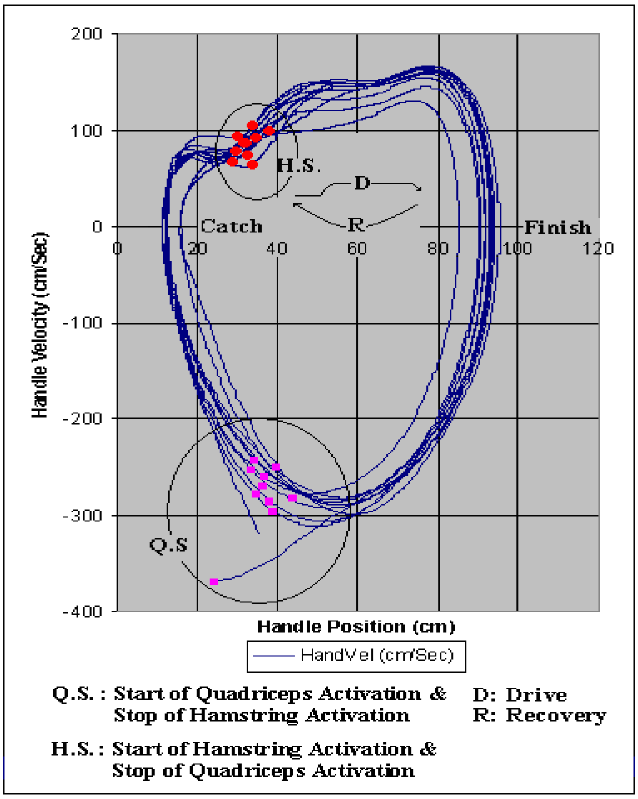

Fig. 3: Handle velocity against handle position.

It can be seen that the rower switches at regular points in the rowing cycle with surprisingly high precision, approximately +/- 30ms. This suggests a learned task with sub-cortical control. RG 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.

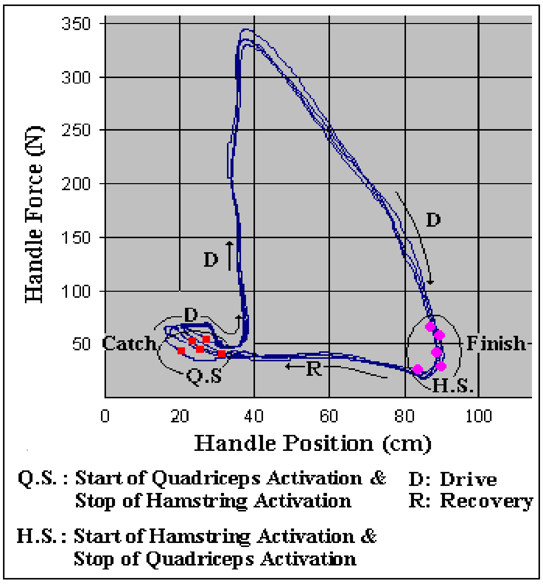

Fig. 4: Handle force against handle position.

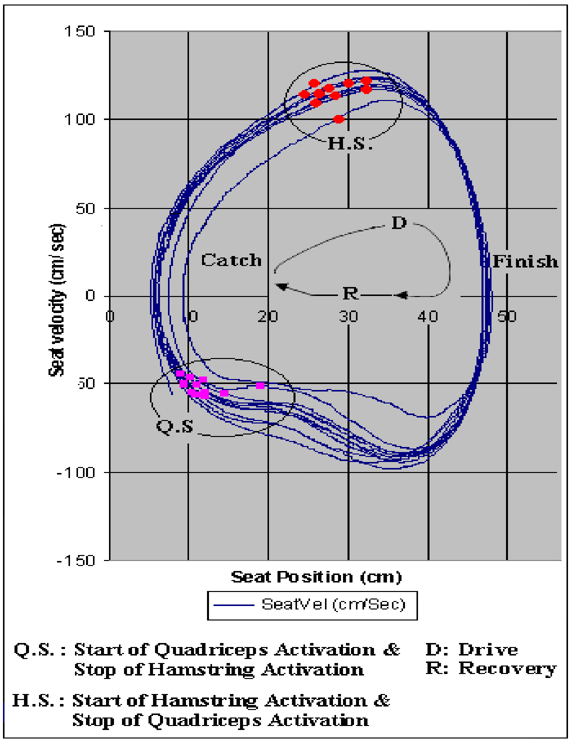

Fig. 5: Seat velocity v seat position.

Table 1: Timing of the rowing phases.

Phase	Mean Time	Standard Deviation
Drive	0.811 sec	0.0301
Recovery	0.481 sec	0.0296

This is somewhat shorter than normal (typically 1.1-1.4 m). From table 1 the stroke rate is approximately 46 per minute which is faster than normal (typically 18-36). The high stroke rate and short length is expected since the trunk does not move.

Summary /Conclusions

RG 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 the long term changes (>1 yr) that we have observed. Handle loads were about half those of elite able-bodied rowers – this may result in significant loading of the long bones - in elite rowing joint contact forces range between 3 and 9 times body weight. This may explain the increased BMD seen in FES rowers, for example RG has had a 14.7% increase in BMD (DEXA) left neck of femur and now has 0.782 g/cm^2 (95% confidence level).

Acknowledgement

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