

MANUAL AND AUTOMATIC CONTROL OF FES-ASSISTED INDOOR ROWING EXERCISE

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Abstract: An indoor rowing exercise system has been developed for paraplegics in which voluntary upper body movements are combined with electrically stimulated movements of the paralyzed leg muscles for total body exercise. Manual and automatic functional electrical stimulation (FES) control strategies have been used to control the stimulation intensities and coordinate the voluntary and FES generated movements. In manual control, voluntary button presses control the timing of stimulation while in automatic control a two-level hierarchical controller manages the movement coordination and stimulation delivery to the paralyzed muscles. Paraplegic volunteers found both controllers intuitive and easy to use. Automatic control spends more electrical stimulation per rowing cycle but it is more convenient and natural to use, continuous concentration on the movement and repeated thumb presses are not necessary, and it extends the user base of the FES rowing to paraplegics with higher level injury who can not press on the buttons but can pull/push the handlebar.

I. INTRODUCTION

To increase the cardiovascular fitness of people with spinal cord injury who because of a sedentary life style and loss of voluntary muscle mass are at increased risk for cardiovascular disease and mortality [1], hybrid exercise systems have been developed to combine the voluntary exercise of the upper body with FES exercise of the lower extremity (e.g. [2]). As an alternative to the existing unnatural, expensive, and clinic-based hybrid exercise systems, we have adapted Concept 2 (Concept 2 Inc., USA) indoor rowing machine for FES rowing exercise [3]. FES rowing is performed by the voluntary movements of the upper body that must be coordinated with the FES generated movements of the paralyzed legs. Here we describe two coordination strategies including manual and automatic control and compare their performance in a pilot study.

II. METHODS

The Concept 2 indoor rowing machine was modified to provide better trunk support, constrain the motion of legs to sagittal plane, and protect the knee joints against impact [3] (Fig. 1). It has two sensors to measure the positions of seat and handle and two control buttons which the user can press to deliver electrical stimulation through four channels of stimulation to quadriceps and hamstrings in both legs. The monophasic stimulation pulses are current regulated at 120mA with 20Hz frequency and variable pulse within 0–500 μ s.

An FES rowing cycle is composed of several phases that must be performed in an orderly manner (Fig. 2). In

manual control system, the user voluntarily performs the upper body part of the rowing maneuver and at the same time presses on the two control buttons on the handle to time the delivery of maximum constant-level stimulation to the quadriceps (in Drive and Handle Pull) and hamstrings (in Recovery) to coordinate the rowing maneuver. In automatic control system, the user voluntarily performs the upper body part of the maneuver and FES controller automatically performs the lower extremity part of the maneuver. Automatic control has two levels of hierarchy. The high-level controller applies a set of rules to the instantaneous positions of the seat and handle to identify the current phase of the motion and dispatch the appropriate low-level controller to execute that phase of motion. The low-level controller in turn applies maximum constant-level stimulation to the quadriceps (in Drive and Handle Pull) and hamstrings (in Recovery).

In a pilot study a paraplegic volunteer who was 51 years old, 70.7 kg, T4 complete, and 31 years after injury tested the two control systems. He gave informed consent prior to taking part in the investigation.

III. RESULTS

FES rowing exercise with both controllers was intuitive and the paraplegic volunteer quickly learned to row in coordinated manner. According to the client, rowing with automatic control was more convenient and easier than rowing with the manual control system. Two typical cycles of rowing by two FES control strategies are shown in Fig. 3.



Fig. 1. Modified Concept 2™ for FES rowing exercise.

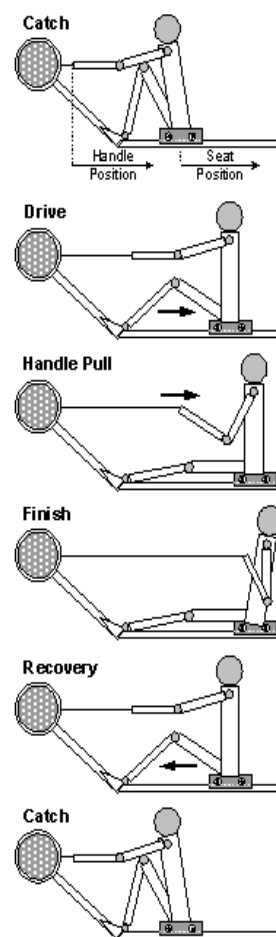


Fig. 2. Different phases of a complete FES rowing cycle.

Statistics of two-minute continuous rowing is shown in Table 1.

IV. DISCUSSION

Smooth and orderly phase-to-phase and cycle-to-cycle transitions are essential for successful rowing exercise, which must be achieved by delicate coordination of voluntary and FES movements. In manual control, coordination is achieved by the user's central nervous system, which has to voluntarily make decisions to repeatedly press on the control buttons. This control system is intuitive and easy to use. It is also easy to implement because it does not require feedback sensors and sophisticated FES controllers. Further, the user can learn the appropriate timing of the stimulation to save the muscle energy, which could delay the onset of fatigue and increase the duration of rowing exercise. The manual control however requires active concentration of the user to maintain coordination and repeated thumb presses on the control buttons are inconvenient to some users.

These problems are eliminated in the automatic control, which, as the result, is easier to use by the paraplegic clients. Automatic control also extends the user base of the FES rowing to those with affected hand because it does not require repeated thumb presses on the control buttons.

In this study, the lower level automatic controller simply applies maximal constant-level stimulation to the muscles and does not try to adjust the level of stimulation intensity. As the result, the total stimulation per rowing cycle is higher than the manual control, which could reduce the rowing exercise duration before the onset of fatigue. More sophisticated closed-loop lower-level controllers are planned to continuously adjust the stimulation level according to the position and velocity of the seat motion. Such closed-loop controllers are expected to reduce the total stimulation per rowing cycle and provide better control over the rowing maneuver.

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Table 1. Statistics of two-minute continuous rowing by manual and automatic FES controllers.

	Manual Control	Automatic Control
Mean rowing speed (stroke/min)	26.3	28.0
Max seat range of motion (cm)	33.6	29.5
Max handle range of motion (cm)	81.6	75.1
Max seat Drive velocity (cm/s)	85.5	73.1
Max seat Recovery velocity (cm/s)	62.4	54.2
Max handle Pull velocity (cm/s)	105.4	105.8
Max handle Release velocity (cm/s)	183.8	158.8
Mean Quadriceps On time (%)	51.6	52.1
Mean Hamstrings On time (%)	17.6	47.9
Mean all muscles Off time (%)	30.8	0.0
Mean Quad stimulation / stroke (μs)	2838.1	2687.6
Mean Ham stimulation / stroke (μs)	980.8	2476.3

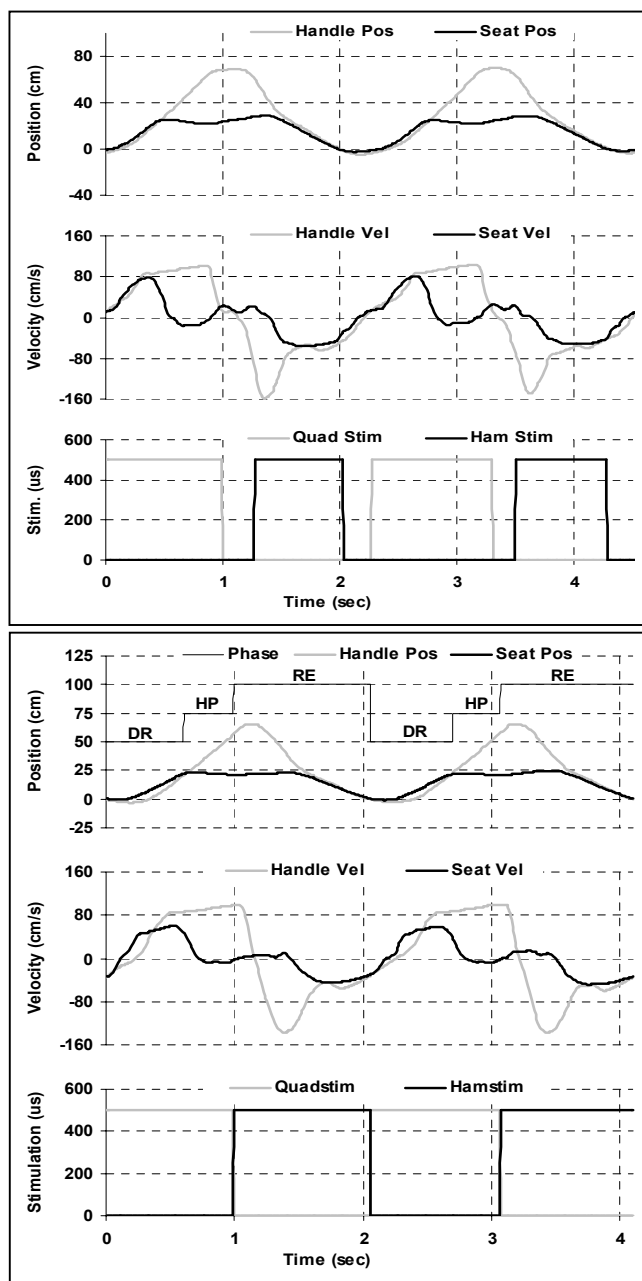


Fig. 3. Two typical cycles of rowing by manual (top) and automatic (bottom) FES controllers. DR – Drive, HP – Handle Pull, RE - Recovery