Development of a Sliding Stretcher FES-Rowing System

Ektas N1, Yusoff NM2, Smith R1, Halaki M1, Hamzaid NA2, Hasnan N3, Davis GM1, 2

1 Discipline of Exercise and Sport Science, Faculty of Health Sciences, University of Sydney, Australia
Email: nalan.ektas@sydney.edu.au
2 Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Malaysia
3 Department of Rehabilitation Medicine, Faculty of Medicine, University of Malaya, Malaysia

Abstract—FES rowing is a complete whole body exercise that has potential to provide aerobic and muscle training benefits for individuals with SCI. Current FES rowing systems comprise ‘fixed’ stretcher designs whereby the disabled rower moves their seated body mass over a sliding bar while the foot stretcher remains fixed. The present work describes the development of an alternate ergometer design for FES rowing, consisting of a sliding foot stretcher and fixed seat system. The FES rowing system prototype described has potential to provide alternative and new exercise opportunities for individuals with SCI.

Index Terms – Functional Electrical Stimulation, exercise, rowing, spinal cord injury

I. INTRODUCTION

Spinal cord injury (SCI) and paralysis of the lower limbs can have a devastating impact on the health and well-being of an individual. The trauma often leads to secondary health complications due to their physical deconditioning from the sedentary lifestyle associated with wheelchair confinement. As a result, increasing leisure-time physical activity and/or structured exercise becomes an important intervention for maintaining health, and limiting the impact of secondary health complications in individuals with SCI [1], [2].

Over several decades, Functional Electrical Stimulation (FES) technologies have been deployed during SCI rehabilitation to promote exercise for individuals with muscle paralysis/paresis, who otherwise have limited options for dynamic lower limb exercise. When combined with simultaneous upper body exercise (termed ‘hybrid’ exercise), arm+FES-leg exercise is able to elicit greater cardiorespiratory responses through the ability to attain higher levels of exercise intensity and greater muscle volume activation [3], [4]. More recently, prototype FES rowing systems have been developed as a hybrid exercise modality. Pilot studies have indicated that FES rowing is safe and well tolerated in the SCI population [5], and can provide superior aerobic training when compared to upper body exercise or FES cycling performed alone [4], [6].

Current FES rowing systems are commonly based on the Concept™ 2 rowing ergometer or similar, where the rower pushes against a fixed foot stretcher and slides their body up and down a rail. While such prototypes have demonstrated the feasibility of FES rowing as an exercise modality for SCI individuals, issues such as early muscle fatigue [7] and a limited ability to generate forces at the handle and foot stretcher [8] have been reported as constraining factors inherent in current “fixed stretcher” FES rowing systems. Biomechanical evaluations of FES rowing are still in the early stages [9], however research using able-bodied participants have determined larger force production and reduced mechanical efficiency with fixed stretcher rowing ergometers [10]-[12], thus warranting further investigation into alternative types of ergometer designs for FES rowing.

The present work describes the development of a prototype FES rowing system consisting of a sliding foot stretcher and flywheel unit. This device could offer an alternative exercise modality for individuals affected by SCI or other neurodegenerative / neuromuscular conditions, facilitating medium-to-high intensity workouts for cardiorespiratory fitness and muscle conditioning.

II. METHODS

A. Design Concept

We have developed an indoor FES rowing system with a fixed seat and floating foot stretcher as the basis for the design. To achieve this, we integrated an adapted Rowperfect Indoor Sculler (Rowperfect PL, Australia) with a neuromuscular electrical stimulator, and developed the necessary software control system to enable a coordinated rowing movement.

B. Modifications to Standard Rowing Ergometer

The RowPerfect is a commercially available rowing ergometer which consists of both a floating seat and floating foot stretcher / flywheel unit. To support the usability of the device as an exercise system for SCI rehabilitation, we have constructed design and technical adaptations to facilitate safety and ease of transfer. The floating seat was replaced by a fixed seating system with an adjustable frame (Fitness Frame II, Equal Adventure, UK) and high back, low pressure seat. A harness was attached for additional trunk support for the disabled rower. A telescopic calf restraint was fitted to the stretcher to prevent abduction of the legs and to constrain the motion of the legs in the sagittal plane. Safety stops were
assembled on the railing to prevent hyperextension of the knee joint.

C. Sensory System

To facilitate capture of mechanical data to quantify the kinematics and mechanical power output during rowing exercise, a sensor system was also integrated and collected using a compact data acquisition device (CompactDAQ, National Instruments Corp., Austin, TX, USA).

A custom designed foot stretcher (Luescher Teknik Specialist Sports Technology, Melbourne, Australia) was instrumented with force transducers (9251, Kistler Instrument Corp., AG Winterthur, Switzerland) to capture three dimensional forces and centre of pressure on the stretcher. Forces on the handle were measured using a uni-directional transducer (TTL-500, Transducer Techniques Inc., CA, USA).

The stretcher and handle were instrumented with precision potentiometers (10kΩ, Bourns Inc., USA) to determine the displacement of the upper and lower body.

Momentary switches were mounted onto the handle to enable the rower to initiate and control the stimulation timing.

D. Control System and Muscle Stimulation

A manual control system was implemented and controlled using a laptop computer via a custom designed user interface. An 8-channel muscle stimulator (RehaStim™, Hasomed GmbH, Magdeburg, Germany) was used to provide bilateral stimulation to the knee flexor or extensor muscles via surface electrodes on the hamstring, and quadriceps plus gluteal muscle groups respectively, by pressing the appropriate switch on the handle.

III. RESULTS

A single able-bodied individual trialled the prototype ‘hybrid’ FES-rowing system as in Figure 1. The subject rowed at approximately 16-17 strokes•min⁻¹, while kinematic and kinetic data was acquired. The FES stimulation parameters were 30Hz, 150µs pulse duration at up to 40mA per channel, which were FES characteristics well-tolerated by the able-bodied participant.

IV. DISCUSSION

The present investigation described the development of a hybrid FES rowing system that integrated a commercial rowing ergometer modified for people with trunk and lower limb paralysis/paresis, with a neuromuscular electrical stimulator, PC software control and sensor system.

Figure 2 portrays handle and stretcher displacements during hybrid rowing for an able-bodied subject. The developed sensory and data acquisition system allows kinematic and kinetic data to be recorded in real time, thus enabling the usability of the system as an exercise ergometer which could also accurately quantify the arm and leg mechanical power outputs during a rowing stroke. Since arm+trunk forces and leg forces can be separately quantified, this system might be deployed in a rehabilitation setting to devise unique training paradigms for neurotrauma or neurodegenerative patients such as high-intensity interlude training (HIIT) or ‘paced’ exercise programs.

The switches mounted on the handle and custom user interface facilitate manual (‘open loop’) control of the rowing motion, whereby the rower can press and hold down one
switch to activate bi-lateral knee extensors, and press and hold down the other switch down to activate bi-lateral knee flexors, as shown in Figure 2. Using this command-and-control strategy, the rower was able to self-regulate the stimulation timing, and hence his/her individualized stroke rate. We are currently investigating this control method in pilot studies using volunteers with SCI. Development of an automatic state controller to regulate the timing of the applied neuromuscular stimulation to the lower-limbs is also currently underway.

In the present implementation, the stimulation current amplitude was controlled by the researchers via the control program interface, however we are also developing alternate mechanisms which may delay the onset of muscle fatigue through pre-programmed protocols where the stimulation level is increased over time based on a specified time constant, or by using automatic controllers which auto adjust the stimulation level based on rowing performance. We anticipate these strategies may delay the onset of muscle fatigue by conserving the level of stimulation current applied to the muscles when are still “fresh”, for example at the start of the rowing exercise session, and increasing to higher stimulation levels when the muscles appear to fatiguing as indicated by a reduction in power output. Whether prescient leg muscle fatigue during hybrid rowing is better ameliorated by pre-programmed neuromuscular stimulation strategies (e.g. “train the machine”) or by novel paradigms of physical training (e.g. “train the human”), or both in combination, is a future research area of high interest to us.

Previously-described FES rowing systems have comprised fixed stretcher designs and sliding seats similar to an on-water rowing shell. However, prior investigations on rowing ergometer design with able-bodied individuals have observed reduced mechanical efficiencies of effort when rowing using fixed-stretcher ergometers, due to the necessity to accelerate and decelerate the body as it slid up and down the rail. These muscle acceleration and deceleration forces are absorbed within the soft tissues resulting in risk of tissue injury. These are important implications in a population of individuals with long-standing muscle atrophy, such as an SCI population, as the rower is required to move their own body mass in addition to the weight of the modified seat. The present work described an alternative FES rowing system consisting of a floating foot stretcher (weighing approximately 19kg [13]) and seating system that remains fixed throughout the rowing motion, which may improve the mechanical efficiency during FES rowing by reducing the total amount of mass that is required to be accelerated. As such, further investigations into the biomechanical as well as physiological outcomes from using this device are warranted and are currently underway in pilot studies.

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REFERENCES