Assessing Kinematics and Kinetics of FES-Rowing

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***Abstract*— 'Hybrid' functional electrical stimulation (FES) rowing is a novel training therapy that enables the spinal cord injury (SCI) population to exercise the innervated upper body together with the electrically stimulated lower body muscles. FES-rowing produces significantly greater aerobic power and peak oxygen consumption than either upper body or FES exercise alone. However, there is minimal information on the mechanical efficiency of FES-rowing in the SCI population. The objective of this work was to characterize effective upper and lower body forces and mechanical efficiency (external work/metabolic consumption) in able-bodied vs. FES-rowers. Six patients with SCI and six able-bodied individuals performed a progressive aerobic capacity rowing test. Differences in kinematics (motion profiles), kinetics (forces applied at the feet and handle), and mechanical efficiency (external work/volume of oxygen consumed) were compared in able-bodied vs. FES-rowers. Able-bodied rowers increased stroke rate with increased rowing intensity by decreasing the recovery time, while FES-rowers maintained a constant stroke rate, with no change in recovery or drive times. While able-bodied rowers increased legs and arms forces with an increased rowing intensity, FES-rowers used primarily their arms to achieve higher rowing intensity. Oxygen consumption increased in both groups, but more so in able-bodied. However, able-bodied rowers not only produce more external work for a higher oxygen demand, they are actually two times more efficient than FES-rowers.**

Even though FES provides a framework that allows exercising, the contribution of the legs stays constant and very low (10%BW) in FES-rowers regardless of rowing intensity. These results imply there are limitations in total force output achievable with FES.

I. Introduction

In the United States, 11,000 people suffer a spinal cord injury (SCI) each year, resulting in an estimated 276,000 people living with a chronic SCI in the US [1]. The SCI population is at the low end of the fitness spectrum with high risk of cardiovascular disease, diabetes, and profoundly accelerated osteoporosis, with a rapid decrease in bone density to approximately 60% of the normal bone mass [2]. Currently, there is no cure for SCI and most physical therapies to date have focused on only upper body exercises, which limits cardiovascular adaptations [3], [4] and do not apply the mechanical loads to the lower limbs necessary for maintaining bone strength. Hybrid functional electrical stimulation (FES) rowing is a novel training therapy designed to enable the SCI population to exercise both the large muscles of the legs and the upper limbs muscles, leading to increased metabolic responses [5]–[7]. Previous studies have shown that isolated FES muscle stimulation increases bone mineral density (BMD) in chronic SCI patients [8] and maintains BMD in acute SCI patients [9]. A recent case report suggests that FES-rowing may provide therapeutic benefits for bone [10]. Hybrid FES-rowing can mirror able-bodied rowing, but the specific of the rowing stroke, the loading produced, and the mechanical efficiency of those with SCI who habitually train with FES-rowing remains still unknown [11]. This study provides a biomechanical analysis of FES-rowing in relation to aerobic work to provide guidance for an optimal exercise regime for the SCI population to improve health benefits. The objective of this work was to characterize rowing stroke, effective upper and lower body forces across exercise intensities, and mechanical efficiency of rowing. We hypothesized that a greater rowing intensity requires greater upper and lower body forces and greater oxygen consumption in both groups.

II. Methods

An adapted Concept2 (Model D) ergometer used for FES-rowers was instrumented with force transducers (handle, toe and heel of the left and right leg) and string potentiometers (rowing seat position). NI LabVIEW software was used to collect real time feet and handle forces and rowing seat position (Fig. 1). Aerobic power was determined using on-line computer-assisted open circuit spirometry (ParvoMedics, Sandy, UT). Expired O_2 and CO_2 were measured during all the rowing tests to determine O_2 consumption and CO_2 production. A heart rate monitor (Suunto, Vantaa, Finland) was used throughout the tests.

Six patients with spinal cord injury (C5-T12, American Spinal Injury Association class A) were recruited from current patients in the Spaulding Rehabilitation Hospital SCI exercise program for FES-rowing. Six able-bodied control subjects were recruited via flyers at university campuses. All the able-bodied and SCI individuals had similar levels of rowing training. For FES-rowing for those with SCI, an Odstock 4-channel electrical stimulator was used to activate the quadriceps and the hamstrings through surface skin electrodes placed over the muscle motor points. All those with SCI were able to perform FES-rowing without any external assistance.

All subjects performed a progressive aerobic capacity rowing test. During the progressive aerobic capacity test, the subjects performed FES-rowing (able-bodied rowing) increasing wattage every 2-minutes until volition exhaustion. The initial stages used wattages that were subject specific and intended to represent 70%, 80%, and 90% of the peak achievable workload for each individual. This was estimated from the corresponding percentage of age-predicted heart rate for the able-bodied (220 beats/min-age), and from a prior peak aerobic capacity test that had been performed for the exercise program for those with SCI. The 2-minutes stages progressed without rest intervals and after the third stage, rowing intensity was increased progressively until subjects reached volitional exhaustion. This peak was used to derive the relative intensity of the first three rowing stages. For those with SCI to reach the targeted rowing intensity, the electrical stimulation was increased as requested by the individual.

Force and position data were recorded at 100Hz sampling frequency and a 10Hz low-pass first order Butterworth filter was used to remove unwanted noise. The data was divided into 1-minute intervals for which drive time, recovery time and average stroke rate were obtained. Additionally, each stroke was normalized to 100% rowing stroke to obtain force-time stroke profiles to determine peak force achieved at the handlebar and at the feet during 1-minute intervals. External work produced at the feet and handle was evaluated using a 2D rowing model, as function of the force recorded and rowing seat displacement. The mechanical efficiency of each rowing test was calculated as the ratio of the average external work over the volume of oxygen consumed during the last 30 seconds of each 2-minutes rowing intensity bout. Changes in stroke characteristics (drive time, recovery time and average stroke rate) were assessed via repeated measures ANOVA within group across relative total workload. Changes in feet and arms forces were assessed using a linear regression model across groups and across average total work. Differences in efficiency between FES-rowers and able-bodied rowers were assessed using a Wilcoxon Rank-Sum test.

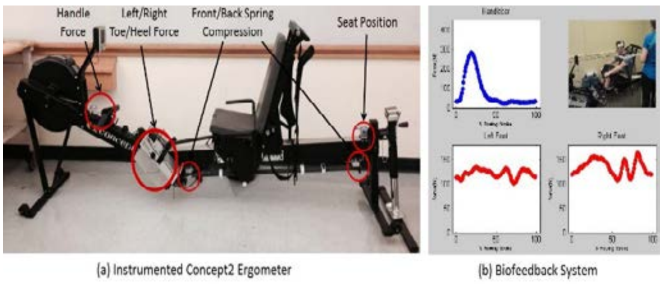

Figure 1: (a) Concept2 ergometer instrumented with force transducers (Handle, L/R Toe/Heel) and string potentiometers (Seat); (b) Biofeedback system for real time data collection.

III. RESULTS

Differences in kinematics (stroke characteristics: average stroke rate, drive time, recovery time), kinetics (forces applied at the feet and handle), and mechanical efficiency (total external work/volume of oxygen consumed) were compared in able-bodied rowers vs. FES-rowers at three submaximal bouts of intensity.

With increased rowing intensity, able-bodied rowers increased stroke rate ($p=0.02$) by decreasing recovery time ($p=0.05$) while maintaining a constant drive time. FES-rowers did not increase stroke rate and maintained a constant recovery and drive times even with increasing rowing intensity. Able-bodied rowers spent 53% of the rowing stroke in the drive phase, while FES-rowers spent only 45% of the rowing stroke in the drive phase.

Across all intensities, FES-rowers produced lower magnitudes for both peak forces and work produced by upper and lower body than able-bodied rowers. With increased workload, able-bodied rowers increased feet force ($p<0.01$), while FES-rowers maintained a constant feet force (Fig. 2). For the upper body, peak handle force increased for both groups, but even more so in FES-rowers (both $p<0.01$).

FES-rowers had lower oxygen consumption and produced less external work than able-bodied rowers across all intensities. The ratio of external work to internal work provided a measure of mechanical efficiency as the total work produced over the volume of oxygen consumption. Oxygen consumption increased in both groups, but more so in able-bodied rowers (Fig. 3). Our results showed that able-bodied rowers not only produce more external work for a higher oxygen demand, they are actually two times more efficient than FES-rowers (0.199 ± 0.006 vs. 0.101 ± 0.022 (total work)/VO_2; $p=0.03$).

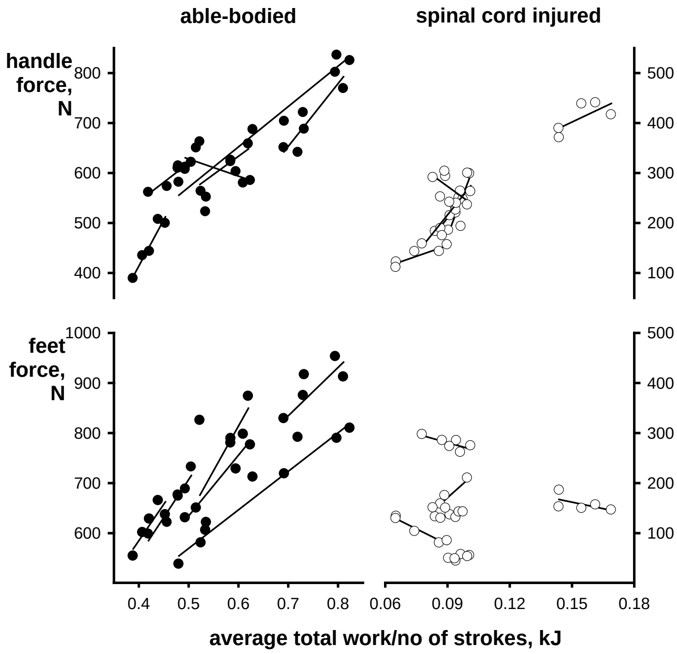

Figure 2: Upper and lower body forces with increased rowing intensity in able-bodied rowing vs. FES-rowing.

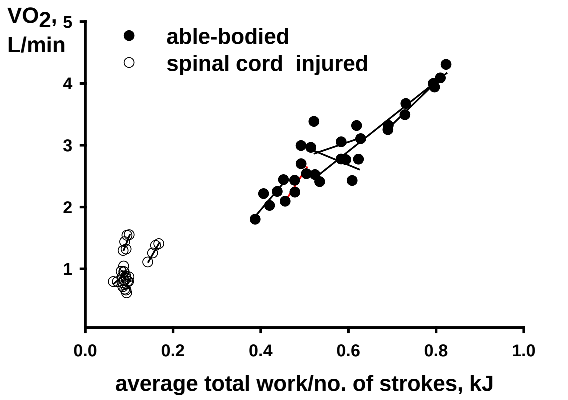

Figure 3: VO_2 consumption with increased rowing intensity in able-bodied rowing vs. FES-rowing.

IV. DISCUSSION

Even though hybrid FES-rowing mimics able-bodied rowing, the specifics of the rowing stroke, the loading produced and the mechanical efficiency is different in FES-rowing than in able-bodied rowing. FES-rowers demonstrated different rowing stroke kinetics than able-bodied rowers. Able-bodied developed an effective coordination between the upper and lower body movement, the movement pattern being facilitated by the trunk swing predominantly in the sagittal plane. However, the FES-rowers had an altered coordination between the arms and the legs during drive phase; their inability of using the trunk swing resulted in a complete arm pull during the first half of the drive phase, followed by a leg extension during the second half, instead of coordinated arm and leg motion.

Across all intensities, able-bodied rowers produced three times higher peak external forces at arms and legs than FES-rowers. However, while able-bodied rowers increased legs and arms forces with increase in intensity, FES-rowers achieved a higher rowing intensity by only increasing their arm force, while the leg force was maintained constant. The different rowing stroke kinetics and lower magnitudes of peak arms and legs forces of FES-rowers are probably due to both biomechanical and physiological reasons. FES-rowers are not able to use their trunk, limiting an effective coordination between their arms and legs resulting in only very small increases in rowing intensity. Furthermore, the non-physiological recruitment of muscle fibers through electrical stimulation allows engaging the lower body of FES-rowers, but the legs achieve quickly the maximum possible work, without being able to increase the force production. With increased intensity, the oxygen demand is higher in able-bodied rowers than in FES-rowers. This is not surprising given that FES-rowers produced less external work than able-bodied. However, able-bodied rowers not only produce more external work for a higher oxygen demand, they are actually two times more efficient than FES-rowers.

Though FES-rowing has been investigated for training purposes for several years, only a few kinematic and kinetic parameters have been reported and only in single case reports [10-12]. This study characterizes FES-rowing within a group of subjects, allowing for broader comparisons. We found that even though FES-rowing provides a framework that allows exercising, the FES stimulated muscles are limited in the amount of force produced. Regardless of rowing intensity, the contribution of the legs stays constant and very low in the SCI population. These results imply that the inefficiency of FES-rowing limits the total force output achievable with FES. Although this may not impact the favorable aerobic benefits of this form of exercise, it does have implications for mitigating bone loss after a spinal cord lesion. Increasing force production and loads on the lower body will enhance the potential bone health benefits of FES-rowing.

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