MODIFIED CONCEPT 2™ ROWING MACHINE WITH MANUAL FES CONTROLLER FOR TOTAL BODY EXERCISE IN PARAPLEGIA

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Abstract

Concept 2 indoor rowing machine (Concept 2 Inc., USA), an exercise and training machine for able-bodied population, was modified for total body exercise in paraplegia. A new seating system provides trunk stability and constrains the leg motion to the sagittal plane. A 4-channel electrical stimulator activates the quadriceps and hamstrings in drive and recovery phases of rowing cycle. Force sensing resistors (FSR) on the handle measure the thumb press as the command signal to the electrical stimulator. Optical encoders measure the position of the seat and handle during rowing. To synchronize the movement of the upper and lower body, a manual control system uses the voluntary thumb presses to determine the timing of the stimulation to the leg muscles. The manual control system was intuitive and easy to learn and resulted in well-coordinated rowing. Evaluation of the modified rower by paraplegic volunteers showed that it is effective, safe, and an affordable exercise alternative for paraplegics.

Introduction

Cardiovascular diseases have now replaced infectious disease, renal failure and pneumonia as one of the main causes of death in persons with spinal cord injury (SCI) [1]. Because of a sedentary life style and loss of voluntary muscle mass, adults with SCI are at increased risk for cardiovascular disease and mortality. Upper body activities such as wheelchair propulsion and arm cranking are commonly prescribed to reduce the risk factors for heart disease. Blood pooling and the lack of "muscle pump" in the inactive paralysed lower limbs however, limit the level of exercise and its corresponding effect on cardiovascular fitness [2]. Functional electrical stimulation (FES) is the only known methodology that can be used to exercise the paralysed muscles. Therefore, it is logical to combine voluntary exercise of the upper body muscles with FES exercise of the paralysed leg muscles to increase the cardiovascular training effects. This form of combined or hybrid exercise has been shown to lessen venous pooling and increase stroke volume, oxygen uptake and metabolic rate when compared with arm ergometry or FES leg ergometry alone [2;3]. Most common hybrid exercise for persons with SCI combines arm cranking with FES cycling using ERGYS (Therapeutic Alliances Inc., USA). This hybrid exercise is however unnatural, expensive and must be used in a clinic with the help of clinicians. As a more affordable and natural alternative for possible home use, we developed an indoor rowing machine for total body exercise by SCI population. We modified Concept 2, a commercially available indoor rowing machine, for use by SCI population. Since smooth rowing requires a delicate coordination between the upper body and lower extremities, we developed the necessary controls to achieve such coordination.

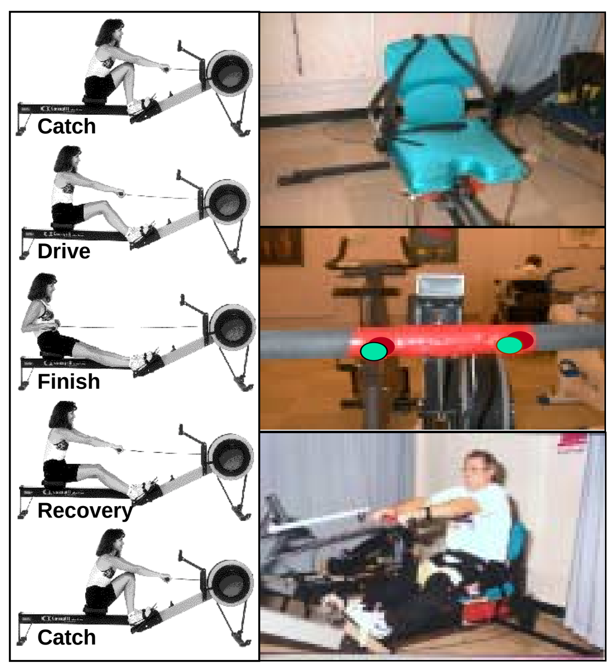

Figure 1. *Standard Concept 2 rowing machine with one rowing cycle (left) and the modified version for FES rowing (right).*

Methods

Concept 2, the most popular indoor rowing machine, was used as the starting point for design to minimize the development efforts and also be assured of the future enhancements and support by the vendor.

Modifications to Concept 2: A new seating system was developed, which can be easily exchanged with the standard seat for alternate use of the machine by paralyzed or able-bodied users (Fig. 1). The new seat has high back, adjustable backrests, and adjustable seat belt to stabilize the trunk when necessary. A two-bar mechanism was attached to the seat to constrain the motion of the legs to sagittal plane. During rowing, when the subject pulls the handle, a relatively large pulling force proportional to the square of the pull velocity, must be counteracted by the quadriceps that keep the knees extended. To help the quadriceps muscles to withstand the large pulling force, a novel proportional braking system was installed under the seat. The brake produces a braking force under the seat proportional to the pulling force on the handle so that the harder the subject pulls the handle, the higher the braking force under the seat counteracts it. This prevents the seat from momentarily slipping forward and interfering with the smooth rowing transition. The range of motion of the seat is limited by two adjustable safety stops on the rail. Shock absorbers in the back and front side of the seat dampen the contacts between the seat and safety stops and help in momentum transfer from one phase to the other. A 4-channel electrical stimulator was developed with Motorola MC68332 microcontroller at its center. The stimulus pulses were rectangular and monophasic and were delivered to the quadriceps and hamstrings in both legs. The stimulus output is current regulated at 120mA with 20Hz frequency and variable pulse within 0–500 microseconds. Apart from high processing power, electrical stimulator has capabilities for multi-channel sensory measurements, communication with a PC for real time control and data transfer, and flexibility for further expansion. One of the seat rollers and the handle chain pulley were instrumented with optical encoders to measure the position of the seat and handle during rowing. Although these measurements can serve more sophisticated closed-loop FES controllers of the leg muscles, they will be used here to evaluate the performance of the manual control system. The handle was instrumented with two force-sensing resistors (FSR) to receive the subject's control commands as explained below.

Manual control System: The electrical stimulation of the leg muscles is under the subject's manual control. The subject starts in the catch position (Fig. 1). S/he then presses on the right FSR using the right thumb. When the thumb press on the FSR exceeds a threshold (determined to ignore unintentional contacts), a constant level stimulation (determined to produce maximum muscle force) is applied to the motor points of the quadriceps on both legs via carbon-rubber surface electrodes. The knees extend and the seat moves back along the track (Drive in Fig. 1). During the latter part of this phase, the subject pulls on the handle. FES is maintained on the quadriceps to keep the legs fully extended. In addition, the proportional brake engages to prevent any reversal of seat motion. When the handgrip is fully withdrawn (Finish in Fig. 1) the subject releases the right thumb pressure, applies pressure to the left FSR and slackens off the handlebar and the damper cord retracts (Recovery in Fig. 1). These actions cause: constant level stimulation to be applied to the hamstrings; stimulation is removed from quadriceps; the brake mechanism is released and the seat can return to the starting position. The cycle repeats when the subject returns to the starting catch position. To accommodate the weaker muscle force in paraplegia, the subjects were instructed to extend their knees before starting to pull the handle. This prevents the large pulling force from reversing the seat motion during the drive phase.

Clinical Trials*:* Three prototypes of the modified indoor rowers were developed and used by paraplegic clients in the Steadward Center. An efficacy study with six paraplegic volunteers showed that the FES rowing is safe, acceptable, and efficient exercise system that can result in better cardiovascular fitness than arm or leg only exercise. The results of evaluating the manual control by two volunteers are presented next. The first volunteer (V1) was 66 years old, 89.9 kg, T12 complete, and 5 years after injury. The second volunteer (V2) was 51 years old, 70.7 kg, T4 complete, and 31 years after injury.

Results

The position of the handle (which tracks the arm movement) and seat (which because of the constraints tracks the knee joint movement) are used to evaluate the performance of the manual control in coordinating the voluntary movement of the upper body to that of the FES controlled lower extremities. As basis for comparison, two typical cycles of normal rowing trajectories by a healthy subject are shown in Figure 2. As shown in the figure, the motion is well coordinated and intra-cycle and cycle-to-cycle transitions are smooth. Two typical cycles of the rowing trajectories and corresponding electrical stimulation patterns for two paraplegic subjects are also shown in Figure 2. Subject specific stimulation timings are adopted to achieve the desired rowing patterns.

Discussion

As an anticipatory action, subject V1 initiates the quadriceps stimulation before complete recovery to the catch position. As the result, the knee extension or the backward motion of the seat leads the handle pull.

Subject V2 on the other hand, has achieved better timing and the seat and handle motions are well coordinated. Both subjects followed the instructions to start pulling the handle only after the knees are completely extended. Therefore, the seat position reaches its max before the handle and stays there for longer period while the handle is pulled. This is the main difference between the normal and FES rowing trajectories. The manual control of stimulation timing is intuitive and subjects learned to use it in less than 5 minutes. It is also flexible and lets the users find the best stimulation timing for movement coordination that suits them. Manual control however, requires concentration, may over-stimulate the muscles resulting in early fatigue, and thumb press may be inconvenient or impossible for users with higher-level lesions. We plan to develop closed-loop FES controllers to automate the stimulation delivery and better regulate the stimulation intensities to avoid early fatigue. Adherence to and acceptance of the rowing program was excellent and the users were interested in continuing to use the FES rowing regularly. The developed system has a great potential as an affordable home based exercise system for SCI population.

References

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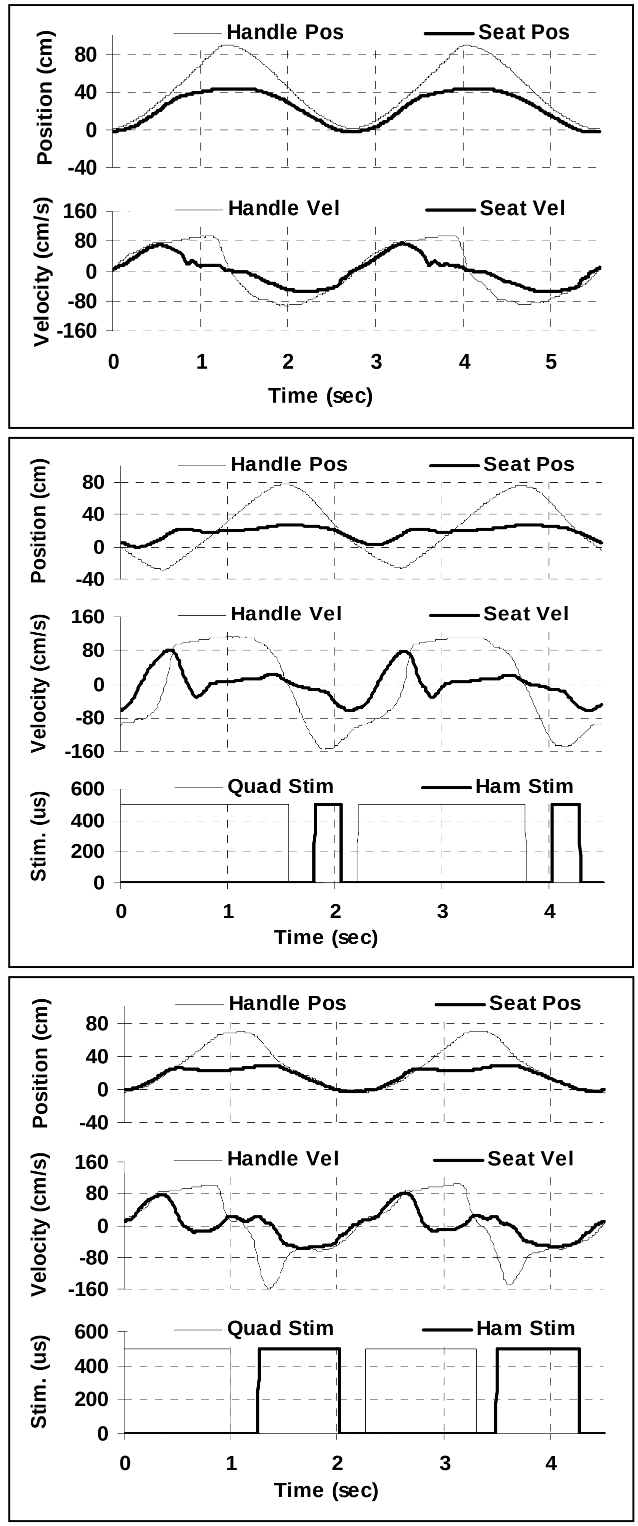

Figure 2. *Trajectories and electrical stimulation patterns in two typical rowing cycles for a normal subject (top), and two paraplegic volunteers V1 (middle) and V2 (bottom).*