Rowing with FES

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Abstract—People with spinal cord injury (SCI) need to increase their level of physical activity to reduce the risk of cardiovascular disease but their exercise options are very limited. Functional electrical stimulation (FES) assisted indoor rowing has been developed as a total body exercise option that combines the exercise of the innervated upper body with the exercise of the electrically stimulated leg muscles in a natural manner. An existing indoor rowing machine was modified for use by the paraplegic users and two types of FES controllers were developed to control the level of stimulation to the paralyzed leg muscles. Manual FES controller was operated by the users thumb presses on the two control buttons on the handlebar, was easy to implement and operate, and has been the most widely used form of control in FES rowing. Automatic FES controllers produced rowing movement comparable to manual control strategy but did not require the user’s thumb presses, could be used by the users with higher level of SCI, and could potentially be used to control more leg muscles to further increase the intensity and cardiovascular training effects of FES rowing exercise.

Index Terms—control, electrical stimulation, exercise, rowing.

I. INTRODUCTION

FUNCTIONAL electrical stimulation is a promising technology for the SCI population but the technology involved in generation and safe delivery of electrical stimulation pulses to reanimate paralyzed limbs is relatively complex. A great deal of effort has been spent on development of devices to generate stimulation waveforms, electrodes to deliver the stimulation pulses to the muscles, and control systems to shape the appropriate patterns of stimulation to produce functional limb movements. Advances in these areas have enabled many FES applications but the majority of these have been limited to the controlled environment of the research laboratories. The wider clinical application is still hindered by the limitations in technology, especially in the area of stimulation electrodes and control systems.

Variety of implanted electrodes with better selectivity than the surface electrodes have been developed but their reliability and safety must be improved. Additionally, more sophisticated control systems must be developed to take full advantage of the improved access to the muscles. The overall benefits must outweigh the risks of invasive implantation procedures and higher costs to overcome the resistance of the patients and providers. The efforts in these areas are necessary for the development of clinically useful FES systems and must continue. But in the meantime, many successful FES systems can be developed using non-invasive surface stimulation technology. The surface electrodes are less selective than the implanted electrodes and have more day to day variations in their interface to the muscles but they are safe and non-invasive and can be easily removed when the FES system is no longer necessary or wanted by the SCI client. More importantly, it is easier to convince the patients to use non-invasive technologies, which is an important factor for development and feasibility demonstration of FES systems and promotion of their use in clinical environments.

In this paper, I will review one such application where surface stimulation technology is combined with simple and intuitive control strategies to enable people with SCI to perform FES rowing exercise to improve their cardiovascular fitness and by extension their quality of life. I will specifically focus on FES control issues in FES rowing and the necessity of solving man-machine coordination problem. I will present control strategies with varying levels of complexity, present their performance data, and discuss their applications in current and future FES rowing systems.

II. EXERCISE AND FITNESS AFTER SPINAL CORD INJURY

Because of the limb paralysis, people with SCI tend to live a sedentary lifestyle accompanied by a lower level of physical activity than their able-bodied counterparts. Reduced level of physical activity combined with atrophic loss of voluntary muscle mass increase the risk of cardiovascular disease and mortality in this population [1;2]. Therefore, the physical activity and exercise are doubly important for improving the health and well being of the SCI population.

Exercise involving only the upper body such as wheelchair propulsion and arm cranking are commonly prescribed to reduce the risk factors for coronary heart disease [3;4]. However, the intensity of exercise and its corresponding effect on cardiovascular fitness are limited by the small volume of the muscles in the upper body. Electrical stimulation of the larger leg muscles, therefore, has been used to increase the cardiovascular stress and consequently increase the cardiovascular training effects [5;6]. Electrical stimulation of the leg muscles has also been combined with voluntary upper body exercise to further increase the cardiovascular training effects. This is called combined or hybrid exercise and most commonly involves FES cycling and arm crank ergometry. The combined exercise has been shown to increase oxygen uptake and metabolic rate when compared with arm crank ergometry or FES cycling alone [7;8]. FES rowing is another form of hybrid exercise that was introduced to broaden the exercise choices for the SCI population [9-11]. Rowing is a total
body exercise that is more natural to perform than the other hybrid FES exercises and it is more motivating because its SCI users can compete against each other and against able-bodied rowers [9].

III. NORMAL VERSUS FES ROWING EXERCISE

Exercise or training in indoor rowing machines simulates the actions of the rower in a rowboat. These actions are composed of a rowing cycle that is performed repeatedly as long as the rower wishes to continue. There are a number of states or phases within a rowing cycle that must be executed in a specific sequence starting from the Catch position (Fig. 1). The orderly execution of these movements within a rowing cycle and smooth transition from one cycle to another are essential for fluent and smooth rowing movements.

In normal rowing the central nervous system (CNS) controls both upper and lower bodies and is responsible for precise coordination of their movements. In FES rowing, the CNS can still control the upper body movements but it has no control over the paralyzed leg muscles, whose active movement must be restored by the FES controller. The FES rowing therefore requires a rowing machine that can accommodate the needs of the SCI users and a FES controller to produce lower body movements that are precisely coordinated with the CNS controlled movements of the upper body.

Figure 1: Indoor rowing exercise by able-bodied and SCI users. In normal rowing, the CNS coordinates the movements of the upper and lower bodies. In FES rowing, the CNS still controls the upper body but the movement of the paralyzed legs must be restored by the FES. Different phases of a single rowing cycle are shown on the top. The references for measurement of the handle and seat positions and the two muscle groups stimulated in FES rowing are also shown.

IV. INDOOR ROWING MACHINE FOR PARAPLEGIC USERS

Different versions of the FES indoor rowing machines have all been developed by modifying existing rowing machines used by able-bodied users and share common features [9-14]. This approach minimizes the development effort and has the added benefit that the same machine could be used by both SCI and able-bodied users.

The prototype developed by Davoodi et al. [10] used Concept 2 indoor rowing machine (Concept 2 Inc., USA) as the basis for development and modified it to accommodate SCI users. The modifications included a new low pressure seating system with high back rest to provide better trunk stability for paraplegic users (Fig. 2). Paralyzed or able-bodied users can easily exchange the new seat with the standard seat for alternate use of the machine. A two-bar mechanism was used as leg stabilizers to constrain the motion of the legs to one degree of freedom movement in sagittal plane. To help the electrically stimulated quadriceps muscles withstand the large handle pulling forces, a brake applied a braking force to the seat that was proportional to the handle pulling force. Two safety stops limited the seat motion to protect the knee joints against hyperextension or hyperflexion. Two force sensing resistors were installed on the handlebar to receive the user’s control commands. To provide sensory feedback to the FES controller, one of the seat rollers and the handle chain pulley were instrumented with optical encoders to measure the positions of the seat and the handle. A microcontroller-based electrical stimulator managed the user interface, sensory measurements, control calculations, stimulation delivery, and communications with a PC to store the control data for off-line analysis. It provided four channels of stimulation to quadriceps and hamstrings in both legs. The monophasic stimulation pulses were current regulated at 120 mA with 20Hz frequency and variable pulse within 0 – 500 µs.

Figure 2: Standard Concept 2 rowing machine and modifications to adapt it for FES rowing.

V. CONTROL OF FES ROWING EXERCISE

The goal of the FES rowing control system is to restore the lower body part of the rowing maneuver while the patient voluntarily performs the upper body part of the maneuver. This can be achieved by controlling the timing and intensity of the electrical stimulation to the paralyzed leg muscles to produce lower body movements that are coordinated with the upper body movements. Because of the close coupling between the upper and lower body movements, the coordination of the FES and CNS is essential for the successful execution of the FES rowing maneuver. Two main approaches have been used in the past to resolve this man-machine coordination problem: manual control strategy and automatic control strategy.

A. Manual Control of FES Rowing by the Clinician

In the first FES rowing prototype [11], the task of controlling the stimulation to the muscles was delegated to the clinician who instructed the patient to pull/push the handlebar, and turned the quadriceps or hamstring muscles’ stimulation on/off at the appropriate moments within the rowing cycle. This approach to control was used to
demonstrate the feasibility of FES rowing but it was impractical for regular exercise and training by the SCI users. Rowing maneuver is a dynamic movement that requires precise moment-to-moment coordination of upper and lower extremity movements. Such level of coordination was impossible to achieve between the clinician and the patient who had to rely on relatively slow visual feedback and verbal communication to coordinate their actions. Achieving an acceptable level of coordination was further complicated by the inability of the clinician and the patient to anticipate each others’ control actions. Anticipation and prediction are essential for successful coordination of dynamic multi-limb movements by the CNS and in their absence it was impossible to execute fluent and smooth rowing movements.

**B. Manual Control of FES rowing by the Patient**

The main problem with the manual control strategy employed by Laskin et al. [11] was that it was unable to coordinate the upper and lower body movements and it was unnatural and inconvenient to use by the SCI users and the clinician. These issues were resolved by a manual control strategy that was performed by the patient and did not require the clinicians contribution [10].

In the modified manual control strategy, quadriceps muscles were stimulated bilaterally in the drive and handle pull phases of the maneuver to extend the knee joints and the hamstrings were stimulated in the recovery phase of the maneuver to flex the knee joints. The decision for turning the stimulation of the paralyzed leg muscles on/off was made by the patient who was also responsible for performing the voluntary upper body part of the rowing maneuver. By pressing on the control buttons under the right and left thumbs, the patient turned the constant level electrical stimulation of the quadriceps or hamstrings muscles on, respectively. Depressing the buttons turned off the stimulation to the respective muscles.

In this manual control strategy, therefore, the control of the upper and lower body parts of the rowing maneuver was completely under the control of the rower’s CNS who could start, stop, and control the pace of the rowing exercise independently. This approach to manual control eliminated the clinician from the control loop making it more similar to the rowing exercise performed by the able-bodied users. More importantly, the unification of the control centers for the upper and lower bodies allowed the CNS to more effectively coordinate their movements. Furthermore, this approach took advantage of the unique control and learning capabilities of the CNS that are essential for multi-limb coordination, acquisition of the new skills required for FES rowing, and adaptation to internal and external perturbations.

The rules of the manual control were simple and intuitive and the patients quickly learned to use them to successfully perform FES rowing exercise. Movement trajectories and stimulation patterns for two cycles of normal and FES rowing with the modified manual controller are shown in Fig. 3. The comparison of the trajectories show that the upper and lower body parts of the rowing maneuver, represented by the handle and seat positions, respectively, were well coordinated. The rowing movement, therefore, benefits greatly from the use of the reserve control capacity in the patient’s CNS. This is exhibited in good coordination between the upper and lower body movements and the ability of the patients to learn, over time, the appropriate timing of the electrical stimulation for successful rowing. The latter is evident from the stimulation train in Fig. 3, where the patient had learned to turn the stimulation off when it was not needed.

**C. Automatic Control of FES Rowing**

The users of the manual control strategy must continuously make voluntary decisions to repeatedly press and release the stimulation control buttons in the handlebar, which requires prolonged concentration to achieve coordinated rowing movements. The repetitive thumb presses on the control buttons causes some discomfort in some users and the higher level SCI users could not press on the buttons and still needed the assistance of the clinicians to operate the control buttons. The automation of the stimulation delivery by an automatic FES controller, therefore, would relieve the user from having to press on the control buttons and allow the SCI users with higher-level SCI to perform rowing exercise.

The automatic control strategy for FES rowing [15-17] have used a hierarchical approach, where a high-level controller identifies the current state of the rowing cycle and low-level state-dedicated controllers regulate the pattern of muscle stimulation as long as the system remains in that state (Fig. 4).
D. High-Level Automatic Control Strategies

The high-level decision making in the automatic controller was performed by a finite state controller. Finite state control of FES systems was first proposed by Tomovic and McGhee [18] who observed that most human movements such as gait is composed of sequential pattern of movements. Since then finite state control method has been used in various FES applications such as the control of gait, standing up, and sitting down [19-22]. A finite state controller or machine consists of a set of states, a set of input events, a set of output events, and a set of state transition rules [23]. The state transition rules for complicated systems can be extracted using advanced machine learning techniques [24;25]. For simpler systems, these rules can be handcrafted by an expert with domain knowledge.

Fig. 5 shows the state diagram and the state transition rules for the high-level finite state controller [15]. The finite state controller applies a set of handcrafted state transition rules to the input sensory information to identify the current state of the rowing movement and dispatches the appropriate low-level controller for that state. After the initial calibration procedure, the subject assumed the Catch position and was free to start or stop the rowing exercise at any time by pressing on the start or emergency/stop control buttons on the handle. By pressing on the start button, the system entered the Drive state in which the low-level controller stimulated the quadriceps and relaxed the hamstrings. The knees extended and the seat moved back along the track. In full knee extension, the system entered the Handle Pull state in which the low-level controller continued to stimulate the quadriceps muscles to keep the knees extended while the subject pulled on the handle. When the high-level controller detected that the knees were fully extended and the handle was fully withdrawn, the system entered the Recovery state in which, the low-level controller stimulated the hamstrings and relaxed the quadriceps. As the result, the knees flexed while at the same time the subject extended the arms. Simultaneous occurrence of the full knee flexion and full arm extension signalled the completion of one rowing cycle. At this point, the system immediately entered the Drive state of the next rowing cycle. The rowing cycles repeated until the subject decided to stop by pressing on the emergency/stop control button, which turned off the electrical stimulation to all of the muscles.

E. Low-Level Automatic Control Strategies

The low-level controllers are state-dedicated and control the level of electrical stimulation of the muscles as long as the system remains in that state. The most basic low-level controller applies open-loop constant-level stimulation to the muscles. In this method, the low-level controller applies constant-level stimulation to the quadriceps in the Drive and Handle Pull phases (to extend the knee joints and keep them extended while the handle is pulled) and to the Hamstrings in the Recovery phase (to flex the knee joints) of the rowing cycle [15]. The main advantage of this control strategy is its simplicity and because it does not require sensory feedback, it is also easier to implement. But on the other hand, the continuous constant-level stimulation of the muscles could cause early muscle fatigue, produce jerky movements and high knee end velocities that could damage the knee joint.

To enable a better control on the knee joint trajectories, a closed-loop On/Off switching curve control was also developed [16]. In movements such as standing up and sitting down, the velocity-position graph of the knee joint closely resemble a quadratic curve with zero initial and final velocities. Such graphs have been used as switching curves in FES control of standing up and sitting down [20;26;27]. Similar quadratic curves have been observed in Drive and Recovery phases of the rowing cycle that tend to consistently follow quadratic trajectories with near zero initial and final velocities [16]. The on/off switching curve control for FES rowing therefore attempts to follow the desired switching curve as closely as possible by turning the stimulation on/off depending on whether the current joint velocity falls below/above the switching curve. Although it is desirable to use the quadratic switching curves, for practical reasons, a linear switching curve with non-zero initial velocity and zero final velocity may also be used. This non-zero initial velocity is helpful for keeping the stimulation on and generating enough muscle force to initiate the movement [16;20;27]. This low-level control strategy can delay the muscle fatigue by turning the stimulation off when it is not needed and by following the quadratic knee joint trajectories; it can reduce the knee end velocities. Additionally, following the switching curve trajectories allows the rowers to complete each phase of the rowing maneuver at a pace that is comfortable to them. This is possible because the desired joint velocity in the
switching curve varies as a function of the joint position and it does not have to be completed in a fixed time period as would be required if reference trajectories were functions of time (such as those used in robotics). The on/off control of the muscle stimulation, on the other hand, requires feedback sensors and constant switching of the muscle stimulation could result in jerky movements.

In both low-level control strategies described above, the muscles were activated by constant-level stimulation that was kept fixed irrespective of the momentary requirements of the movement. During the rowing maneuver, however, the required knee joint torque and the corresponding level of stimulation must vary continuously as a function of the handle pulling force, the desired joint movement, and internal and external disturbances such as muscle fatigue. This requires the continuous variation of the muscle stimulation level within each state of the rowing cycle. To achieve a finer control of the muscle stimulation levels, a low-level fuzzy logic controller was developed [17]. Fuzzy logic controllers are nonlinear and because of the many tuning parameters in their rule base and input/output membership functions, they are capable of controlling complex systems. These parameters could be adjusted automatically or by an expert with domain knowledge to provide the diverse control responses required during the rowing movement. The inputs to the fuzzy logic controllers were the position and velocity of the seat and the outputs were the stimulation levels of the quadriceps and hamstrings muscles. The rules and the membership functions were adjusted manually to obtain the desired response from the controller.

The results of using the automatic control strategy by a SCI rower are shown in Fig. 6. The high-level finite state controller was used by all of the low-level control strategies described above. The high-level controller was consistently successful in identifying the phase of the rowing movement as shown in the plots of the movement phase. The open-loop constant level stimulation strategy produces similar trajectories as the manual controller but because the stimulation is constantly kept on, it could overstimulate the muscles and cause early fatigue. The switching curve control strategy reduced the amount of muscle stimulation by turning it off when the velocity was above the reference velocity but the frequent switching of the stimulation to the muscles inconvenienced the users and interfered with the smooth flow of the rowing maneuver. The fuzzy control strategy, reduced muscle stimulation by varying its level according to the demands of the movement and because the variations in the stimulation level were continuous, it produced smooth rowing maneuver with movement trajectories similar to those produced by the manual controller.

VI. DISCUSSION AND CONCLUSIONS

FES indoor rowing machine was developed to broaden the fitness choices for the SCI population. It has been shown that FES rowing provides a higher intensity exercise resulting in higher peak VO2 consumption than can be achieved from other alternatives such as arm crank ergometry or FES cycling [12;28-30]. The intensity of exercise is important for improvements in blood lipids and the reduction of the risk factors for cardiovascular diseases [31;32]. Therefore, the higher intensity exercise offered by FES rowing could help improve the cardiovascular fitness of a population whose main cause of death and mortality is coronary heart diseases [1;2].

![Figure 6: Trajectories and electrical stimulation patterns for two typical cycles of FES rowing using high-level finite state controller with three different low-level control strategies: open-loop constant level stimulation (top), on/off switching curve controller (middle), and fuzzy logic controller (bottom).](image)
the one used by the able-bodied population could increase the confidence of the FES rowers, motivate them to adhere to the exercise regimen, and has enabled them to compete against able-bodied rowers [9;12]. In recently developed FES rowing machines, new features and refinements have been introduced to further accommodate the needs of the SCI users. For example, in recent models, the back end of the monorail could be elevated to take advantage of the gravity in Recovery phase of the movement. The seat and the backrest are also inclined backward o compensate for the slope of the monorail. Instead of the seat assembly, the leg stabilizer is installed on the rowing machine’s frame to constraint the movement of the lower legs to sagittal plane [9;12-14]. Further, the stability and durability of the seat carriage have been increased by adding two more rollers to roll along the bottom side of the monorail [9;12].

After the first feasibility demonstration in 1993 [11], the lack of a practical FES control system was one of the main factors preventing the use of FES rowing by the SCI users. The main complicating factor was the necessity of coordinating FES with CNS or solving the man-machine coordination problem. Without such coordination, performing coordinated and smooth rowing maneuvers would be impossible. In other modes of exercise such as FES cycling, the paralyzed muscles could be controlled independently and there is no need for a close moment-to-moment coordination of the FES and CNS.

The manual control of FES by the patient was the first strategy that enabled the users to perform FES rowing exercise independently and in a coordinated manner. This control strategy was easy to implement and required only two switched to register the patients command inputs. It was also easy to operate and the users quickly learned the skills to operate two control buttons. The users also liked the level of control afforded to them by the manual control, which allowed them to start, stop, and control the pace of the rowing exercise at will. FES rowing applications to date have been limited to two channels of stimulation for quadriceps and hamstrings. If the number of channels are increased to stimulate more leg muscles, the manual control of the larger number of control buttons would be difficult, if not impossible. It is also desirable to continuously vary the level of stimulation to produce smoother movements and to minimize early fatigue. In an attempt to enable the patients to manually control the stimulation levels, we allowed the stimulation level to vary with the level of the force applied by the thumb presses on the control buttons. But because the users are not aware of the forces their paralyzed leg muscles produce, they continued to press harder and harder on the control buttons even after the muscles had fatigued and could no longer produce additional forces. The insistence on pressing harder on the control buttons to increase the speed of rowing caused thumb discomfort and, therefore, the strategy was discarded in favor of the constant-level stimulation strategy. In our experience, therefore, the manual control strategy is not appropriate for the finer control of the muscle stimulation levels in FES rowing. Since its introduction, the manual control has been the primary control method used by the FES rowers to exercise and has been used to perform clinical trials to demonstrate the efficacy of FES rowing exercise [12;29;30], to enable the users to participate in indoor rowing competitions [9;12], and to develop and test new FES rowing machines [13;14;33]. A slightly different variation of the manual control in which pressing on a single switch stimulates quadriceps and releasing it stimulates the hamstrings have also been used [9;12;33]. This modification reduces the number of switches the user has to control from two to one but it also keeps the stimulation to one of the muscles on at all times. For example, in the study by Halliday et al. [33], for the first 50% of the rowing cycle, the quadriceps muscles were stimulated and for the remaining 50%, the hamstrings were stimulated. This strategy, therefore, does not allow the rower to learn the optimal timing of the stimulation to minimize fatigue. In fact, the FES rowers who used the manual control strategy with two independent control buttons, adopted a stimulation timing (Fig. 3) that was similar to the muscle activation patterns adopted by the able-bodied rowers [33].

The high-level finite state controller was robust in detecting the rowing states and coordinating the orderly execution of lower and upper body parts of the rowing maneuver. Although the high-level controller was automatic, it still afforded the user with a high level of control over the FES system which is an essential factor for the user’s acceptance of the system. The user can start and stop the exercise at any time and control the pace of the rowing exercise by varying the speed of the voluntary upper body part of the maneuver (e.g. by slowing down or speeding up the Handle Pull phase of the maneuver). This is possible because the finite state controller will not transition to the next state as long as the current state has not been completed.

All three low-level control strategies produced rowing trajectories that were similar to those produced by the manual control strategy. The open-loop constant-level stimulation strategy was simple to design and implement and did not require feedback sensors but it kept the stimulation continuously on, contributing to overstimulation and early fatigue. In FES rowing, the electrically stimulated leg muscles are relatively weaker and fatigue faster than the innervated upper body muscles. Therefore, the duration of the FES rowing exercise is limited by the onset of fatigue in the leg muscles. Muscle fatigue does not handicap FES rowing as much as other FES applications because rowing exercise can be stopped in a safe manner until the muscles have recovered and the user is ready to restart. But frequent rests and restarts are inconvenient and it is better to avoid them, if possible. Further, maximizing the duration of non-stop rowing is critical for winning in competitive FES rowing. The purpose of the switching curve control strategy was to reduce the muscle stimulation and provide better control of the knee end velocities. The limited successes in achieving these objectives, however, were offset by the user discomfort caused by the frequent switching of the stimulation to the muscles. The fuzzy logic controller, on the other hand, had the highest flexibility to effectively control different phases of the rowing maneuver. Even with a set of handcrafted rules and manually designed membership functions, the fuzzy controller outperformed the other low-level controllers. It reduced the amount of the stimulation to the muscles and produced smoother and more
fluent rowing movements [17]. The performance of the fuzzy logic controller could be improved even further by automated tuning of its parameters [34, 35].

The automatic control of FES rowing exercise relieves the users from having to press on the control buttons and it enables the users with affected hand, who can still push and pull on the handlebar but cannot press on the buttons, to perform the FES rowing exercise. But it is more complicated and requires higher level of expertise for design and implementation than the manual control strategy. Feedback sensors must be installed to measure the positions of the seat and the handlebar, the sensors must be calibrated for each user, and there are more control parameters to tune than the manual controller. To date, the manual control method has been the preferred strategy for control of FES rowing because it is simple and effective and its users like the high level of control it affords them over the FES system. Automatic control strategy must be used, however, for patients with higher level of SCI and if additional leg muscles must be stimulated to further improve the performance of FES rowing [12, 33].

REFERENCES

