Cooperative Control of Man-Machine FES Systems

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Abstract

Man-machine coordination problems arise in most rehabilitation systems but they are inevitable in FES. FES controllers must coordinate their actions with the residual movements of the patient to be effective. Over the years several approaches have been used to achieve such coordination but a systematic approach is still lacking. In this paper, we use two examples to demonstrate effective strategies for man-machine coordination in FES. In the first example, FES control of indoor rowing exercise, we compare manual and automatic strategies for coordination. In the second example, we present a biomimetic strategy to achieve better integration and coordination of FES control of reaching.

1. INTRODUCTION

Recent advances in FES hardware are enabling reliable and selective stimulation of paralyzed muscles. For example, BIONs™ are tiny stimulators that can be injected into paralyzed muscles and controlled remotely to activate individual muscles [1]. These stimulators are now being supplemented with multimodal feedback sensors that will provide hardware for more sophisticated closed-loop FES systems. The operation of these advanced implant systems requires equally sophisticated control systems, which have yet to be developed. One particularly complex problem is the source of command signals and their integration with sensory feedback from the movements of the patient. All FES systems have to address this problem but it is more critical in increasingly sophisticated FES systems with extensive man-machine interactions.

In the absence of a systematic approach, creative, problem specific strategies have been developed to coordinate man and machine in FES systems. In this paper, we will report on man-machine coordination strategies that we have successfully applied to a clinical FES rowing system. Then we will describe a biomimetic approach for man-machine coordination that is designed to provide fuller coordination and integration in more complex FES reaching system.

2. METHODS

2.1. FES Rowing

To provide paralyzed patients with an alternative total body exercise system, we developed a FES system for indoor rowing exercise [2]. The patient voluntarily performs the upper body part of the rowing maneuver while the FES performs the lower extremity part (Fig. 1). FES stimulates the muscles of the knee joint to extend and flex the legs at appropriate phases of the cyclical exercise. We used two strategies for patient-FES coordination: *manual control* and *automatic control*.

In *manual control*, coordination is achieved explicitly through residual voluntary movement of the hands. At appropriate moments, the patient presses and holds down one of the control buttons in the handlebar to activate the knee extensors or knee flexors, which then, respectively, move the seat backward or forward. Thus the patient's CNS must learn new skills to control both the upper and lower extremities in synchrony.

In *automatic control* strategy, the coordination is achieved by exchange of sensory information between CNS and FES controllers. Here, the CNS and FES operate independently but they synchronize their actions by each monitoring and reacting to the control actions of the other. The CNS uses visual feedback and proprioception from the intact upper body to monitor, react, and adapt to FES control. FES in turn uses position sensors on the seat and the handle to monitor and react to patient's voluntary movements. To do this, the FES

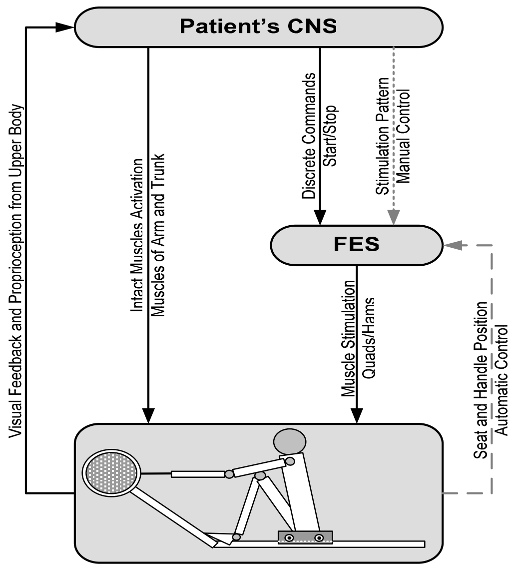

Figure 1. Two control strategies for man-machine coordination in FES rowing. In manual control (dotted line), the stimulation of paralyzed muscles is controlled by a continuous command from CNS. In automatic control (dashed line), prosthetic sensory feedback are used by FES controller to determine the timing and pattern of stimulation.

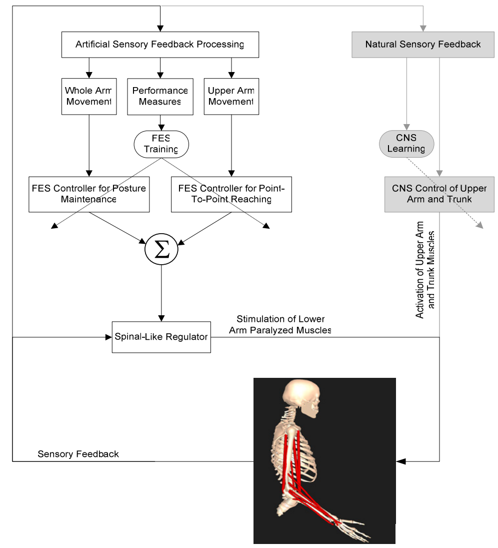

Figure 2. Biomimetic design for FES control of partially paralyzed arm. Upper arm movement is under voluntary control and could be modified by the learning process of the CNS. The movement of the paralyzed lower arm is controlled by the FES that takes advantage of circuitry and residual control in the CNS.

controller had two levels of hierarchy [3]. In the higher level a finite state controller applied a set of state transition rules to the sensory input from the seat and handle to identify the current state in the rowing cycle and dispatch a low-level controller to adjust the level of stimulation to the muscles as long as the system remained in that state. The low-level controllers simply applied constant maximal activation of the knee joint muscles.

2.2. FES Reaching

Restoration of function to the partially paralyzed human arm is a more challenging FES control problem. Some muscles and joints remain under voluntary control while others are paralyzed and their contribution must be restored by the FES. The result is a man-machine system whose successful operation and acceptance by patients depend on proper coordination between the patient and FES.

To achieve a high level of integration and coordination in FES reaching, we are using a biomimetic control strategy. The control system has a hierarchical structure similar to that of the CNS, employs control circuits that take advantage of the complex intrinsic mechanical properties of the musculoskeletal system, and taps into the control and learning capacity of the patient's CNS (Fig. 2). The subject will signify his/her intention to move by voluntarily moving the upper arm, which is largely intact neurologically in most quadriplegic patients. From this voluntary movement, the FES controller must infer the patient's intended movement for the whole arm and generate appropriate FES control signals to complete the task.

The successful operation of the biomimetic control strategy depends on several factors but the most important will be the ability of patients to integrate with FES and produce adequate commands to drive the FES system. We are using a virtual reality environment to test such abilities in intact human subjects. In this environment, a subject moves his/her shoulder joint to control the movement of a simulated FES limb whose movements are presented from the patient's perspective via stereoscopic goggles. This test environment is helping us explore the capabilities of human subjects to produce the command signals for a multijoint FES system and optimal patient-FES interfaces.

3. RESULTS

Patients successfully learned the rowing exercise using either manual or automatic strategies.

The virtual reality experiments to date have been designed to validate the test environment by demonstrating basic psychophysical phenomena. An able-bodied subject was asked to reach a range of targets in 3D virtual workspace using different kinematic functions that derived distal joint motion from shoulder motion. The task completion times were measured to evaluate the difficulty of each patient-FES interface and the rate at which the subject learned to perform successfully the reaching task. The preliminary results showed that the virtual reality is a viable environment for testing and evaluation of the patient-FES interface and the subjects had no difficulty controlling a simulated arm in this environment. Further, the results showed that the task completion times decreased with practice, control of more degrees of freedom are more difficult and more intuitive interface strategies (the ones familiar to the subject) are easier to learn and more accurate in operation.

4. DISCUSSION AND CONCLUSIONS

In order to improve performance and patient acceptance, the FES systems must not only increase their level of sophistication but their level of integration with the patients. They should provide more intuitive man-machine interfaces that allow the patients to be in full control of the combined system.

In general, it is a desirable strategy to employ the residual movement capacity to operate the FES system. As shown in the manual control of FES rowing, this has several benefits. It greatly simplifies the control of the FES system by delegating the decision making to the CNS. By unifying the center of command in the CNS, the produced movement will be automatically coordinated. Also, the higher level of control by the patient could increase the acceptance and use of the FES system. The users are usually uncomfortable with FES systems they don't understand or can't control effectively.

The main disadvantage of the above strategy is that human subjects are limited in the number of variable they can control simultaneously. Therefore this strategy will not be effective in controlling multiple muscles, multiple joints, or when the relation between the muscle stimulation and the corresponding movement is too complex. In these applications the FES control system must be designed to handle the complexities of the musculoskeletal system and provide the patient with a man-machine interface that is easy to operate. For example, in automatic control of FES rowing, the low-level controller was kept separate from the high-level controller, which was responsible for patient-FES interface. So, more sophisticated muscle stimulation patterns were employed in the lower-level controller while keeping the patient-FES interfaces the same [4,5]. We are following a similar strategy in FES reaching which is a more complex man-machine coordination problem. We are developing a sophisticated FES controller that can be operated by the patient using a simple and intuitive interface. The expectation is that biomimetic FES controllers with natural man-machine interfaces will be easier to learn and operate by the patients.

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