

Closed-Loop Control for FES: Past Work and Future Directions

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Abstract

The spinal cord can be damaged by injury or disease, which can lead to medical complications including the loss of motor function. FES is one technique that can be used to replace lost motor function. Many potential clinical applications of FES require closed-loop control of electrical stimulation. This paper outlines the challenges to control that are presented by FES. Also, a set of design criteria for clinical FES applications is proposed; these criteria were developed with input from medical and technical personnel as well as spinal cord injured individuals. Lastly, a review of the state of the art in closed-loop control of FES is provided, and a framework for future work on clinical FES systems is suggested.

1. INTRODUCTION

Restoring motor function to individuals with spinal cord injuries (SCI) is an active research topic in rehabilitation engineering, and functional electrical stimulation (FES) can be used to achieve this goal. FES involves artificially inducing a current in specific motor neurons to generate a skeletal muscle contraction. FES can be used to induce joint movement by stimulating the flexor and/or extensor muscles of the joint. The resulting joint angle can be controlled by modulating the amplitude of stimulation. FES has been used for a wide range of applications including providing a tenodesis grasp to quadriplegic individuals [1], facilitating standing for individuals with complete SCI [2], providing FES-based cardiovascular exercise to SCI patients [3], and reinforcing gait patterns during walking for incomplete SCI patients [4].

To date, most FES systems that are in use outside of research labs are open-loop systems, meaning that the controller receives no information about the actual state of the system. These systems require continuous user input to perform well, which limits their usefulness to situations in which the user can devote his or

her full attention to operating the FES device. However, there are many potential applications of FES technology for SCI individuals that require the FES system to work autonomously. These applications include neuroprosthesis systems for balancing during standing, torso control during sitting, and FES-assisted walking. A critical step in the development of clinically useful¹ FES systems is finding a suitable algorithm for closed-loop control of the stimulation. This paper discusses the control challenges presented by FES, and presents a set of design criteria for clinical FES systems. Some existing strategies for closed-loop control of FES are reviewed, and a framework for future research in this area is proposed.

1.1. FES Control Challenges

FES presents several significant control challenges. First, muscle response characteristics are nonlinear and time-varying. The response of stimulated muscle changes nonlinearly as the muscle fatigues. Also, regular use of FES causes a training effect, so the response of the stimulated muscles changes over time as they become stronger and more fatigue resistant.

Second, certain motor reflexes at the spinal cord level may be preserved in individuals with spinal cord injury. These reflexes are often unpredictable and may impede joint movements. Spasticity is also common in SCI, and is characterized by varying degrees of increased muscle tone and hyperactive spinal reflexes. In the absence of supra-spinal signals, muscles can develop a tendency to maximally contract in response to a wide range of muscular or cutaneous stimuli, causing the limbs to be in an abnormally flexed position.

Third, the neuromuscular system is a highly coupled system; for example, the torque that can be exerted by the quadriceps muscle is a function of the knee joint and hip joint angles, among other factors. Fourth, there is a

¹ By “clinically useful”, it is meant that the device is used in the community, instead of in a research lab.

significant time delay between stimulation and the onset of a muscle contraction, in addition to the processing and transmission delays involved in the electrical stimulation system.

2. METHODS

A set of general design criteria for clinical FES systems are reported below. These criteria were developed with input from neurologist, physiatrists, therapists, engineers, and patients who have participated in FES programs at the Toronto Rehabilitation Institute and University Hospital Balgrist (Zurich, Switzerland) since 1997. In order to be clinically useful, a FES system must be portable, reliable for daily use, robust to changes in the response of the muscles to electrical stimulation, and easy to use. Specifically, any closed-loop algorithm that is to be used in a clinical FES system must:

1. compensate for the nonlinear, time-varying, and coupled nature of the muscle being controlled, including the effects of fatigue and training.
2. be stable in the presence of the time delays and perturbations (reflex contractions) that are inherent to the system.
3. be implemented in portable, battery powered electronics, and should be designed for at least 16 hours of operation each day (this operation may be intermittent, depending on the application).
4. be compatible with efficient setup and calibration procedures that are simple enough to be performed by a therapist or a patient. It should also be possible to easily incorporate the calibration procedure into the user's daily routine.

The system should be tested with individuals who are similar to the intended end user of the system. SCI subjects exhibit a significantly different response to electrical stimulation than healthy subjects, so the two types of subjects cannot be used interchangeably for testing purposes. Also, subjects should undergo a standard training process before testing begins in order to condition the muscles and increase their fatigue resistance.

3. RESULTS

Several strategies for closed-loop control of FES muscle contractions are reviewed below. Jaime et al [5] and Matjačić et al [6] implemented PID controllers for unsupported standing in paraplegic subjects. Matjačić et al

pointed out that the derivative action of such controllers tends to amplify high frequency noise, which can lead to system instability if the data is noisy. Hunt et al used H-infinity control [7, 8] and linear quadratic Gaussian control [9] for unsupported standing in paraplegic subjects. This group reported stable standing and were able to reject a 1 degree perturbation about the ankle joint.

Hatwell et al used a model reference controller for FES control of knee joint movement in paraplegics [10]. The controller tracked angles at the extremes of the range of joint movement quite well, but exhibited poor control of mid-range angles. The authors also noted that their algorithm assumed a linearized plant, and so may not compensate for the nonlinear recruitment characteristics of muscle and disturbances arising from spastic reflexes.

Chang et al reported a combined neural network/PID control system for FES-based knee joint control [11]. The neural network was trained to obtain the inverse dynamics of the knee, and was then used for feedforward control. The PID controller was used as a feedback controller in parallel with the feedforward controller to compensate for tracking errors caused by disturbances and modelling errors. The system was tested on one able-bodied subject and one paraplegic subject. The authors found that the combined neuro-PID controller performed better than classic fixed-parameter PID control.

Previdi and Carpanzano used a gain scheduling control strategy that interpolated between locally valid linear quadratic regulators for controlling FES-induced knee joint movement [12]. Each local regulator was designed based on a linearized local model of the knee joint behaviour, which was estimated from a set of input/output data. Ferrarin et al developed an adaptive control algorithm for FES-induced knee joint movement [13]. The controller used an inverse dynamic model of the quadriceps muscle to deliver stimulation to both the muscle and a direct dynamic model of the muscle. The error between the measured and predicted knee angles drove the adaptation mechanism. Error was minimized by iteratively updating two time-varying parameters of the direct model. The algorithms were tested with two paraplegic subjects. The authors found that the adaptive algorithm was better able to cope with fatigue than a PID feedforward/feedback algorithm. Jezernik et al used sliding mode FES control to

regulate knee joint angle [14]. The controller was tested on six neurologically intact subjects and two untrained paraplegic subjects. Good tracking of a desired knee joint trajectory was achieved for up to 8 seconds.

4. DISCUSSION AND CONCLUSIONS

The PID controllers reported in [5, 6, 11] could work for clinical FES applications, but would require the use of accurate sensors to avoid instability. The H-infinity controller described by Hunt et al showed promising results when rejecting a minor perturbation. However, its ability to perform in a more realistic situation where it is required to reject larger perturbations has yet to be determined. The model reference controller reported by Hatwell et al could be clinically useful if it was altered to work with a more realistic nonlinear plant. The gain scheduling controller [12] also shows promise for clinical FES applications provided that fatigued muscle can be accurately represented by the controller's model structure. Ferrarin et al reported promising results with their adaptive controller for healthy subjects; these results should be verified with SCI subjects. Jezernik's sliding mode controller may be a useful controller for clinical applications if its tracking time could be increased. In general, none of the reported controllers are capable of meeting the design criteria for clinical FES systems outlined above. Several of the controllers showed promise, but must be modified to be more robust to fatigue and perturbations, and must be tested with trained, SCI subjects to verify their effectiveness.

FES has been in existence since the 1960's, and yet few SCI patients have been provided with FES assistive devices. This is due in part to the challenges that controlling FES presents, including the nonlinear, coupled, and time-varying response of electrically stimulated muscle, the problems posed by fatigue, reflexes, and spasticity, and the time delays inherent in any FES system. Designing clinical FES is a very challenging task. However, the human body itself provides clear evidence that it is possible to control skeletal muscle contractions to perform useful work. We hope that this paper will provide the FES research community with a review of the state of the art in closed-loop control for FES, and will help to re-focus research efforts on getting FES out of the lab and making the technology available to as wide a range of people as possible.

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Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada for financial support.