Biomimetic Design of FES Control Systems

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Abstract
Control systems for functional electrical stimulation (FES) are usually based on explicit control of individual joint torques by individual muscles. However, the biological controller appears to use distributed spinal interneuronal circuits to control overall limb posture and reflex adjustments. The controllability and stability achieved by the biological sensorimotor system motivates a similar strategy for FES. We are using a combination of motion analysis, modeling and simulation methods to determine whether biomimetic FES controllers are feasible for reach and grasp tasks and whether they will improve the ability of the operator to take advantage of the residual voluntary control that is present in spinal cord injury and stroke patients.

Introduction
While microelectronic technology has provided sophisticated interfaces to interact with the nervous system (Smith et al., 1998; Loeb and Richmond, 2000), control of movements by electrically stimulated muscles (FES) has not benefited much from strategies for control of robotic manipulanda. The musculoskeletal system has its unique properties that are unlike robotic systems, including slow and nonlinear actuators and sensors arranged in partially redundant sets of mono- and multiarticular muscles. It would be difficult to demonstrate that such a system is controllable in the framework of conventional control theory. The graceful, effective and efficient movements generated by the intact biological sensorimotor (SM) system constitute an "existence proof" that control is indeed possible. We are using realistic mathematical models of the various components of the biological and prosthetic systems to understand which of their attributes are critical to achieving this high degree of controllability and stability.

FES controllers need to derive their command signals from the residual biological system of the patient. The hierarchical structure and adaptive capabilities of this system provide additional constraints on the design of the FES control system. Our modeled control systems are designed to reflect the natural hierarchy of the biological sensorimotor systems. We are using the models to address the question of how to distribute and manage the adaptive control that must occur at multiple levels of both the patient and the prosthesis.

Methods
1. Biological Sensorimotor Control
SM systems are organized into hierarchies whose details are unlike their robotic counterparts (Loeb et al. 1999, Lan and Crago, 1994). The highest levels of both robotic and SM systems involve abstract planning of movement (Flanders and Soechting, 1990), which is required to deal with kinematic redundancies of the multiarticulated limb or manipulandum. The planned movement must then be integrated with learned properties of the limb plus any external loads or perturbations to generate descending commands. In robotic systems, these commands are usually torques to be generated by torque motors operating at each joint and equipped with accurate sensors and fast servocontrol circuitry. In SM systems, the descending commands drive highly distributed interneuronal circuits in the spinal cord rather than individual motor nuclei. These circuits mix inputs from a wide range of sensory modalities and generate outputs with substantial delays due to nerve conduction and muscle activation. The spinal circuits are responsible for regulating the gross behavior of the musculoskeletal system in a stable manner (He et al., 1991; Li et al. 2000) so that a static posture is maintained or a repeatable pattern of motion is produced despite substantial computational noise and external perturbations.

The SM system has an extraordinary ability to learn to perform motor tasks under novel or altered conditions. This ability arises from both a high degree of plasticity in the central nervous system (CNS) and a rich and effective set of spinal interneurons with desirable patterns of connectivity. Thus the SM system, in spite of its inherent limitations, can perform sophisticated tasks through practice and learning.

2. Design of FES Control System
The combined system architecture is illustrated in Figure 1, in which an FES control system is driven by voluntary commands (filled arrow), and the FES induced movement (open arrows) is integrated with residual voluntary movement to complete a motor task.

Our model FES control system is shown in Figure 2. The patient generates command signals at the shoulder, which provides two degrees of freedom of shoulder translation and three degrees of freedom of glenohumeral rotation. The shoulder translations are reserved for controlling hand opening/closing and orientation independently. The glenohumeral rotations may be mapped to indicate distal arm postures, including elbow and wrist angles (Desmurget and Prablanc, 1997). The NN controller interprets these voluntary commands and learns to generate outputs to a regulator modeled after the spinal interneuron network. The interneuronal network generates the actual commands to the muscles after integrating feedback from
One important feature of the task is that the shoulder movements that are used to command the FES system are an integral and natural part of the reach and grasp task itself. The muscles that generate the command movements are endowed with proprioceptors that still provide information to the brain about the actual trajectory and reflected loads of the FES controlled limb. Voluntary adjustments of the force and length of these muscles can compensate directly for perceived errors in the movement both by changing the trajectory of the proximal limb segment and by the consequent changes in the command signals to the NN controller. We hope to take advantage of the natural adaptive control capabilities of the patient’s remaining SM system, which should be facilitated by designing the FES system according to biomimetic principles with which the SM is already familiar.

Results

1. System Design

The purpose of these modeling and simulation studies is to develop and evaluate adaptive FES systems for reach and grasp tasks. Our objective is to use voluntary shoulder and upper arm motions in C5/6 injury quadriplegic patients to control elbow, wrist and finger muscles to accomplish reach and grasp.

Our present focus is on building models of the individual components of the control system, so as to allow for simulation studies and training of the NN controller. The specifications of these component models are important in themselves, because they must eventually reflect a viable compromise between the features that are critical for controllability and features that are feasible to incorporate into the prosthetic portions of the FES system. Matlab/Simulink provides a convenient platform for building component models, integrating them into a system model, and for performing simulation and analysis.

2. Biomechanical Model

We are constructing a realistic arm and hand model for simulation studies. Commercially available modeling software, SIMM (Motion Analysis Corp., CA), allows construction of anatomically correct skeletons, definition of muscle points of origin and insertion, as well as musculotendon paths (Delp and Loan, 1995). The graphical arm model can be converted into a Simulink block in Matlab (Mathworks, Inc.) using a new software tool that interfaces SIMM with Matlab/Simulink (Davoodi and Loeb, 2001). The biomechanical model block is then connected to other component blocks. Preliminary work was focused on specification of a realistic arm model both for studying biological motor control and for training FES control systems. We are currently developing a full arm and hand model in collaboration with Palo Alto Veterans Administration Hospital, CA (Murray et al. 2000).

3. Muscle Model

The individual muscles are represented by a complex but physiologically accurate model based upon extensive experimental work in feline muscle. The model accounts accurately for the complex, interactive effects of length, velocity and stimulus frequency on force over the physiological ranges of each of these input variables in both fast-twitch and slow-twitch muscle fibers. The most important of these interactions include the effects of stimulus frequency on force-length and force-velocity relationships. We have since provided an extension of this model to human fiber types based upon the best available data, as described in Cheng et al., (2000). The muscle model is available as a Matlab program called Virtual Muscle™ from our website.

4. Sensors and Regulators

The modalities of biological sensory information include primary and secondary receptors in muscle spindles, Golgi tendon organs (GTO), as well as recurrent inhibition from Renshaw cells. The muscle spindles are probably most important because their unique structure and fusimotor gain control provide accurate kinesthetic information and a natural scheme for reference control of posture and movement (Houk and Rymer, 1981). A spindle model with \( \gamma \) static and dynamic fusimotor control and...
primary and secondary afferents is being developed for the purpose of this study. Initially, known connections of interneuronal regulators (Li et al. 2000) will be evaluated for their functional advantages, particularly their roles in regulating multi-muscle and multi-joint system behaviors.

Prosthetic sensory information that is likely to be available includes distance between intramuscularly implanted devices called BIONs (a similar modality to spindle afferents), EMG/ENG and accelerations (Loeb and Richmond, 2000). We will investigate how prosthetic sensory feedback will be used in combination with a spinal-like circuit to control FES reach and grasp tasks.

5. Command Signal Analysis

An inverse kinematic model of the upper extremity has been created using Vicon’s BodyBuilder software to calculate angular trajectories from marker data. The arm model has 9 degrees of freedom (DOF): 2 DOFs for shoulder translations, 3 DOFs for glenohumeral rotations, 1 DOF for the elbow, 1 DOF for forearm rotation, and 2 DOFs for the wrist. We are using the model to analyze experimental reach and grasp tasks. Preliminary data were collected from two normal subjects performing a reaching task. The outputs of the model were used to recreate the motion in SIMM and were found to be similar to those observed in experiments. A more extensive set of experiments is being planned to verify the inverse kinematic model. The plausibility of establishing a mapping between the shoulder posture and hand position and grasp will be explored from the complete sets of kinematic data for reaching tasks throughout the workspace relevant to a subject in a wheelchair.

6. Control and Learning

The NN controller computes the signals that drive the spinal interneuronal network in response to voluntary commands. Its outputs set the gains of the spinal network either for posture maintenance or for movement control. The weights of the NN controller will be tuned under expected operating conditions using the genetic optimization algorithm. Motion data from normal subjects will be used in training the NN controller. We are currently exploring plausible criterion functions of optimization, and evaluating the computational effectiveness of genetic algorithms in a PC platform.

Discussion

We are undertaking a modeling and simulation approach to understanding sensorimotor control, as well as to designing FES control systems based on biological motor control principles. Although FES stimulation and sensor technologies are still primitive compared to their biological counterparts, mimicking sensorimotor control in FES may achieve a degree of naturalness in the restored movements that may eventually facilitate the process of learning to use the system more effectively. This learning takes place in two levels: one occurs during training the NN controller using a realistic model, and the other involves patients (Hart et al., 1998) adjusting their residual voluntary movements to accomplish a motor task with FES assistance in the paralyzed degrees of freedom.

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References


