A BIOMIMETIC STRATEGY FOR CONTROL OF FES REACHING

R. Davoodi and G.E. Loeb
A.E. Mann Institute and Biomedical Engineering Department, University of Southern California
Los Angeles, CA 90089, USA, http://ami.usc.edu

Abstract: **Victims of spinal cord injury at the cervical level are usually left with a partially paralyzed arm whose upper arm is controlled voluntarily but the lower arm is largely paralyzed. Restoration of reach and grasp functions is essential for independence and quality of life of these patients. Here we describe a biomimetic approach for control of reaching that combines the residual voluntary control of the upper arm with functional electrical stimulation control of the paralyzed lower arm to restore reaching movement. A realistic biomechanical model of the human arm, able-bodied volunteers, and paralyzed patients will be used to develop, test, and deploy the proposed controller.**

I. INTRODUCTION

Because of the richness and variety of its movements, control of the human arm by the central nervous system (CNS) has been studied extensively [1-3]. Many studies have focused on the relation among the variables recorded from parts of the neuromusculoskeletal system such as the neural activity, muscle forces, and kinematic parameters. Others have proposed theories on how the CNS controls arm movements but none accounts well for the performance achieved despite the complexly nonlinear properties of both the sensors and the actuators. As a result, the task of restoring the lost functions to the paralyzed arm is very much like trying to repair a complicated system with little knowledge about its operational principles.

Nonetheless, the need of paralyzed patients for even a limited set of arm movements has motivated the development of several functional electrical stimulation (FES) controllers for reach and grasp functions [4-6]. Most of these systems have been limited to laboratories; commercial systems such as FreeHand® (NeuroControl Corp., USA) have had limited success. The acceptance and continued use by the patient are central to the success or failure of the FES systems. The patient must be convinced that in return for extensive surgeries and expenses, the FES system will achieve the goals of being easy to operate and maintain and producing useful and relatively normal-looking movements.

In our laboratory we have developed tiny general-purpose electrical stimulators known as BIONs® that are injected into muscles and powered and controlled by an RF magnetic fields generated by an external controller [7]. This could encourage the acceptance of FES systems by eliminating the need for extensive initial surgery and wiring inside the limb. Here we focus on another important aspect of acceptance by describing a strategy to develop and fit control systems that will achieve the clinical goals. The control system has a biomimetic architecture that is intended to integrate the known circuitry and capabilities of the CNS.

II. STRUCTURE OF THE CONTROL SYSTEM

The architectural design of the control system is driven mainly by the requirements of the task. The arm has to perform two basic functions, posture maintenance (PM) and point-to-point reaching (PTPR), under full voluntary control of the subject. To satisfy these requirements, the controller uses a hierarchical structure with the residual voluntary control of the upper arm by the CNS at the top, PM and PTPR controllers in the middle, and spinal-like regulator at the lowest level of the control hierarchy (Fig. 1). The biomimetic controller is a man-machine system that enables the CNS and artificial FES controllers to share the burden of controlling the partially paralyzed human arm by cooperation. The framework allows both control systems to work and adapt to each other's capabilities and weaknesses.

The operation of the system is under full voluntary control of the subject. When the subject voluntarily keeps his/her upper arm in a given position, the PM controller maintains the current position of the lower arm. When the subject moves his upper arm with the intention to perform PTPR movement, the PTPR controller drives the lower arm with a speed proportional to that of the upper arm and according to normal reaching synergies. Thus, the subject can modify the voluntary command signal during the execution of the movement to compensate for visible trajectory errors or for unexpected load or perturbation conditions that will be reflected back to and sensed by the intact shoulder muscles. When the upper arm stops, the PM maintains the currently reached posture. If the current posture is not satisfactory, corrective PTPR movements could be performed voluntarily.

III. DEVELOPMENT OF THE CONTROL SYSTEM BUTTOM-UP

A bottom-up approach is being used to design and test the components of the biomimetic control system.

A. Musculoskeletal System

The musculoskeletal system has unique properties that greatly influence the architecture of the control system. The control system will be more effective if it accommodates and takes advantage of intrinsic mechanical properties of the musculoskeletal system. To ensure that the whole system copes with this emergent behavior, we will use both actual subjects and realistic computer models of the human arm as a test-bed for design and evaluation of the FES controllers.

Because a computer model provides a safe and convenient environment for initial stages of control development, we have developed a realistic biomechanical model of the human arm (Fig. 2). The model represents an average adult arm and is based on data from cadaver measurements reported in the literature. Particular emphasis has been placed on the accuracy of parameters that are important for control, including the moment arms for muscles that act on multiple degrees of freedom and the range of sarcomere lengths over which each muscle operates. The model simulates a clinically relevant case seen often in quadriplegia in which the upper arm remains largely under voluntary control but active movement of the other arm joints must be restored through FES. The model has five segments and nine rotational degrees of freedom in five joints that are involved in 3D reaching tasks. Fifteen electrically stimulated muscles actuate elbow, forearm, and wrist joints [8].

We use a combination of commercial and custom software developed in our laboratory to model the arm in Simulink (Matlab) environment. We first develop the anatomical model of the arm in SIMM (Musculographics Inc., USA) as shown in Fig. 2. We then convert this anatomical model to a dynamic Simulink block using MMS, general-purpose software for converting any SIMM model to a Simulink block [9;10]. The muscles' force production and sensors (e.g. muscle spindle, Golgi tendon organs, accelerometers, inclinometers, etc.) are also modeled as Simulink blocks using general-purpose software developed in our laboratory: Virtual Muscle [11] and Virtual Sensor [12]. The modeling tools developed in our laboratory are available free of charge from http://ami.usc.edu.

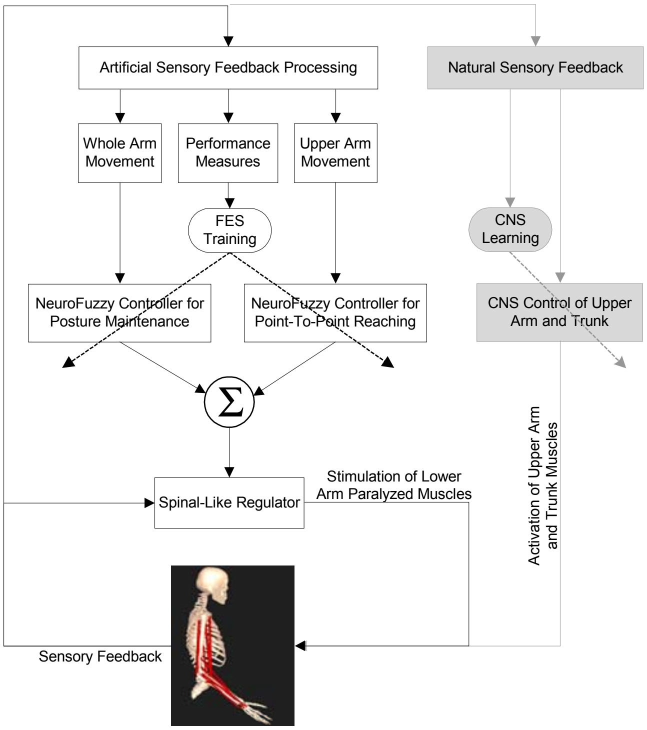

Fig. 1. Biomimetic design for FES control for partially paralyzed arm. Upper arm movement is under voluntary control and could be modified by the learning process of the CNS. The movement of the paralyzed lower arm is controlled by the FES that takes advantage of the CNS capabilities and known circuitry to form a flexible and adaptive controller for the arm.

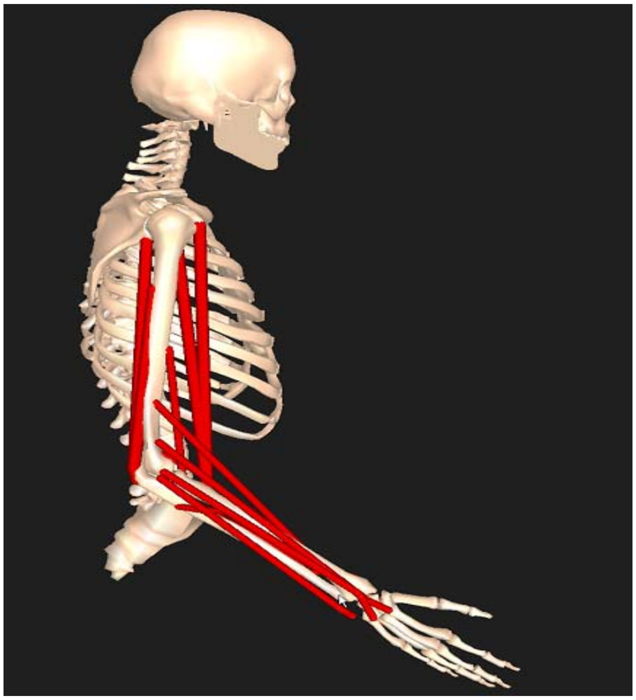

Fig. 2. Realistic biomechanical model of the human arm as a test-bed for evaluation of the FES reaching controllers.

B. Spinal-like Networks at the bottom of the control hierarchy

We know enough about spinal circuits and their functional capabilities to assume that they play a useful role as a buffer control circuit between the musculoskeletal system and the higher-level control centers in the motor cortex [13-16]. What we don't know is the exact nature of this role and the way these primitive circuits could be emulated in controllers for FES and robotics. We are interested in the notions that these circuits can be programmed by descending control to provide rapid, local regulation of stiffness and to transform the musculoskeletal system with large degrees of freedom to a limited set of primitive synergies that are easier to control by the higher-level controllers [14;15]. Therefore we are exploring the use of spinal-like control circuits that in combination with the prosthetic sensors and BIONic muscle stimulators could produce functionalities similar to those of the spinal circuits. These spinal-like circuits do not need to exactly mirror their biological counterparts as long as they exhibit similar capabilities. The obvious starting point is the known connectivity in the spinal cord that could be adapted to work with the new sensors and actuators. But we will also explore an evolutionary approach in which genetic programming can select spinal-like interneuronal circuits that would be suitable for the modified FES system that does not have access to the same sensors and actuators as the actual spinal cord. The critical aspect is the choice of optimization criteria so that the emerging circuits are useful components of the overall control strategy.

C. PM and PTPR Controllers

PM and PTPR are intermediate level controllers that control the activation of muscles by modulating the gain of the spinal-like circuits in order to maintain posture and produce point-to-point reaching movements. Because the outputs from these two controllers are added together, the transition from PM to PTPR and vice versa should be smooth and seamless. The PM controller will always provides output to compensate gravity for the current posture of the arm, similar to the specialized circuits that maintain standing postures [17]. This will greatly simplify the task for the PTPR controller because it will operate a musculoskeletal system whose degrees of freedom and complexity have been reduced by the spinal-like circuits and its nonlinear gravity term has been canceled by the PM controller. Voluntary movement of the upper arm will cause the PTPR controller to produce a control signal on top of that produced by the PM controller to move the lower arm from one point to another with a speed proportional to that of the upper arm. This will ensure equifinality of the upper arm and lower arm movements and will bring the lower arm to a halt when the upper arm stops moving. The control rules for the PTPR controller will be defined to ensure that the PTPR movements are produced according to normal reaching synergies. The incorporation of normal synergies in the PTPR controller should make it familiar to and learnable by the motor cortex, as will be described later. When the speed of upper arm movement is zero (or less than a threshold) PTPR will behave like a feedback controller to help PM maintain the currently reached posture. The reason for using the current posture instead of a projected posture is that it can be measured on-line (as soon as the upper arm stops moving) and provides greater flexibility. The predefined desired postures and trajectories are too rigid and difficult to plan a priori so that they are synchronized with the subjects voluntary movements. The combination of PM and PTPR controllers provide a flexible framework that allows the user to voluntarily perform successive point-to-point reaching movements similar to that proposed by the equilibrium point hypothesis [1]. We will use Neurofuzzy controllers for both the PM and PTPR controllers. Neurofuzzy control combines the capabilities of the fuzzy and neural network controllers. This enables us to incorporate heuristics by having an expert in motor control or biomechanics handcraft the rules of a working initial controller. If necessary, this initial controller could be refined further using neural network training algorithms such as genetic algorithms and reinforcement learning [18;19].

D. Artificial Sensory Feedback Processing

The large number of bulky sensors and their associated wiring are one of the main drawbacks of the feedback control in FES systems. We are currently developing second-generation BIONic stimulators with miniature sensors to replace the signals normally received from the proprioceptors. The possible sensors include accelerometers, gyroscopes, bionic spindles that measure the distance between the two BIONs, and EMG/ENG [7]. These unobtrusive, wireless sensors will be implanted as needed into the muscles and bones. Despite their convenience, the signals from these sensors are somewhat nonintuitive and difficult to interpret by the human expert, not unlike the signals from naturally occurring proprioceptors. When possible, we will incorporate the signals from these sensors directly into the control system structure without any transformation. For example, spinal circuits that normally work with the proprioceptors will be redesigned to work with these sensory modalities. But additional coordinate transformation will be required to estimate angular positions and angular velocities of the joints and the position of the hand in the workspace. These more intuitive signals can be used by the human expert to define the initial control rules of the fuzzy controller or by the learning algorithm to assess the performance of the control system.

E. Man-Machine Cooperative Control System

The residual voluntary control of the CNS over the upper arm in the highest level of the control hierarchy is responsible for planning, initiation, execution, and termination of the movements. This kind of complete voluntary control over the movement is essential for the acceptance of the FES control system. FES controller, on the other hand, operates as a slave to the CNS controller. It does not initiate any movement but tries to coordinate its activities with the CNS to successfully accomplish the task initiated by the CNS. The FES controller replaces the low-level sensorimotor circuitry that has been lost or bypassed as a result of the clinical disorder.

F. Learning and Adaptation

Learning and adaptation could occur in both CNS and FES controllers during initial training and later to adapt to the changing physical parameters in response to chronic FES. In theory both controllers could learn simultaneously to cooperatively control the same plant. The advantage of the simultaneous learning is that a global objective function could be used as a unifying factor to achieve a coordinated action. Because both controllers have to achieve the same objective, they have to synchronize their control actions [18;19]. However, the dynamics of two controllers learning simultaneously to control the same plant is largely unknown and there are no known algorithms to ensure stability and convergence, especially when one of the controllers is the CNS. Further, it is not clear how the learning process in the CNS reacts to a changing system or what is the optimal rate of change that the CNS can deal with. We will study the dynamics of mutual learning to find the best strategy but we will start with simple scenarios in which only one controller can learn at a time. For example, the FES controller can be adapted off-line using the model of the patient and then fixed to provide the CNS with a well-behaved system.

IV. SUMMARY AND CONCLUSIONS

We are using a biomimetic approach for restoration of the lost functions to the partially paralyzed human arm. A FES controller is being designed according to biological motor control principles and the known connectivity of spinal interneuronal circuits to facilitate the restoration of the CNS control over the paralyzed lower arm. 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.

ACKNOWLEDGEMENT

Funded by Alfred E. Mann Institute for Biomedical Engineering, University of Southern California.

REFERENCES

[1] E. Bizzi, N. Accornero, W. Chapple, and N. Hogan, "Posture control and trajectory formation during arm movement," *J. Neurosci.*, vol. 4, 2738-44, 1984.

[2] M. Kawato, Y. Maeda, Y. Uno, and R. Suzuki, "Trajectory formation of arm movement by cascade neural network model based on minimum torque-change criterion," *Biol. Cybern.*, vol. 62, pp. 275-288, 1990.

[3] R. Shadmehr, F. A. Mussa-Ivaldi, and E. Bizzi, "Postural force fields of the human arm and their role in generating multijoint movements," *J. Neurosci.*, vol. 13, pp. 45-62, 1993.

[4] K. L. Kilgore, P. H. Peckham, G. B. Thrope, M. W. Keith, and K. A. Gallaher-Stone, "Synthesis of hand grasp using functional neuromuscular stimulation," *IEEE Trans. Biomed. Eng*, vol. 36, pp. 761-770, 1989.

[5] Popovic, D., Popovic, M., and Crago, P. E., "Nonanalytical Control For Assisting Reaching In Humans With Disabilities," in Winters, J. M. (ed.) *Biomechanics and Neural Control of Movement* Springer-Verlag, 1997.

[6] A. Prochazka, M. Gauthier, M. Wieler, and Z. Kenwell, "The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia," *Arch. Phys. Med. Rehabil.*, vol. 78, pp. 608-614, 1997.

[7] G. E. Loeb and F. J. Richmond, "BION implants for therapeutic and functional electrical stimulation," in Chapin, J. K. and Moxon, K. A. (eds.) *Neural prostheses for restoration of sensory and motor function* CRC Press, 2000.

[8] R. Davoodi and G. E. Loeb, “A computer model of the human arm to study the control of FES-assisted reaching,” Proceedings of the 24th annual international conference of the engineering in medicine and biology society, 2002.

[9] R. Davoodi and G. E. Loeb, "A Software Tool for Faster Development of Complex Models of Musculoskeletal Systems and Sensorimotor Controllers in Simulink," *Journal of Applied Biomechanics*, vol. 18, pp. 357-365, 2002.

[10] R. Davoodi, I. E. Brown, and G. E. Loeb, "Advanced modeling environment for developing and testing FES control systems," *Med Eng Phys*, vol. 25, 3-9, 2003.

[11] E. J. Cheng, I. E. Brown, and G. E. Loeb, "Virtual muscle: a computational approach to understanding the effects of muscle properties on motor control," *J. Neurosci. Methods*, vol. 101, pp. 117-130, 2000.

[12] M. Mileusnic, I. E. Brown, and G. E. Loeb, Development of a Muscle Spindle Model. Proceedings of the 24th annual international conference of the IEEE Engioneering in Medicine and Biology Society, 2002.

[13] G. E. Loeb, J. He, and W. S. Levine, "Spinal cord circuits: Are they mirrors of musculoskeletal mechanics?," *J Mot. Behav.*, vol. 21, pp. 473-491, 1989.

[14] G. E. Loeb, W. S. Levine, and J. He, "Understanding sensorimotor feedback through optimal control," *Cold Spring Harb. Symp. Quant. Biol.*, vol. 55, pp. 791-803, 1990.

[15] G. E. Loeb, I. E. Brown, and E. J. Cheng, "A hierarchical foundation for models of sensorimotor control," *Exp. Brain Res.* , vol. 126, pp. 1-18, 1999.

[16] G. E. Loeb, "Learning from the spinal cord," *J Physiol*, vol. 533, 111-117, 2001.

[17] S. Mori, K. Matsuyama, J. Kohyama, Y. Kobayashi, and K. Takakusaki, "Neural constituents of postural and locomotor control systems and their interactions in cats," *Brain and Development*, vol. 14, pp. S109-S120, 1992.

[18] R. Davoodi and B. J. Andrews, "Computer simulation of FES standing up in paraplegia: A self-adaptive fuzzy controller with reinforcement learning," *IEEE Trans. Rehabil. Eng.*, vol. 6, pp. 151-161, 1998.

[19] R. Davoodi and B. J. Andrews, "Optimal control of FES-assisted standing up in paraplegia using genetic algorithms," *Med. Eng Phys.*, vol. 21, 609-617, 1999.