CHARACTERIZATION AND CONTROL OF MUSCLE RESPONSE TO ELECTRICAL STIMULATION

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The maintenance of upright posture in neurologically intact human subjects is mediated by two major nervous pathways. The first, leading from the cerebral cortex through the spinal cord to motor neurons, activates muscles which produce postural movements. The second, leading from various sensory organs to higher centers, provides sensory feedback regarding the postural state. The path through the spinal cord is no longer intact in victims of spinal cord injury and loss of normal control of muscle activity results. Functional neuromuscular stimulation (FNS) has been shown as a feasible method for obtaining muscle contraction in paraplegics and has been proposed as a means for control of antero-posterior sway to make upright posture possible for these individuals. Before muscle can be controlled through the use of FNS, the response of muscle to electrical stimulation must be understood. In past studies, linear control theory has been applied to the analysis of this response and to the testing of various controllers. The aim of this study was to demonstrate some control issues in FNS using linear control theory, as it applies to electrical stimulation of muscle for stabilization of posture. The linearity of the muscle response was improved through closed-loop control using pole compensation techniques. The excess phase shift of the system due to the time delay in the muscle response, however, limits the ability to increase the open-loop gain in order to obtain improved performance. A suggestion for further study is the application of this methodology for uses in posture control.

Keywords—Muscle, Electrical stimulation, Control theory, Spinal cord injury.

INTRODUCTION

Most upper motor neuron paralyzed muscles can be made to contract by the application of an electrical stimulus. This fact has lead to the exploration of Functional Neuromuscular Stimulation as a potential rehabilitation method to restore functional
movement. Applications of electrical stimulation to the control of paralyzed muscle have been studied since the 1960s (17). Studies have applied open-loop stimulation to the muscles of the legs to obtain crude gait in paraplegic individuals (5,9,12). When using FNS to invoke muscle activity, the force obtained from the muscle is sensitive to sources of variability in the stimulation system as well as the physiological system (16). Stable, repeatable control is desired over a wide range of conditions which include electrode shifting, muscle fatigue and other factors which make control of the muscle difficult. Open-loop control is subject to non-linear and non-repeatable input-output relationships due to sources of variability (3,16). A properly designed closed-loop control system can reduce the sensitivity to these disturbances and increase the repeatability of results (4,14,18). Nevertheless, open-loop control of muscles to stabilize the knees during standing has been successful (9). One of the first experiments involving the application of FNS to standing in paraplegics was conducted by Kantrowitz in 1960; standing was produced in a T-7 paraplegic by open-loop stimulation of the vasti and glutei muscles. The electrical stimulation, delivered through surface electrodes, was used to produce hip and knee extension, therefore causing the subject to rise from sitting to standing; it was necessary, however, for the subject to use his arms for balance (8).

Many studies of the control of electrically stimulated muscle illustrate the need for a systematic approach towards identification of the characteristics of stimulated muscle. Once the entire system has been identified, a closed-loop controller can theoretically be designed and tested and predictions of system performance under varying conditions can be made. Current approaches to system identification in this application include white noise methods (11,18) and discrete-time recursive weighted least-squares identification (18). A third method of system identification which could be used for this application is small signal linear system identification. It has been noted that this technique may actually be highly appropriate for this application (18).

The single-link inverted pendulum model of posture suggests a static value of ankle torque about which small amplitude regulation occurs (6,7). Small signal linear identification involves the application of low amplitude sinusoidal stimulation at various operating points; therefore, the range of torque produced at the ankle approximates the range of operation during quiet standing posture as described by the single-link inverted pendulum model. The frequency of the perturbations is stepped through a range of discrete values. These values are spread over the expected operating bandwidth of the muscle. This process is fully automated and the analysis is completed in a short time compared to the time necessary for analysis of spectra resulting from random inputs to the system. In view of these advantages and the lack of extensive published data on this technique in this application, the small signal linear system identification method was used for this study. Small signal identification has been extensively used in studies of the myotatic reflex, where small amplitude sinusoidal changes in length have been applied to muscle fiber to study the resulting muscle spindle discharge (e.g. 13).

**METHODODOLOGY**

**Subjects**

This study was conducted using two groups of human subjects, under protocols approved by the IIT Institutional Review Board. The first group consisted of neurologically intact subjects having no present or previous complaints of neurological