Control of Ankle Position using Neural Feedback

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***Abstract*-This paper describes a closed loop control system that uses afferent neural activity from muscle spindle fibers as feedback for controlling ankle position. The gastrocnemius muscle was stimulated through a dual channel intrafascicular electrode implanted in a fascicle of the tibial nerve. Dual channel intrafascicular electrodes were also used to record spindle fiber activity from the tibialis anterior and the lateral gastrocnemius muscles to estimate ankle joint angle. Experiments were conducted in neurally intact anesthetized cats and in unanesthetized decerebrate cats to demonstrate the feasibility of this control scheme.**

I. INTRODUCTION

Restoration of functional control to paralyzed limbs and muscles through neuromuscular stimulation has been an area of active research for many years [1,2,3]. Functional neuromuscular stimulation systems (FNS) using closed loop automatic control schemes with feedback from artificial force and joint position sensors have improved the precision and accuracy of artificially activated limb positioning by compensating for muscle fatigue and other external perturbations.

An alternative to using artificial sensors is to use the natural sensors which are already present within the body. During natural volitional control of muscles, sensors such as muscle spindles and Golgi tendon organs relay muscle length and tendon force information from the limb through the peripheral nervous system to the central nervous system. These natural sensors remain intact and active in the paretic limb below the level of lesion in spinal cord injury patients. The use of natural sensors would eliminate the durability and cosmetic problems associated with artificial external sensors, but requires that the information be extracted from peripheral nerves.

The present study used intrafascicular electrodes to record from and stimulate peripheral nerves [4,5]. A simple closed loop control system that uses afferent neural activity from muscle spindle fibers as feedback was developed for controlling ankle position (fig 1). The system was evaluated on a neurally intact anaesthetized feline model.

II. METHODS

Acute experiments were conducted on 10 adult cats (Body Weight, 3.6±1.1 Kg) anaesthetized with sodium pentobarbital. Dual longitudinal intrafascicular electrodes (dLIFE) were implanted into single fascicles innervating the medial gastrocnemius, lateral gastrocnemius, and tibialis anterior muscles. The medial gastrocnemius dLIFE was used for stimulation while the lateral gastrocnemius and tibialis anterior dLIFEs were used for recording. All electrodes were implanted within a few centimeters of the innervation zone of their target muscles. Since this placed the recording electrodes in close proximity to the stimulating electrodes and the active muscle, EMG and stimulus artifact noise were suppressed by using an isolated stimulator, wrapping the implanted fascicle with a flexible Faraday shield, and using differential dual channel recordings.

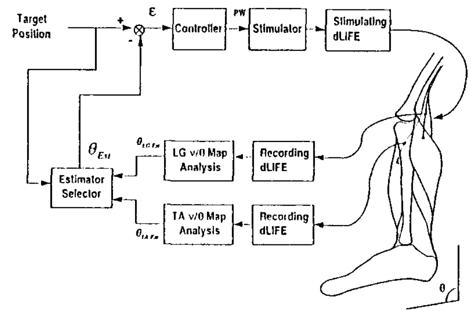

Fig 1. Schematic system diagram. The animal preparations consisted of three dual longitudinal intrafascicular electrodes (dLIFE). The afferent activity from muscle spindles in the tibialis anterior and lateral gastrocnemius muscles were recorded through two recording dLIFEs and used to estimate ankle position. A PI controller modulated the stimulus strength based upon this estimated ankle position presenting the stimulus through a dLIFE implanted into a fascicle innervating the medial gastrocnemius muscle.

The ankle position was estimated by correlating the joint angle to the frequency of recorded multiunit activity using an activity to joint angle map similar to those in [6, 7]. Maps were generated by externally sweeping the ankle joint through the range of motion of the joint. The joint angle estimate was found by matching the frequency of recorded activity to the closest frequency in the joint angle map. Since a good correlation to joint angle only exists during movements that result in the stretching of the muscle spindles, the joint angle was estimated using the activity from lateral gastrocnemius during dorsiflexion, and from tibialis anterior during plantar flexion.

A PI controller was implemented to modulate the pulse width of a fixed amplitude, 50 Hz stimulus train activating medial gastrocnemius based upon the error between the target joint angle and the estimated joint position. To demonstrate control of the ankle joint using this system two tests were devised: a joint angle hold test and a joint angle tracking test.

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In these tests the ankle was loaded at the foot pad through a mechanical arm linked to a servocontrolled DC motor. The ankle joint positions were measured through a potentiometer coupled to the mechanical arm. A load cell mounted at the end of the mechanical arm directly measured the load force on the cat's footpad.

III. Results

A. Joint Angle Hold Test

The joint angle hold test required the system to stimulate the gastrocnemius muscle to maintain a fixed target joint angle in the presence of an external load varying between 100 and 300 g. Five target positions were evaluated: 95°, 102°, 110°, 117°, 125° (neutral ankle position = 90°). Figure 2 shows the results of this test.

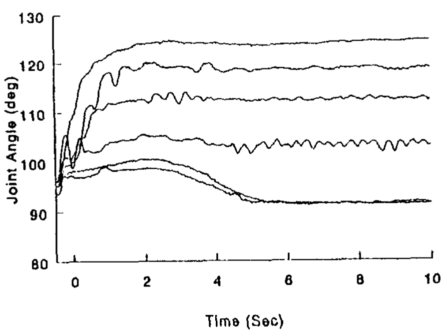

Fig. 2. The joint angle hold test results for the 5 target joint angles showing the ankle joint angle during the runs

B. Joint Angle Tracking Test

The tracking test required the ankle to track a sinusoidal target while loaded with a constant force load at the footpad. Sinusoidal trajectories for five different cycle frequencies 2.5, 1.25, 0.625, and 0.313 Hz were tested at four different conditions of load and angular amplitude of the trajectory: 35° range with a 500 g load, 35° range with a 300 g load, 20° range with a 500 g load, and 20° range a with 300 g load. Figure 3 shows a typical experimental run.

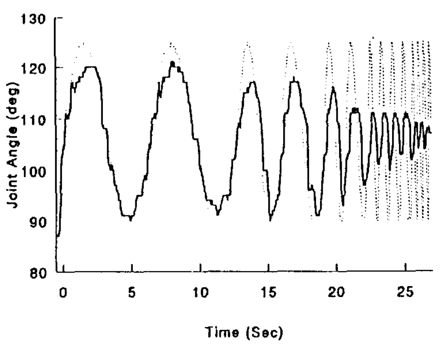

Fig. 3. Typical joint angle tracking run. The condition tested in this run was to track a sinusoidal trajectory over a 35° range with the ankle loaded with a 300 g force at the footpad. The dotted line indicates the target joint angle.

IV. Discussion

The results from the joint angle hold tests indicate that the control scheme was able to reach and maintain the target joint position while compensating for muscle fatigue and a varying external load within the physiological range of motion for ankle extension (90° ≤ joint angle ≤ 120°). The joint angle tracking test indicate that the system was able to track trajectories cycling at less than 1 Hz. Tracking performance did not differ significantly for the four different amplitude/load conditions tested. The performance for trajectory cycle rates greater than 1 Hz degraded probably due to the "acceleration sensitivity" of muscle spindles [8,9]. The nominal errors in positioning the ankle in both the joint angle hold test and the trajectory tracking test were about 4 to 7°, which are on the order of the linear directionality errors seen for relaxed human subjects [6]. We conclude that the neural feedback scheme could be used to provide useful feedback in a closed loop FNS system.

V. References

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