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Motion Control of the Rabbit Ankle Joint Using a Flat Interface Nerve Electrode

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Abstract—A **flat interface nerve electrode (FINE) improves spatial fascicular selectivity by reshaping a peripheral nerve and realigning the fascicles inside the nerve trunk. Enhanced fascicular selectivity enables the control of different muscles with a single electrode. However, building a control algorithm using a multi-contact nerve electrode is a challenging problem due to the complexities of the neuromuscular skeletal systems. We developed a motion control algorithm for the neuromuscular skeletal systems using a FINE. The proposed control algorithm separates the static and dynamic properties and finds an inverse model efficiently with little prior knowledge of the system. The algorithm was tested on the motion control of the rabbit ankle joint with a FINE placed on the sciatic nerve. The results show good tracking performance of the proposed control algorithm.**

Keywords—**Flat Interface Nerve Electrode, Motion Control, Functional Electrical Stimulation**

I. Introduction

Electrical stimulation of a peripheral nerve can restore volitional motion control of paralyzed muscles by stimulating the nerve and thus activating the muscles innervated by the nerve. Nerve cuff electrodes reduce the damage to the nerves compared to more invasive electrodes, and multi-contact nerve cuff electrodes have been used to reduce the number of implanted electrodes while trying to maintaining selectivity [1][2]. Generally nerve cuff electrodes show less selectivity because of relatively long distance from a contact to the target axons. Among nerve cuff electrodes, a flat interface nerve electrode (FINE) increases fascicular selectivity by reshaping a nerve and realigning the fascicles inside the nerve trunk [3]. The increased spatial selectivity enables controlling different muscles with a single electrode.

Developing a control algorithm for functional electrical stimulation (FES) is a challenging problem due to the inherent complexities of the neuromuscular skeletal systems and the difficulties in the nerve-electrode interface. The neuromuscular skeletal system complexities include nonlinear, time varying, time delayed, strongly coupled and redundant properties. Unlike natural neural excitation, the electrical stimulation of a nerve causes limitations in FES control due to the reversal of the recruitment order, charge spillover to the unwanted axons, and increased muscle fatigue due to higher frequency stimulation than natural excitation to reduce the ripples in the muscle force, etc. [4]. In addition, lack of the accurate models of the neuromuscular skeletal systems aggravates the difficulty in building FES control algorithm. The modeling difficulties are mainly due to large parameter variations among the subjects and the lack of the noninvasive methods to measure model parameters and structures such as muscle force and fascicular distribution inside a nerve trunk.

In this paper, we propose a control algorithm for FES motion control using a multi-contact FINE. In this algorithm, no mathematical modeling procedure is required. Instead, an inverse model of the system is obtained efficiently with input and output data by separating steady state properties from dynamic properties [5]. The control algorithm was tested on the motion control of the rabbit ankle joint.

II. Methodology

Animal Preparation

New Zealand White rabbits were used for the acute experiments. Animals were initially anaesthetized with the injection of ketamine (80mg/kg) and xylazine (8mg/kg), and then maintained with isoflurane mixed with pure oxygen or medical gas. The sciatic nerve around the branching point to tibial and common peroneal nerve was exposed and a 14 contact FINE (7 contacts on one side and 7 contacts on the other side) was placed around the sciatic nerve proximal to the branching point. The knee joint was fixed at approximately 90° and the foot was attached to the armature of the measurement instrument.

Instrumentation

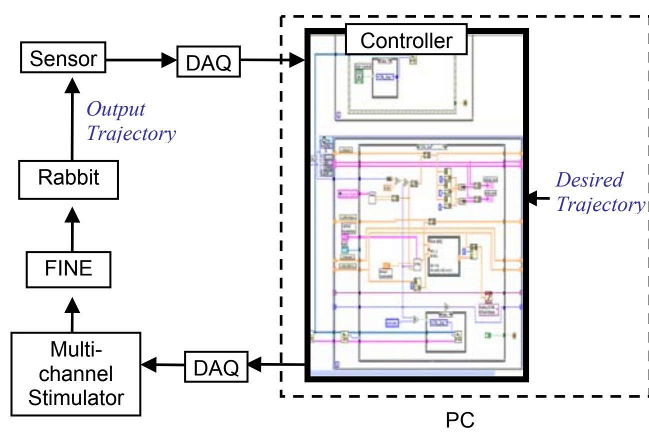


Fig 1. Block diagram of the closed loop control mechanism of the rabbit ankle joint

Figure 1 shows the block diagram of the closed loop motion control mechanism of the rabbit ankle joint. The ankle joint angle (dorsiflexion/plantar flexion) and the subtalar joint angle (inversion/eversion) are measured with an angle encoder and a potentiometer respectively. The controller was implemented using LabView (National Instruments) in a PC. As shown in figure 2, the multi-channel current stimulator has a A-M Systems 2200 analog stimulus isolator (A-M Systems, Inc.) in order to convert the voltage stimulus waveform from the PC to the corresponding current waveform (x100μA/V), and two 8 channel analog multiplexers MAX308 (Maxim Integrated Products, Inc.) to assign the current pulses to the proper contacts. The multi-channel stimulator is optically isolated from the PC and powered by batteries. As shown in figure 2-(b), the outputs of the controller are the control signal (Ctrl) and the stimulation pulse signal (Stim). Only one channel becomes active at one time sequentially, and the corresponding current pulse is passed from the analog stimulus isolator to the active channel. In this way, the stimulation waveforms of the 14 contacts can be controlled with just two analog output channels of the data acquisition (DAQ) board (NI PCI-6221). The stimulation frequency was set to 33Hz to generate tetanic contraction, and charge balanced biphasic cathodic first current pulses were used and the pulse width at each phase was set to 50 μs. The time delay between the stimulus pulses at two adjacent contacts was 200 μs, which is less than the refractory period in neural firing. The pulse amplitude at each channel is modulated by the controller.

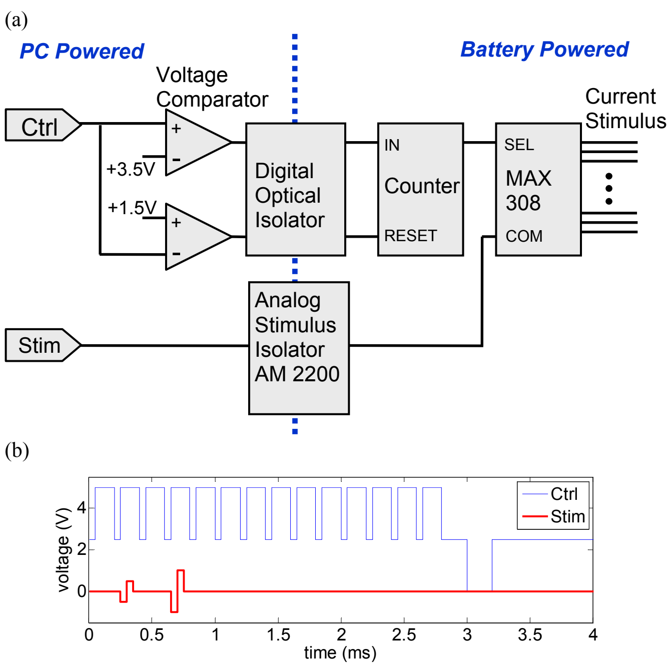


Fig 2. (a) Multi-channel stimulator block diagram (b) The control waveform (Ctrl) for polling each contact and an example of the stimulus waveform (Stim)

Controller design

The proposed controller is composed of an inverse steady state controller (ISSC), a feedforward controller, and a feedback controller as shown in figure 3. To build an ISSC, the contacts with lowest threshold for dorsiflexion or plantar flexion are selected among 14 contacts. Then, by changing the stimulation amplitudes at these contacts, input-output data at quasi-steady state, which is defined as 1 second after stimulation with zero initial conditions, are obtained. ISSC stores the inverse mapping of the input output relation in a table using linear interpolation. A feedforward controller is a dynamic inverse model of the combination of ISSC and the system in series. An autoregressive moving average (ARMA) model is used to model the forward dynamics of the combination of the ISSC and the system, and the inverse of the ARMA model is used as a feedforward controller. A recursive least square (RLS) method is used to find the coefficients of the ARMA model. A linear PD controller was used as a feedback controller to compensate for system variations and the inaccuracy of the feedforward controller.

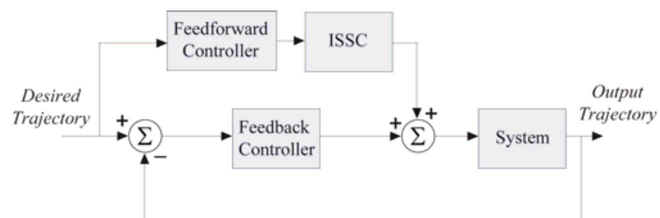


Fig 3. The controller structure

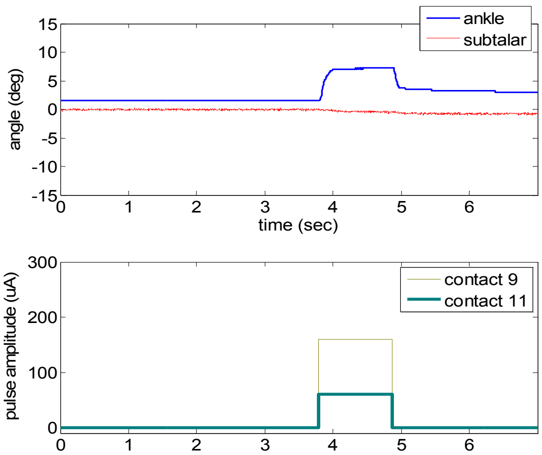
III. Results

Examples of the results of the stimulation with constant amplitudes, pulse width and frequency for one second are shown in figure 4. The current stimulation with constant parameters made the ankle joint angle converge to certain values depending on the pulse amplitudes. In this experiment, contact 9 and 11 generated dorsiflexion and plantar flexion with the lowest thresholds respectively. However, there was little inversion/eversion motion for any of 14 contact stimulation. An ISSC was built upon these steady state input-output data and the result is shown in figure 5.

To build a feedforward controller, low pass filtered random trajectories with cut-off frequency of 1Hz were used as reference trajectories. These command signals were applied to the ISSC while the feedforward and feedback controllers were disconnected. Then the obtained system output trajectories and the reference trajectories were used to train the feedforward controller. The PD gains were manually tuned by trial and error.

The results of the proposed controller for the sinusoidal reference trajectories with two different frequencies are shown in figure 6. The RMS errors for the signals with the frequency of 0.5 Hz and 1.0 Hz were 1.2° and 1.4° respectively, which are less than 10% of the amplitude of the reference trajectories. These results indicate good tracking performance of the proposed controller.

(a)



(b)

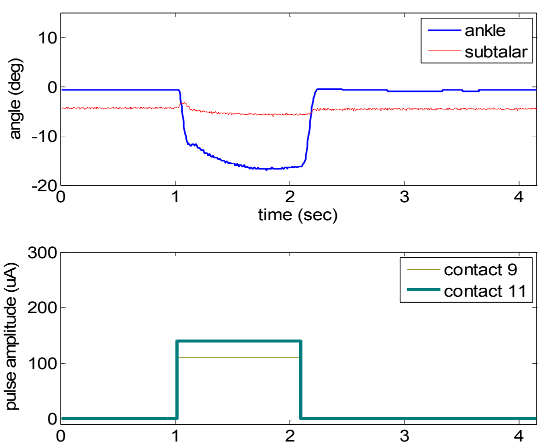


Fig 4. Examples of the nerve stimulation with constant amplitudes. The pulse width is 50μs, and the stimulation frequency is 33Hz.

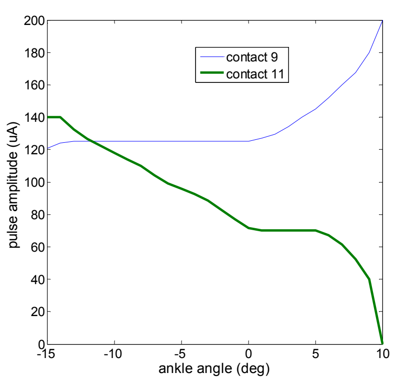
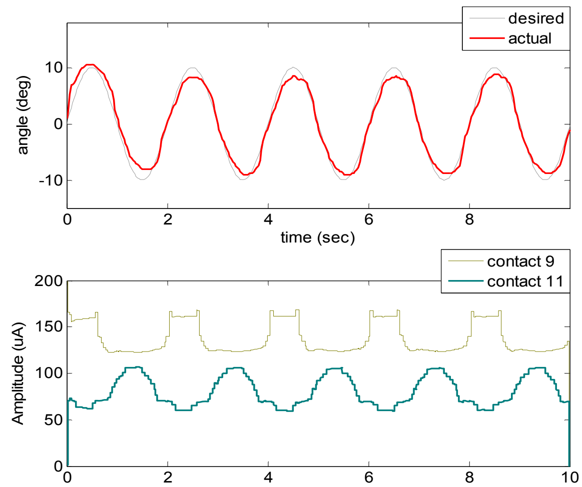


Fig 5. ISSC is built with steady state input-output data

(a)



(b)

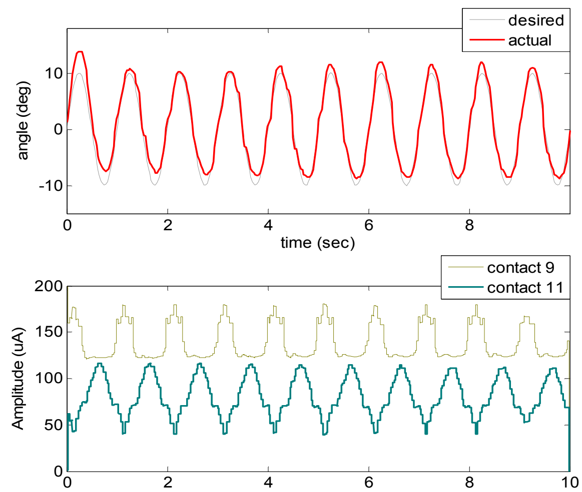


Fig 6. Results of the proposed control algorithm for sinusoidal reference trajectories with the frequency of (a) 0.5 Hz and (b) 1.0Hz. The pulse amplitudes at the corresponding contacts are modulated while the pulse width and stimulation frequency were fixed.

IV. Conclusions

An algorithm for FES control using a FINE was developed and tested on the motion control of the rabbit ankle joint by stimulating the sciatic nerve. The proposed control algorithm found an inverse dynamics model of the system using only input-output data by separating steady state properties from dynamic properties. For the rabbit experiments, a closed loop controller was implemented. The electrical stimulation of a multi-contact FINE on the sciatic nerve could control the motion of the ankle joint within small errors. However, the inversion/eversion motion could not be successfully generated due to either anatomical structure of rabbit ankle-subtalar joint system or lack of the sufficient fascicular or subfascicular selectivity.

ACKNOWLEDGMENT

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