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Fuzzy Logic Control of Ankle Movement Using Multi-electrode Intraspinal Microstimulation

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Abstract— **In this paper, we propose a fuzzy logic control (FLC) for control of ankle movement using multi-electrode intraspinal microstimulation (ISMS). It has been demonstrated that ISMS via multi-electrode implanted into a given motor pool has several advantages over the single-electrode ISMS. In the current study, we investigate the closed-loop control of ankle movement using multi-electrode ISMS. For this purpose, a pair of electrodes was implanted into the each motor pool of dorsiflexor and plantar flexor muscles in the spinal cord. For each muscle, an independent FLC was designed. The response of neuromuscular system has a time-delay with respect to the input stimulation. To compensate the effect of time-delay, the future value of desired response was considered as the input of the FLC as well as the error signal. The results of experiments on animals show that the proposed control framework can provide a good tracking performance.**

I. Introduction

Intraspinal microstimulation (ISMS) has been proposed as a means to activate the paralyzed skeletal muscle through electrical stimulation of the lumbo-sacral portion of the spinal cord. It has been demonstrated that ISMS has several advantages over peripheral nerve or direct muscle stimulation [1]-[2]. It was shown that graded muscle contraction in individual muscle or muscle groups could be generated by electrically stimulating motor neurons in the lumbo-sacral spinal cord [1]-[2]. The gradual force recruitment characteristics of ISMS have been attributed to its ability to activate motor neurons in a near normal physiological order based on their size [3]. It was demonstrated that intramuscular stimulation is characterized by rapid muscle fatigue and that ISMS is able to elicit prolonged and stable force generation [4].

Although ISMS is expected to have several advantages over peripheral nerve or direct muscle stimulation, several challenging problems remain to be solved. An important issue is the selective stimulation of the hind limb muscles. Mushahwar et al. [5] demonstrated that the selective activation of muscle groups can be achieved through ISMS. They showed that the selective activation of quadriceps, tibialis anterior or triceps surae/plantaris muscles occurs when the target muscle's motor pool is directly stimulated. However, increasing the stimulation intensity to increase the force level and the ranges of motion causes the spread of current to adjacent motor pools and the activation of the other motor pools.

To solve this problem, we have already demonstrated that the selective activation of the muscle can be enhanced by delivering the stimulation signal through the electrodes at multiple locations within a given motor activation pool [6].

Mushahwar et al. [7] showed that fatigue is essentially eliminated by interleaved stimulation when the stimuli are delivered through two separate electrodes simultaneously in an interleaved manner. Tai et al. [2] used three different electrode combinations (single electrode only, electrode pairs and three electrodes) for evaluating the effects of multielectrode ISMS. They showed that the isometric torque evoked by ISMS with a three electrode combination could be enhanced or suppressed when compared with that evoked by single or paired electrode stimulation.

All these studies demonstrated the several benefits of the ISMS through a distributed set of electrodes implanted in a given motor activation pool including finer control of force generation, selective activation, and fatigue resistance. Despite these benefits, multi-microelectrode stimulation poses a challenge to movement control. During multi-microstimulation, the neuromusculoskeletal system can be considered as an uncertain multi-input and single-output nonlinear system.

Moreover, the existence of uncertain time-delay in neuromuscular system response with respect to stimulation signal is a challenging problem in control design. Since the existence of time delay is often a main cause of instability and may degrade the performance of the closed-loop system.

In previous work [8], we developed a robust control strategy for movement control via ISMS using single electrode implanted in each motor pool within the spinal cord. In current study, we develop a control strategy which is based on fuzzy logic for control of ankle movement using ISMS via a two microelectrodes implanted in motor pool of each muscle. In addition, a simple method is presented to compensate the effect of time-delay.

II. Method

A. Controller Design

The configuration of the proposed control strategy is schematically depicted in Fig. 1. For each motor pool-muscle-joint complex an independent fuzzy controller was designed. The objective of the controllers is to generate stimulation signals to force the joint angle to track a desired trajectory in the presence of system uncertainties, time-delay, and disturbances.

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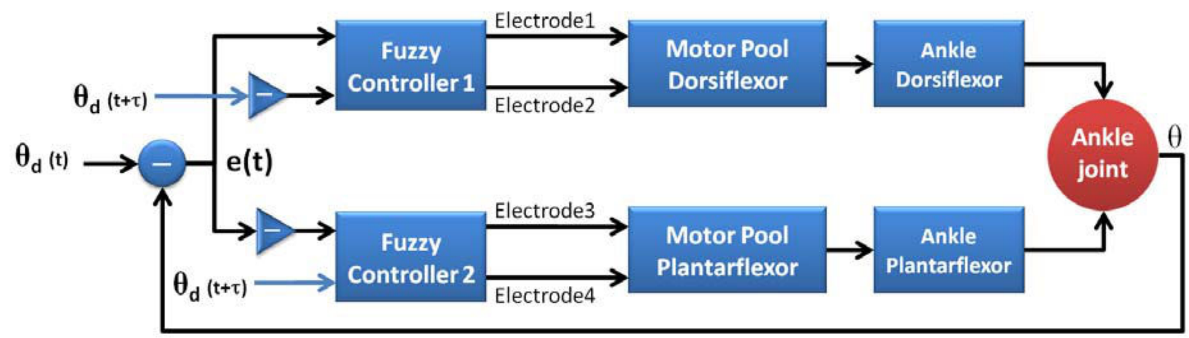


Fig. 1. Block diagram of the proposed fuzzy logic control for control of the ankle movement using multielectrode intraspinal microstimulation (ISMS).

Each controller has two inputs and two outputs. To overcome the effect of time-delay, control outputs are generated based on the tracking error and the future value of the desired trajectory. Due to this fact, the error signal (i.e., $e(t)$) and the future value of the desired trajectory (i.e., $\theta(t+\tau)$) are considered as the inputs of the each fuzzy controller. The information about the desired trajectory in the future as well as the present tracking error is used in the formation of the fuzzy rules (Table I). Here, τ is the overall time-delay including neuromusculoskeletal time-delay, stimulator delay, video frame capture time, and processing time.

In this paper, we used mamdani (min) implication [9] to determine the influence produced by the antecedent part of the fuzzy rule on the consequent part of the rule. Defuzzification was carried out according to the center of area (COA) method. Singleton and Gaussian-type membership functions were used for input and output variables. Fuzzy sets consisted of negative big (NB), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB).

B. Animal Preparation

Three male adult Wistar rats (350-400 g) were used in this study. The rats were anesthetized with intraperitoneal injection of urethane (1.65 g/kg). Then a partial laminectomy was performed to expose the T12-L2 segments and the dura mater over these laminas was opened longitudinally. The rats were placed in a stereotaxic frame (SR-6R, Narishige Group Product) which allows hindlimbs move freely (Fig. 2). All surgical procedures and experimental protocols were approved by the local ethics committee.

TABLE I. FUZZY RULES

Desired \ Error		NB	NS	Z	PS	PB
NB	Output1	Z	Z	Z	Z	Z
	Output2	Z	Z	Z	Z	Z
NS	Output1	M	Z	Z	Z	Z
	Output2	Z	Z	Z	Z	Z
Z	Output1	B	M	Z	Z	Z
	Output2	Z	Z	Z	Z	Z
PS	Output1	B	B	S	Z	Z
	Output2	M	Z	Z	Z	Z
PB	Output1	B	B	B	M	Z
	Output2	B	M	Z	Z	Z

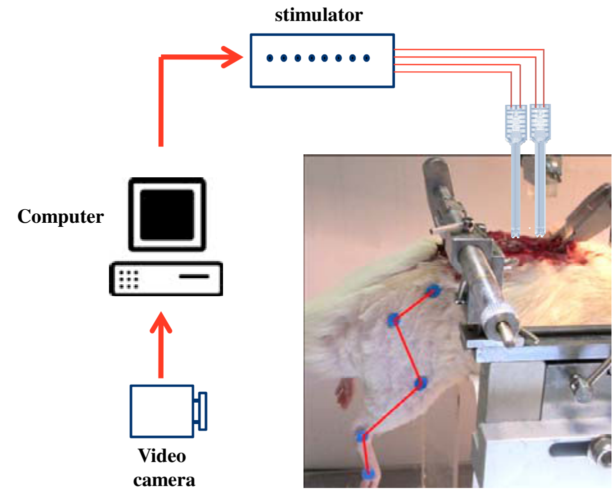


Fig. 2. Schematic of the experimental setup for closed-loop control of the knee movement using ISMS.

C. Data Acquisition and Stimulation Electrode

To measure the joint angles, colored markers were attached to each link. A webcam was focused to capture the location of the markers during limb movements elicited by ISMS. The hind limbs were filmed at the rate of 50 frames/s. We used NI Vision development module in LabVIEW to estimate the joint angles.

An eight-channel computer based stimulator (STG4008-1.6mA Multi Channel Systems MCS GmbH) was used to stimulate the spinal cord. The stimulator can generate charge balanced, biphasic current pulses. The pulse amplitude, pulse width, and frequency of the stimulation signal can be varied online using custom software package written in LabVIEW. Stimulus pulses were delivered through a custom-made multi-electrode array implanted in the ventral horn of the L1 spinal segment. The multi-electrode array was made of tungsten electrodes (127 μm in diameter, A-M Systems, WA) with fixed inter-electrode spacing of 300 μm. The stimulating electrode was mounted in a Narishige micromanipulator which controlled its three-dimensional position in the lumbo-sacral portion of the spinal cord.

D. Experimental Procedure

Multielectrode array was positioned at the locations within the ventral horn where selective stimulation of the dorsiflexor (plantar flexor) muscle could be obtained by each electrode. To determine the best electrode position for selective muscle stimulation, the electrode array was vertically advanced through the spinal cord in 50-µm steps, dorsoventrally, and then, the electrode was withdrawn and moved 100 µm mediolaterally and/or rostrocaudally to an adjacent location where the testing was repeated. At each stop along the electrode track, biphasic pulses with 80-µs duration, 60-µA amplitude, and 50-Hz frequency were delivered to the spinal cord through the microelectrode to identify the effective positions for selective dorsiflexion (plantar flexion). The positions that produced the highest movement range on the ankle joint and the least effect on the other joints were selected Two electrodes were implanted in each motor pool of the muscle with 300-µm spacing.

In the current study, pulse amplitude (PA) modulation at a constant frequency (50 Hz) and constant width (80 µs) was used to stimulate the spinal cord. The proposed control strategy was implemented in Lab VIEW. The sampling period for control updates was 20 ms. The interleave time between two electrodes implanted into a motor pool was set to zero (i.e., no stimulus interleave time).

III. Results

In this section, the control strategy presented in Section II was used to control the multi-joint movements by activation of agonist-antagonist muscles through ISMS. The error signals used for controllers of two muscles are calculated as

$$\begin{bmatrix} e_e \\ e_f \end{bmatrix} = \begin{bmatrix} +1 \\ -1 \end{bmatrix} [\theta - \theta_d]$$

where e_f and e_e are the error signals for the flexor and extensor controllers, respectively; θ is the measured joint angle, and θ_d is the desired trajectory.

We use the root-mean-square (RMS) error and normalized RMS (NRMS) as the performance indices to measure the tracking accuracy as

$$\text{RMS} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\theta(t)-\theta_d(t))^2}$$

$$\text{NRMS}(\%) = \frac{1}{(\theta_d^{\max}-\theta_d^{\min})}\sqrt{\frac{1}{T}\sum_{t=1}^{T}(\theta(t)-\theta_d(t))^2} \times 100$$

where θ and θ_d are the measured and desired joint angle, respectively.

A. *Selectivity*

Fig. 4 shows a typical result of the generated dorsiflexion by ISMS when the stimuli were delivered through each electrode separately and simultaneously. It is clearly observed that the range of dorsiflexion can be increased by multi-electrode stimulation without losing the selectivity (Fig. 4(c)). However, increasing the *amplitude* of the stimulus pulses delivered to the activation pool of the dorsiflexor through a single electrode [Fig. 4(d)-(e)] causes the activation of the knee flexor.

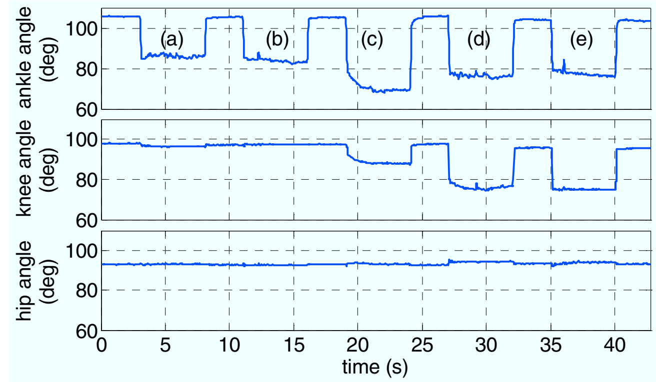
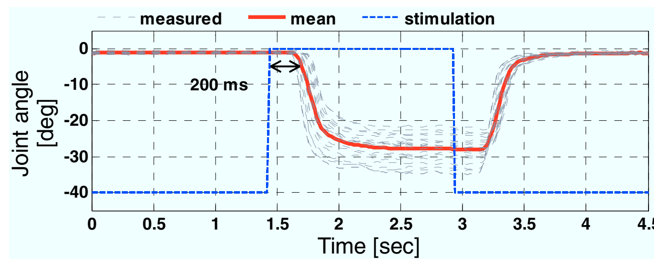
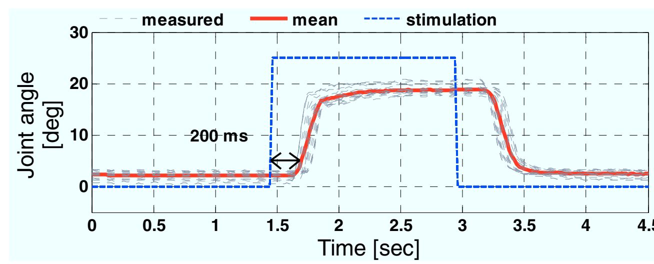


Fig. 4. Results of the separate (a, b, d, e) and simultaneous (c) stimulation of two sites in the activation pool of the dosiflexor with 80-µs pulse duration and 50-Hz frequency. (a, b) 60-µA pulse amplitude; (c) 60-µA amplitude for both electrodes; (d, e) 100-µA amplitude.



(a)



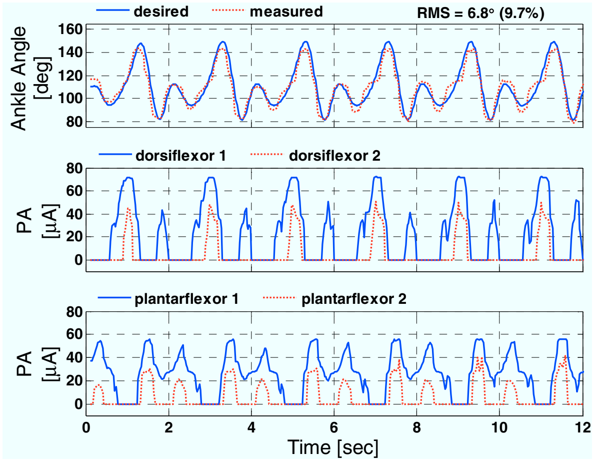
(b)

Fig. 5. Results of the ISMS with a 1.5-s-long sequence of constant pulse widths and pulse amplitudes. (a) Dorsiflexion (b) Plantar flexion.

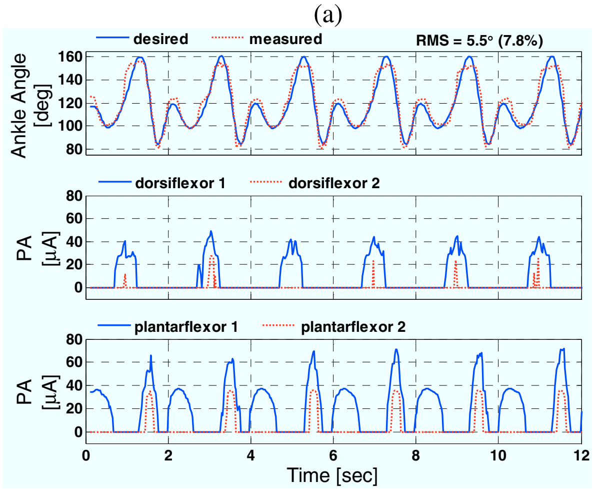
B. *Tracking Control*

To implement the proposed fuzzy logic controller, it is necessary to estimate the time-delay of the system (i.e., τ). To estimate the time-delay, a 1.5-s-long sequence of constant pulse widths and constant pulse amplitudes was delivered to the spinal cord. Fig. 5 shows the neuromusculoskeletal responses to ISMS. It is observed that there is approximately 200s time-delay in response.

Examples of the ankle joint angle trajectories obtained with the proposed FLC during one experimental trial for three rats are shown in Fig. 6. The mean of tracking error is 6.1° (8.7%). The most interesting observation is the fast convergence speed of the proposed control strategy. The ankle movement trajectory converges to the desired trajectory less than 1 s.



(a)



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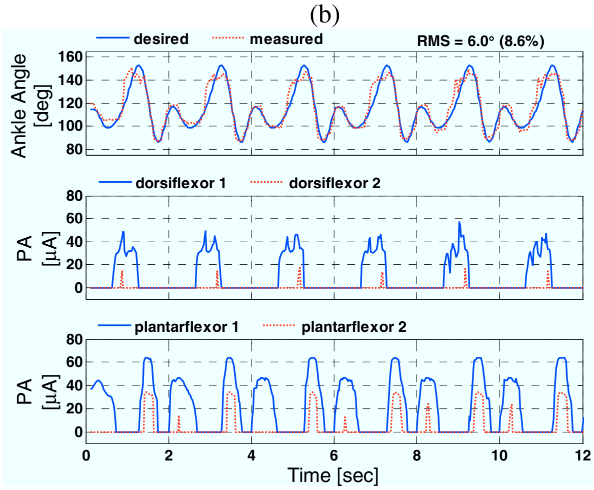

(c)

Fig. 6. Typical results of the ankle movement control using proposed fuzzy logic control during one trial of experiment. (a) Rat 1 (b) Rat 2 (c) Rat 3.

Table II summarizes the tracking errors obtained during 10 experimental trials for each rat. The average of tracking error over 10 experimental trials is 6.4°±0.4° (9.2%), 5.7°±0.2° (8.2%), and 6.8°±0.5° (9.7%), for rat1, rat2, and rat3, respectively. The average of tracking error over the three rats is 6.3°±0.6° (9.0%). Standard deviation of the tracking error is less than 0.6°. This indicates the repeatability of the control performance over the different experimental trails and different rats.

TABLE II. ROOT-MEAN-SQUARE TRACKING ERRORS OBTAINED DURING TEN TRIALS USING PROPOSED FUZZY LOGIC CONTROL FOR DIFFERENT RATS.

Trial	Rat1	Rat2	Rat3
1	6.8°	5.5°	6.0°
2	6.5°	5.7°	6.3°
3	6.6°	5.5°	7.0°
4	5.9°	5.6°	7.0°
5	6.0°	6.0°	7.9°
6	6.0°	5.7°	7.0°
7	7.0°	5.7°	6.8°
8	6.8°	5.4°	6.7°
9	6.7°	5.7°	6.9°
10	6.0°	6.0°	6.5°
Mean±STD	6.4°±0.4°	5.7°±0.2°	6.8°±0.5°
NRMS	9.2%	8.2%	9.7%

IV. CONCLUSION

In this paper, we proposed a fuzzy logic control scheme for control of ankle movement using multi-electrode ISMS. To compensate the effect of time-delay in neuromuscular response, the future value of desired trajectory was also considered as the input of the controller. The fuzzy rules were designed based on present value of the error signal and future desired response. The results show that the proposed controller can provide an accurate tracking performance using multi-electrode ISMS. In the current study, the control of one joint was considered. The control of multi-joint using the proposed method remains to be solved.

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