Neuro-adaptive fuzzy sliding mode control of the knee joint movement using intraspinal microstimulation

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Abstract

In this paper, we demonstrate that accurate tracking control of joint movement can be achieved using intraspinal microstimulation. For this purpose, intraspinal microwires are implanted in the lumbo-sacral of two rats. A robust control strategy is proposed which is based on synergic combination of an adaptive fuzzy sliding mode control (AFSMC) with an adaptive neural control. The proposed controller requires no prior knowledge about the dynamics of system to be controlled and no offline learning phase. The results of experiments on two rats show that the neuro-AFSMC provides accurate tracking control with fast convergence for different reference trajectories and it could generate control signals to compensate the muscle fatigue.

Keywords: *Intraspinal microstimulation, adaptive fuzzy, sliding mode control.*

Introduction

Intraspinal Cord microstimulation (ISMS) has been proposed as a means for restoring the motor function [1]-[3]. In [1], it was demonstrated that isometric torque can be generated about the knee joint by ISMS of the cat L6 spinal cord using a single microelectrode. It was shown that selective activation of muscle groups and graded control of force in individual muscles or muscle groups can be obtained through ISMS [2], [3]. All of these studies suggested that ISMS could be used for functional neuromuscular stimulation applications.

A major challenge to restoring a desired functional limb movement using ISMS is the development a robust control strategy for determining the stimulation patterns. To solve this problem, Mushahwar et al. [4] examined the feedback-controlled movement of the cat's foot by modulating the stimulus amplitudes through two electrodes producing ankle dorsi- or plantarflexion using a proportional-differential (PD) controller. They demonstrated that the principle of closed-loop control could be achieved with ISMS, however, developing a robust control strategy with low tracking error and fast convergence remains as an open problem.

A serious problem to developing a control strategy for restoring functional movement using ISMS is the complexity of the CPG and the highly nonlinear, time-varying properties of the neuromuscular systems. CPGs are complex adaptive systems where movements emerge from the dynamic interaction among the neural system, the body and the environment in a self-organized manner.

A useful and powerful robust control scheme to deal with the uncertainties, nonlinearities, and bounded external disturbances is the sliding-mode control (SMC) [5]. In this paper, we introduce an adaptive robust control strategy which is based on SMC and fuzzy logic system, for control of movements using ISMS. The experimental results show that accurate trajectory tracking with fast convergence could be achieved using ISMS.

Material and Methods

Animal Preparation

Experiments were conducted on two adult male Wistar rats (250–300 g body weight).The rats were anesthetized by urethane (1.5 g/kg) administrated intraperitoneally. A partial laminectomy was performed to expose the L1, L2 segments and the dura mater over this laminas was opened. The rats were positioned in a stereotaxic (SR-6R, Narishige Group Product) setup which allows hindlimbs move freely.

Data Acquisition and Stimulation Protocol

To measure the joint angels, a colored marker was attached to each joint. A webcam was focused to capture the locations of the markers during limb movements produced by electrical stimulation. We used NI Vision development module in LabView to estimate the joint angles. A custom made computer based eight channel stimulator was used to stimulate the spinal cord. The stimulator can generate charge balanced, biphasic current pulses. The 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 microwire (127 µm in diameter) implanted in the ventral horn of the L2,L1 spinal segment. The stimulating electrode was mounted in a Narishige micromanipulator which controlled its three-dimensional positioning in the lumbo-sacral spinal cord.

Control Strategy

The control strategy used here is based an adaptive fuzzy SMC (AFSMC) proposed in [6]. The proposed method is a well-defined SMC while the fuzzy logic systems are used to estimate on-line the plant's unknown nonlinear functions. Nevertheless, the proposed adaptive fuzzy SMC suffers from high frequency oscillations in the control input, which is called 'chattering' [7]. Chattering is undesirable because it can excite unmodeled high-frequency plant dynamics. To reduce the chattering, and to preserve the main advantages of the original SMC, we combine the AFSMC [6] with a single-neuron controller [7]. The configuration of the strategy is shown in Fig. 1, where u_1 is the output of the AFSMC and u_2 is the output of the single-neuron controller. The details can be found in [6], [7].

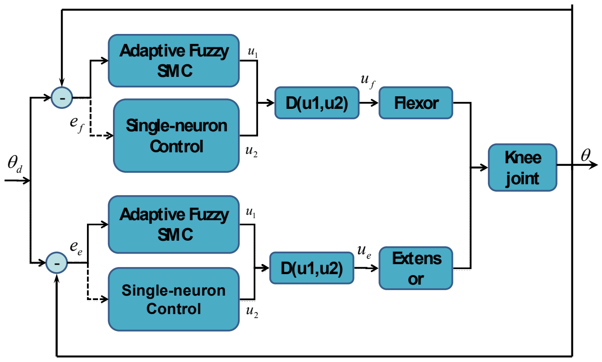


Fig. 1: Adaptive robust control system of knee joint.

Experimental procedure

To determine the best electrode position for generating selective extension and flexion, the wire was vertically advanced through the ventral horn in 100 µm incremental steps in dorsal-ventral dimension. At each incremental stop, biphasic pulses with 50-µs duration, 50-µA amplitude, and 50 Hz frequency were delivered to the spinal cord through the microwire to find the effective positions for the knee flexion and extension. The microwire penetration was always started at the centre of the ventral horn, then the microwire was withdrawn and moved 200 to 400 µm medial-lateral and/or rostral-caudal to an adjacent location where the testing was repeated.

To stimulate the spinal cord, pulse width modulation with balanced bipolar stimulation pulses, at a constant frequency (50 Hz) and constant amplitude 65~70 µA was used. The control algorithm was implemented in LabView. The parameters of the controllers were chosen heuristically to achieve the best tracking performance during the first session of experiment as follows

$$K_{flexor} = 300,\quad \lambda_{extensor} = 50,\quad K_{extensor} = 20,\quad \lambda_{flexor} = 100,$$
$$\phi = 4,\quad \eta_{\mathrm{f}} = \eta_g = 0.2,\quad \eta_0 = 0.01.$$

and then used for subsequent experiments on different days and for all animals.

Results

Tracking performance

Fig. 2 shows typical results of the knee movement control using the Neuro-AFSMC. The controller was turned on at 0.5 s. It is observed that excellent tracking performance with no chattering is achieved using the Neuro-AFSMC. The most interesting observation is the fast convergence speed of the proposed control strategy. The ankle movement trajectory converges to the desired trajectory after about 2 s. The results show that there is a low-level co-activation at the low force levels.

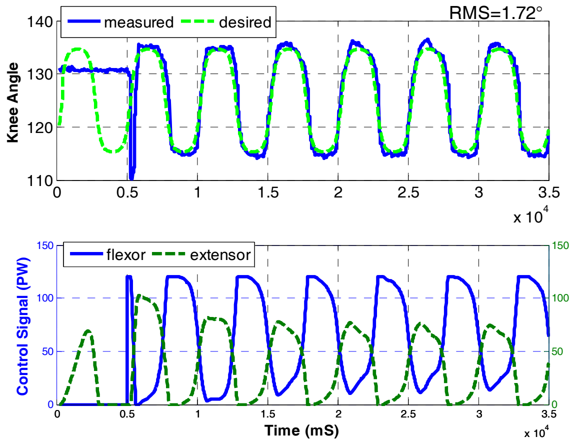
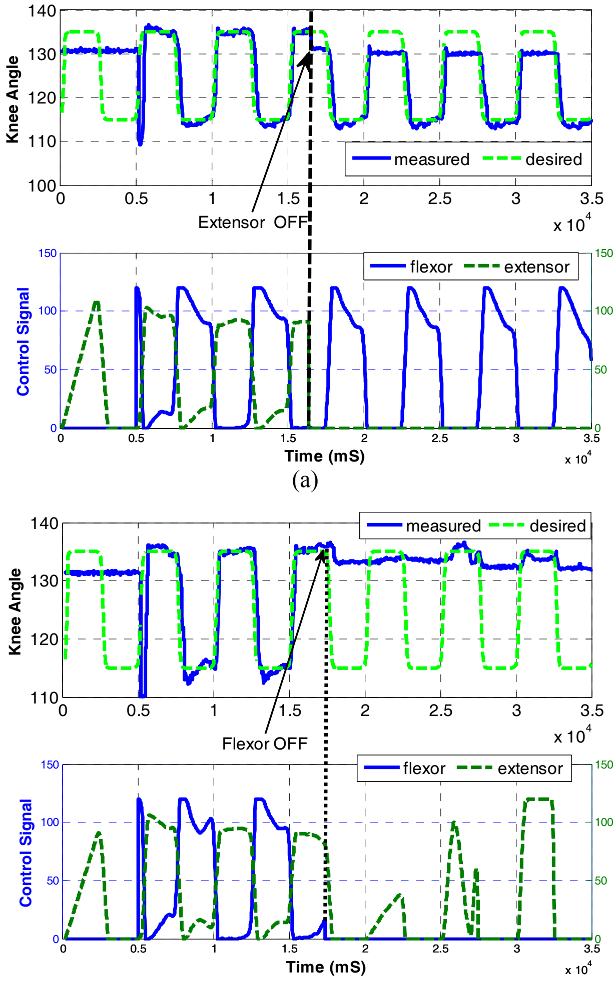


Fig. 2. Results of the knee movement control on Rat 2 using Neuro-AFSMC. Flexor electrode position: 1.600 mm deep from surface in dorsal-ventral direction, 0.600 mm lateral and 1.850 mm caudal on L1 lamina. Extensor electrode position: 1.500 mm deep from surface in dorsal-ventral direction, 0.500 mm lateral and 2.550 mm caudal on L2 lamina.

Fig. 3 show the results of the knee joint angle control when the flexor (extensor) controller was tenured off at 17 s. It is very interesting to note that when the extensor controller was turned off, the tracking performance of flexion movement was degraded.



(a)

(b)

Fig. 3. Results of the knee movement control on Rat 2 when the flexor (a) or extensor (b) controllers were turned off at 17 s.

Muscle Fatigue Compensation

Fig. 4 shows the ability of the Neuro-AFSMC to compensate the muscle fatigue during long period of the movement control. The results show that the method could adjust the stimulation pattern to compensate the muscle fatigue and the tracking performance remains fairly constant throughout the trial. The controller could adjust the stimulation pattern to achieve a consistent tracking performance.

Discussion and Conclusions

In this paper, we showed that accurate tracking control of joint movement can be obtained by using intraspinal microstimulation. For this purpose, we proposed a robust control strategy which is based on combination of an AFSMC with a single-neuron controller. The proposed controller requires no prior knowledge about the dynamics of system to be controlled and no offline learning phase.

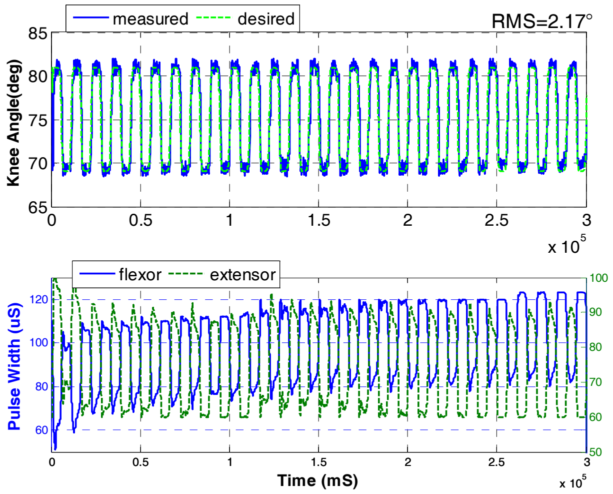


Fig. 4. The ability of the Nero-ASMC to compensate the muscle fatigue during ISMS on Rat 1.

Acknowledgment

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