Inducing Stepping- Like Movement by Controlling Movement Primitive Blocks using Intraspinal Microstimulation

Alireza Asadi

Abstract— ***Recently, intraspinal microstimulation (ISMS) has been developed as a potential technique for restoring the motor function in paralyzed limbs. It has been shown that that there are functional units in the spinal cord (i.e., motor pools, motor primitives) that generates a specific motor output by selecting a specific pattern of muscle activation. Dynamics identification of these spinal primitives is a critical issue in rehabilitation the motor function using spinal microstimulation. In this paper, we have triggered the motor primitives by electrical microstimulation of the interneuron networks within the spinal cord. The major challenge in generating Walking cycles is finding suitable patterns to stimulate each primitive. By using EMG of normal walking we have tuned patterns of each primitive but this procedure is too time-consuming, thus we have applied closed-loop control using neuro-adaptive fuzzy sliding mode control. The results show both procedures can reconstruct walking, But in closed-loop procedure we tune little controller parameters once. Whereas in open loop procedure for each animal different pattern must be find.***

Index Terms— ***functional electrical stimulation, intraspinal Microstimulation, movement primitives, neuro-Fuzzy sliding mode.***

I. INTRODUCTION

Intraspinal Cord microstimulation (ISMS) has been proposed as a method for returning the motor function after paraplegia [1]. Comparing to intramuscular stimulation and surface FES, this method needs low current amplitude and it is fatigue resistant [2]. The use of ISMS for restoring limb control has also been investigated. However, the circuitry controlling locomotion is complicated and numerous joints must be regulated. For deal with such complexity, it was suggested that an ideal solution would require a large number of spinal cord microelectrodes put at specific locations in order to stimulate selective muscle contractions [3]. However, it has also been suggested that stimulation of interneuron of spinal might activate “movement primitives” and so require less electrodes [4].

It was inferred that fixed-pattern force fields generated in the spinal cord may be named as movement primitives. These force fields could create building blocks for more complex behaviors [5].also they showed that the wipe reflex in spinal frogs can be construed as the appropriate time-varying summation of the force field primitives found with electrical stimulation.

It was founded that the simulation of two sites goes to the vector summation of the endpoint forces generated by each site separately. This linear behavior is completely remarkable and provides strong evidence to the view that the central nervous system may generate a wide repertoire of motor behaviors through the vectorial summation of a few motor primitives stored within the neural circuits in the spinal cord [6].

Tresch et al developed a sort of similar computational methods to extract synergies from the recorded muscle activations. In general, these methods try to decompose the observed muscle patterns as concurrent combinations of a number of synergies. This decomposition is earned using iterative algorithms that are initialized with a set of arbitrary synergies. The non-negative weighting coefficients of these arbitrary synergies that best predict each response are then found [7]. Also Tresch et al have compared different algorithms and found that in general, most of the algorithms used to identify muscle synergies carry out comparably. Especially, non-negative matrix factorization, independent component analysis, and factor analysis performed at similar levels to one another. When they applied these methods to experimentally obtained data set, the best performing algorithms identified synergies very similar to one another. These results suggest that the muscle synergies found by a particular algorithm are not an error of that algorithm, but reflect basic aspects of muscle activation [8]. Recently, Asadi and Erfanian [9] proposed a robust strategy for control of multi-joint movement using ISMS. They showed that an accurate and robust control of the multi-joint movement can be achieved by focally stimulating the target’s muscle motor pools in the spinal cord. The success of this level of control (i.e., control at the motor pool level) depends highly on the capability of selective activation of the motor pools. Moreover, the controller must cope with the large number of degrees of freedom of the motor system to produce purposeful, integrated behavior. One solution to the mentioned problem and reduce the degrees of freedom is the control of the movement at the level of module in the spinal cord.

In this paper we try to use primitives for generating waking in rat. Thus in first step, we need to characterize primitives. Also we must determine each primitive belongs to what phase of waking. In most works, isometric methods was used to measure force fields but we use hindlimb joint angles because we want to generate waking and qualification of walking needs joint angles. To activate each primitive, we deliver electrical micro stimulation to primitive sites in spinal cord. In second step we aggregate each primitive to imitate walking.

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For regulating amplitude of stimulations which deliver to primitive's sites open loop and closed-loop manner was used.

II. MATERIAL AND METHODS

A. Animal Preparation

Experiments were conducted on adult female wistar rats (270–300 g body weight).The rats were anesthetized by a mixture of ketamine (100 mg/kg) and xylazine (7.5 mg/kg) administrated intraperitoneally and were maintained anesthesia with supplemental doses of ketamine (30mg/kg per hour). For keep rats alive and refresh as long as possible, inject 10ml of infusion able sodium chloride per hour. A partial laminectomy was performed to expose the T13-L4 segments and the dura mater over these laminas was opened. The animals were positioned in a stereotaxic (SR-6R, Narishige Group Product) setup which allows the hindlimbs to hang free while the head and spinal vertebrae (T12 and L5) were clamped and fixed into the frame. All surgical procedures and experimental protocols were approved by the local ethics committee.

B. 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. Fig. 1 shows our experiment setup. The webcam was perpendicular to limb's sagittal plane. In this work, only movement witch was in the limb's sagittal plane was considered. We used custom made software written in NI Vision development module in LabVIEW to estimate the joint angles. To stimulate the spinal cord, a custom made computer-based sixteen-channel stimulator was used. The stimulator can generate charge balanced, biphasic current pulses. The amplitude, pulse width, and frequency of the stimulation signal can be varied online, using software package written in LabVIEW.

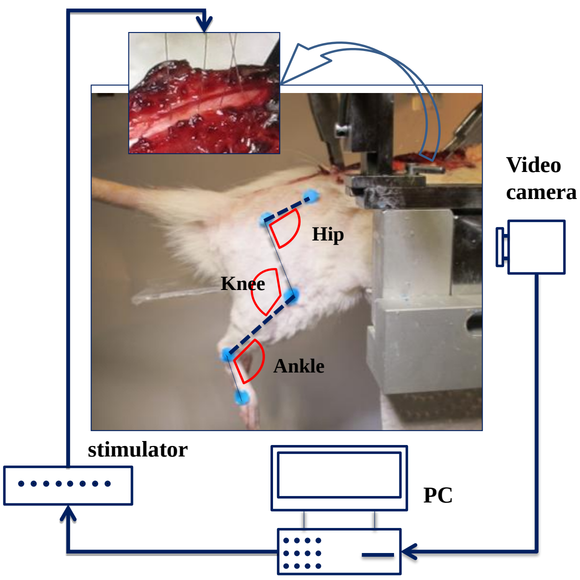


Fig. 1: experimental setup

C. Waking primitives

We try to decompose a walking cycle to sub parts according to EMG and joint angles dynamics. Fig.2 shows 4 parts of one cycle. It is obvious that a cycle can decompose to more part but we try to simplify problem but it may decrease accuracy. The EMG and angle of reference walking is used from [10].

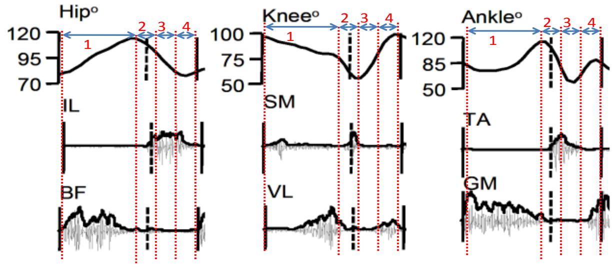


Fig. 2: four Primitive movement of walking [10].

D. Determining Location of primitives Sites

The stimulating electrodes were Teflon-Coated Tungsten wires (A-M System, WA, USA) with a coated diameter of 101.6 µm and 50.8-□m exposed tips. The stimulating electrode was mounted in a Narishige micromanipulator which controlled its three-dimensional positioning in the lumbo-sacral spinal cord. To determine the best electrode position for each primitive a constant stimulation was delivered to spinal and the electrode was vertically advanced through the spinal cord in 100µm incremental steps from surface of spinal in dorsal-ventral dimension and the joint angles was monitored on line. The positions which have dynamic behavior like one of four walking primitives were selected. The procedure always started from most cranial position (beginning of T13) and after reaching end of spinal in dorsal-ventral dimension, electrode was picked up and move 1 mm in cranial-caudal direction until all 4 primitives fined or reaching to end of exploring region (end of L4). The medial–lateral position of electrode is 600 µm from the central line of spinal.

E. Data Acquisition and Stimulation Protocol

The control strategy used here is based an adaptive fuzzy SMC (AFSMC) proposed in [9]. 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' [9]. 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 with a single-neuron a single-neuron controller. The structure of the proposed control framework is shown in Fig. 3. The control module used here is based an adaptive fuzzy sliding mode control (AFSMC) proposed in [9]. 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. The proposed controller requires no prior knowledge about the dynamics of system to be controlled and no offline learning phase. The details can be found in [9].

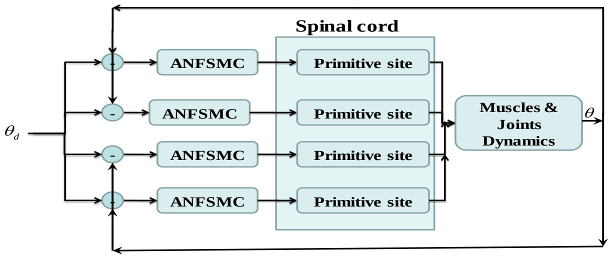


Fig. 3: Adaptive robust control system for primitives closed-loop control

III. RESULTS

A. Primitive's characterization

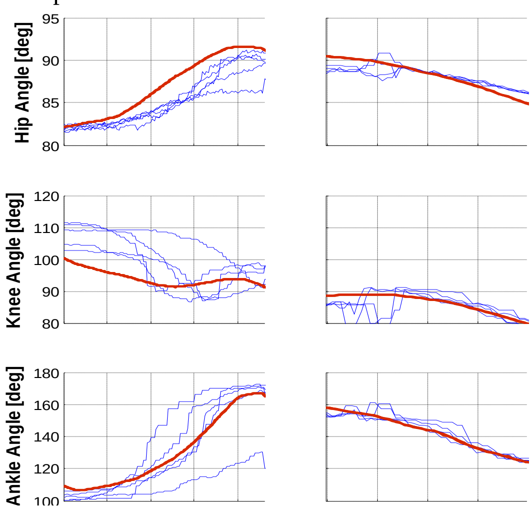
For characterizing dynamic properties of primitives and finding their similarity to walking primitives, we apply different ramp shape pulse width amplitude to stimulation site in the spinal and capture angle responses. Fig. 4 shows responses of primitives. In some cases measured angles almost fitted to desired angles. It was clear that CNS command to primitive sites in spinal is very complicated than a simple ramp, but we try to simulate this command by a ramp.

B. Open loop control of primitives

In past stage we have chosen suitable amplitude four each ramp. If these ramps arranged respectively, open loop walking was reconstructed. Fig. 5 shows a sample open loop trial of two cycle of walking. As you can see the accuracy of tracking is low because of fixed pattern of stimulation. In the other words, we use ramp shape stimulation but clearly the pattern is too complicated. Other problem is chosen suitable amplitude. We use four primitives and for each primitive, suitable amplitude must be chosen which is very time consuming.

C. Closed-loop control of primitives

As you can see open loop control of stimulation which apply to spinal is too difficult, thus we try to control this closed-loop. Details of our control strategy exist in [10]. In the current study, pulse width (PW) modulation at a constant frequency (50 Hz) and constant amplitude was used to stimulate the spinal cord. The proposed controller strategy was implemented with LabVIEW. The sampling period for control updates was 20 ms. Fig. 6 shows a sample of primitive closed-loop control.



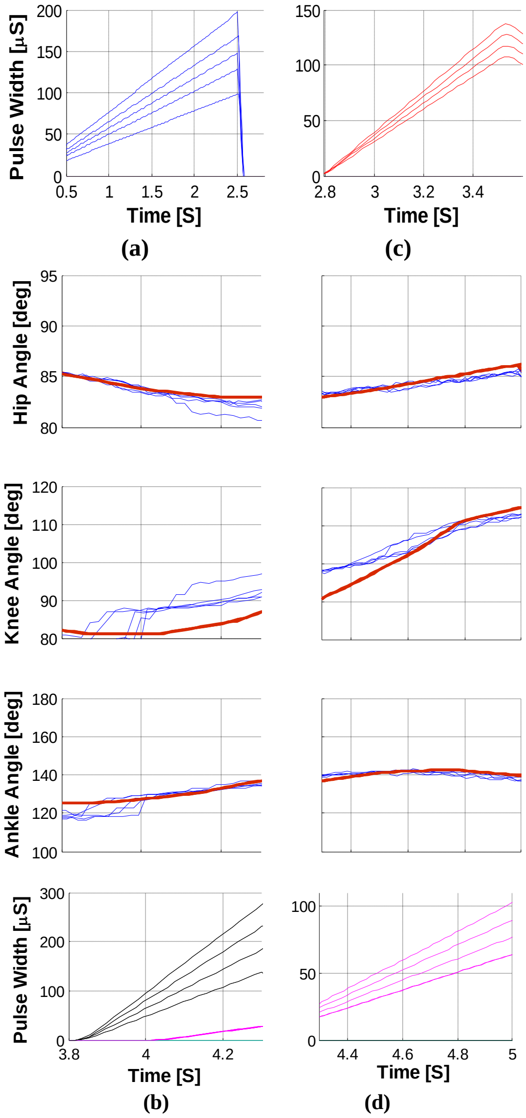
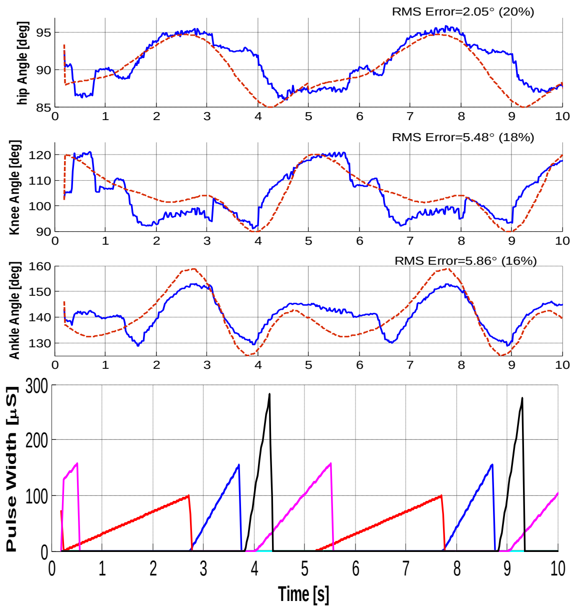


Fig. 4: four primitive responses. Thick line shows the desired walking cycle and thinner lines show different responses for different stimulation patterns.



(a)

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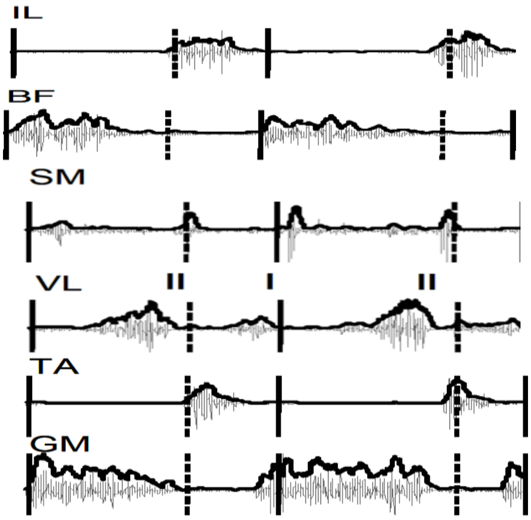

(b)

Fig. 5: (a) open loop walking whit sequence of primitives. (b) These figures show typical flexor (IL, SM, TA) and extensor (BF, VL, GM) muscle activity (hip, knee and ankle), in normal walking [10].

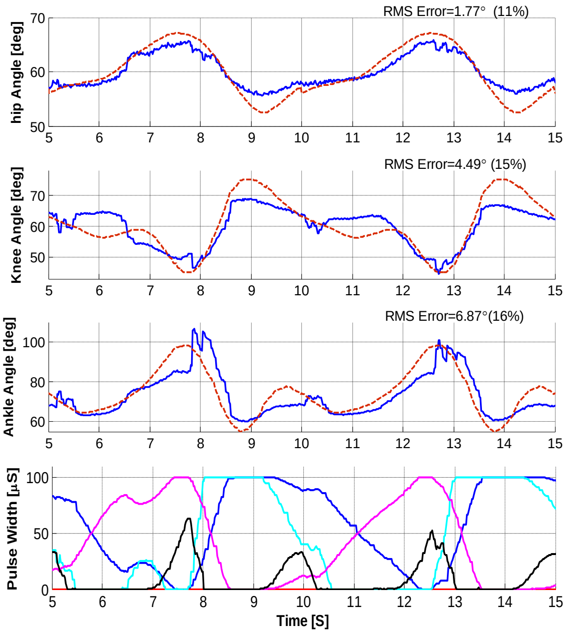

Fig. 6: closed-loop control of primitive stimulation's PW.

IV. CONCLUSION

The results of this study showed that a complex locomotor stepping can be generated by the closed loop control of the motor primitives. The blocks of the movement were visually defined according to the joint angle changes. The ramp shape stimulation can shows dynamic properties of primitives but it is poor and we need complicated stimulus to characterize primitives comprehensively. We have used EMG to find patterns in open loop manner, but our experiment shows that this procedure is time consuming. We have introduced closed-loop control which needs little controller parameters for tuning which tune ones for each primitives. The results of experiments on the two rats showed that the specified motor outputs can be generated by the ISMS of the motor primitives. In this paper we have characterized movement primitives and used them to rebuild walking cycles. Closed-loop control can speed up regulating PW of stimulations which applying to sites of each primitive in spinal cord.

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