Neural Sliding Mode Control of Sit-To-Stand Transfer in Paraplegic Subjects Using Functional Electrical Stimulation

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Abstract

This paper presents a new method for control of arm-supported standing up in paraplegic subjects using functional electrical stimulation (FES). The control goal is to minimize the upper body effort during sit-to-stand (STS) transfer. The proposed control strategy is based on synergistic combination of a single-neuron adaptive control with sliding-mode control (SMC) for controlling the knee and hip joints during the STS transfer. To enhance the controllability of electrically stimulated muscle and to obtain the required vertical velocity during STS transfer, both pulse width and pulse amplitude modulation are used while the pulse width is modulated by the neuro-SMC and pulse amplitude by a fuzzy logic controller. The results of experiments on two paraplegic subjects show that peak hand reaction force is about 40% of the body weight during STS and the mean hand reaction force is about 20% of the body weight.

***Keywords**: Sit-to-stand, Sliding Mode Control, Functional Electrical Stimulation.*

Introduction

SIT-TO-STAND (STS) maneuver is one of the repetitive movements in daily life and it is also a prerequisite for standing, walking, and reaching distant objects. It has been demonstrated that using FES on paraplegic's lower extremities they can complete the STS task. One of the main problems in STS movement in paraplegic patients using FES is the amount of upper body effort during the task. It has been estimated that the electrically stimulated knee extensors provide only up to one quarter of the lifting force. The long term effects of repetitive high transient loading of the arm during activities such as transfers and wheeling have been implicated in the high incidence of overuse syndromes in the spinal injured population.

To overcome the aforementioned disadvantages of open-loop standing up strategy, a number of approaches based-on closed-loop control theory have been proposed [1]-[4]. Donaldson and Yu [1] suggested a theoretical approach for control of standing up, in which stimulation of the lower limbs depends on the body posture and the handle reaction forces (HRFs). Riener and Fuhr [2]-[3] proposed a control strategy based on inverse dynamic model of a paraplegic patient. Given the desired hip, knee, and ankle joint angles and their derivatives (angular velocities and accelerations), the inverse dynamic model estimates the stimulation pulse widths required to maintain the movement which is initiated by the patient's voluntary upper body effort. In a simulation study, it was shown that by this method, the legs can carry more than 50% of the body weight during rising. Davoodi and Andrews [4] proposed a closed-loop self-adaptive fuzzy logic controller based on reinforcement machine learning for FES control of the knee and hip joints in simulated paraplegic standing up.

In this work, we employ a neuro-SMC strategy [5], [6] for control of arm-assisted FES-supported standing up in paraplegic subjects. Most of the regular open-loop FES setups for STS movement include quadriceps and gluteus maximus stimulation in order to fully extend the knee and hip joints. Previous study [7] on STS movement in paraplegic subjects reveal that applying artificial stiffness in the plantar flexion direction could significantly reduce the upper body effort in paraplegic patients standing up using open-loop FES. *In this work*, we use an ankle foot brace with the plantar-assisting spring [7] in combination with the closed-loop FES control of the knee and hip joints.

To generate the required vertical velocity and the joint extending moments during STS transfer, we use a combined modulation of pulse width and amplitude. Pulse-amplitude modulation can provide a coarse control while a smooth control can be achieved by using pulse-width modulation. *In this work*, we use a fuzzy logic controller to regulate the pulse amplitude of the stimulation signals while the neuro-SMC controller is used to regulate the pulse width of the stimulation.

Material and Methods

Each muscle-joint dynamics has its own controllers while the pulse amplitude and pulse width of the stimulation signal are adjusted by a fuzzy logic controller and neuro-SMC, respectively.

Neuro-Sliding Mode Control (neuro-SMC)

In previous work [5], we developed a robust control strategy which is based on sliding mode control (SMC) and neural network (i.e., neuro-SMC) for control of the knee joint using functional electrical stimulation in paraplegic subjects (Details can be found in [5]). In this work, we used this method for regulating the pulse width of the stimulation signals.

Fuzzy Controller

The inputs to the fuzzy logic controller (FLC) are the angular position and angular velocity of the joint, the output is the stimulation amplitude. Gaussian membership functions are used for the input and out variables. Five Gaussian membership functions are used for angular position, three for angular velocity, and five Gaussian membership functions for the output variable. The membership functions are all distributed evenly with 50% overlap over the domain of the variables. The pulse amplitude could vary from 60 to 90 mA. The controller is designed heuristically to use the joint angle and angular velocity as the feedback to regulate the amplitude of the stimulation to generate adequate momentum for the subject to take-off.

Results

Experiments

The experiments were conducted on two thoracic-level complete spinal cord injury patients. The paraplegic subjects were active participants in a rehabilitation research program involving daily electrically stimulated exercise of their lower limbs (either seated or during standing and walking) using ParaWalk neuroprosthesis [8]. The hip, knee, and ankle joint angles were measured by using the motion tracker system MTx (Xsens Technologies, B.V.) which is a small and accurate 3-DOF Orientation Tracker. A Kistler piezoelectric force plate type 9286AA (Winterthur, Switzerland) was used to measure the 3D ground reaction forces (GRF) under both feet (with an accuracy of ±0.5% of the full scale) and the corresponding CoP. The vertical forces on the arm support frame were measured by two Load cells (LRF350, Futek Advanced Sensor Technology, Inc, USA) mounted underneath the both walker handles (Fig. 1). An ankle-foot orthosis (AFO) was developed with plantar-assisting spring. By changing the spring, the rigidity of the AFO could be adjusted [7].

The experiments were performed while the paraplegic subjects were seated in their wheelchair. Both feet were placed symmetrically and parallel to each other on a force plate. For rising, stimulation was voluntarily triggered by the patient wearing AFO, and the body was lifted upward from the initial to the extended upright position by the help of stimulating quadriceps and gluteal muscles using an eight-channel computer-based closed-loop FES system and arm support.

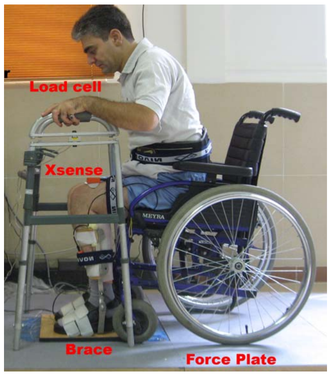

Fig. 1. Experimental setup

Typical results of STS movements using proposed closed-loop control strategy and open-loop technique with predefined stimulation pattern, for paraplegic subject R.R. are shown in Fig. 2. It is observed that both pulse width and pulse amplitude of the stimulation signal are increased during the transition phase of the STS transfer, but, the level of amplitude begins to decrease during the deceleration phase and reaches the minimum predefined level at the end of the movement. During the final phase of STS transfer and through out standing, the ground reaction force has the value about the body weight using the proposed control scheme which indicates that the subjects are able to stand without involving the upper body effort. Moreover, it is observed that the HRF is decreased by using the proposed control strategy with respect to the HRF obtained when open-loop system is used.

Fig. 3 shows the average of the mean handle reaction forces for two paraplegic subjects using the proposed control strategy and open-loop control system. It is observed that the average of mean HRF is 17% of the body weight in subject RR when the proposed controller is used. Using open-loop controller, the hand force is 37%. The results indicate that a 20% reduction in mean hand reaction force is achieved in subject RR by using the neuro-SMC with respect to the open-loop control. Almost, the same result is obtained for the subject MS.

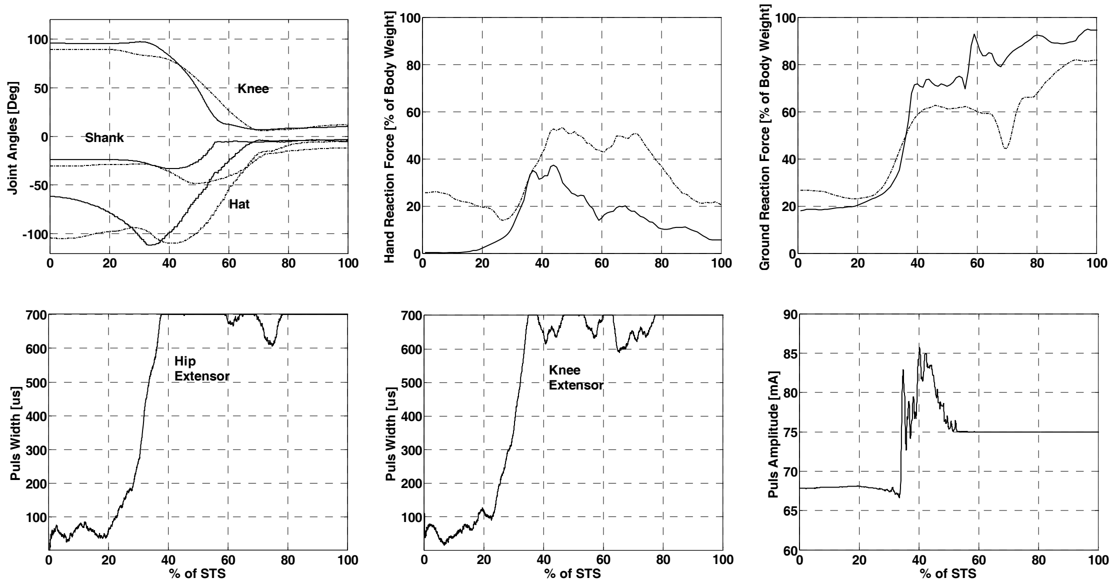

Fig. 2. Control of the STS transfer using combined neuro-SMC and fuzzy logic controller (solid line) and open-loop control (dash-dot line) for paraplegic subject RR.

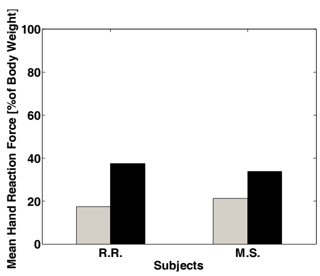

Fig. 3. Average of the mean handle reaction force obtained using combined neuro-SMC and fuzzy logic controller (black) and open-loop controller (gray) for two paraplegic subjects RR and MS.

Conclusions and Discussion

In this paper, a control methodology which is based on combination of a single-neuron control with sliding mode control was proposed for control of the STS movement in paraplegic subjects. To obtain the required vertical velocity during standing up, we used combined modulation of pulse width and pulse amplitude to enhance the controllability of electrically stimulated muscle. The pulse width was regulated by the neuro-SMC, while the pulse amplitude by a fuzzy logic controller. The results of experiments on two paraplegic subjects indicated that the mean hand reaction force was about 20% of the body weight during standing up (Fig. 3).

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