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Implementation of a Modular Fuzzy Logic Controller for Standing-Up, Standing and Sitting-Down in Paraplegia Using a Portable Transcutaneous Neuroprosthesis

Farjadian AB, Erfanian A

Dept. Biomed. Eng., Faculty of Electrical Eng., Iran University of Science & Technology, Tehran, IRAN.

erfanian@iust.ac.ir, A_Farjadian@iust.ac.ir

Abstract

In this work, we present a modular fuzzy logic controller (FLC) for controlling standing up, standing, and sitting down in paraplegic subjects. The controller strategy was implemented on a portable microcontroller-based 8-channel transcutaneous functional electrical stimulation (FES) system, Parawalk. The modular FLC consisted of different FLC with different control parameters for different phases of motion. The results of experiments on a complete paraplegic subject indicate that modular FLC provides good tracking control. Moreover, a programmable sensory-driven control strategy was implemented with a wide range of triggering for two stimulation channels. The sensory-driven strategy was applied on a cerebral palsy with bilateral dropped foot. Clear improvements in heel strike in gait, standing with flat feet, toe clearance during swing phase were observed.

1. INTRODUCTION

Functional neuromuscular stimulation (FNS) is proposed as a method for restoring motor functions in patients with stroke, head injury, cerebral palsy (CP), multiple sclerosis (MS) or spinal cord injury [1]-[3]. Improved performance of these *neuroprostheses* can, in principle, be obtained through feedback control. Moreover, for some FNS applications such as restoring motor function in upper extremity and correction of drop foot disability, the *neuroprostheses* should be rely on control system which is sensory driven. Up to now, different functional neuromuscular stimulators with capability to acquire feedback information have been developed [4]-[5]. A programmable transcutaneous FES system with four channels, called Compex Motion, was developed by Popovic and Keller [4]. The stimulator can be programmed using a graphical user interface to generate any arbitrary stimulation sequence which can be regulated by external sensors. Real-time regulation of stimulation intensity is done using the voltage level of analog input signal and predefined look-up tables. The stimulation sequences and the look-up tables are stored on exchangeable memory chip card. Fisekovic and Popovic designed a self-contained controller for FNS systems [5]. The system can execute pre-programmed control strategy and sensory-driven operation.

A portable, sensory-driven two-channel hard-wired stimulator (O2CHS) was developed at Salisbury District Hospital [3]. The system provides a wide range of triggering for two stimulation channels. Setting up the triggering mode is achieved by using a complex combination of 10 DIP switches and setting 10 miniature potentiometers that are quite cumbersome for the therapist.

In this work, we designed a microcontroller software for our previous developed neuroprosthesis [6], with fuzzy logic controller to perform standing-up, standing, and sitting-down in paraplegia. Moreover, the designed operating system makes the stimulator to be sensory-driven with a wide range of triggering.

2. METHODS

2.1 System Description

The present system is an extension of our previous developed neuroprosthesis, called Parawalk. The Parawalk is a microcontroller-based (ATmega128) electrical stimulator with eight stimulation channels. The details of hardware can be found in [6].

The microcontroller software is responsible for reading the user commands, menu-driven user interfacing, monitoring the functional operation of the system and electrode connectivity, displaying appropriate message on the LCD during different conditions, serial port communication, stimulation pulse generation, data acquisition, data processing, and regulating the stimulation signals according to the feedback information and the pre-programmed control strategy. The system can support up to six analog and four digital inputs. The system software was written using C programming language.

In general, the system has three modes of operation: open-loop, closed-loop, and sensory-driven strategy. In all three modes of operation, an easy to use menu-driven interface is available to user. The system has been pre-programmed for controlling standing-up, standing, and sitting-down during closed-loop operation.

2.2 Modular Fuzzy Logic Control of Movement

In this work, we employed fuzzy logic controller for standing-up, standing, and sitting-down in paraplegia using FNS. In this work, seven fuzzy sets with triangular membership functions were defined. Rule base comprises 35 rules illustrated in Table I. Mamdani inference mechanism and a minimum operator in membership function were used for decision making. Defuzzification has been performed by center of gravity. Inputs to the controller are the error, *E*, and the error change, Δ*E*. Controller output is the change in pulse amplitude.

Table I
RULE BASE FOR FUZZY INFERENCE

ΔE \ E	NB#	NM#	NS#	ZE#	PS#	PM#	PB#
NB#	NM#	NS#	NS#	NS#	ZE#	ZE#	PS#
NS#	NS#	NS#	NS#	ZE#	PS#	PM#	PM#
ZE	NM#	NS#	NS#	ZE#	PS#	PM#	PM#
PS#	NS#	ZE#	ZE#	ZE#	PS#	PM#	PB#
PB#	ZE#	ZE#	PS#	PS#	PS#	PM#	PB

A major impediment to the restoring function in paralyzed limb using FNS has been the highly nonlinear, time-varying properties of joint-muscle dynamics. This provides the motivation for refining the FLC parameters. Due to the fact that the dynamics of muscle-joint change during standing-up, standing, and sitting down, we used five FLCs with different parameters for different phases of motion, seat off and ascending phase, stabilization phase and quiet standing, standing, first phase of sitting down in which knee flexors are activated to unlock the knees, second phase of sitting down which decelerates lowering the subject's body from standing to sitting posture.

2.3 Sensory-driven Strategy

Two foot-switches have been employed to provide a wide range of triggering for two stimulation channels.

The menu-driven user interface and push button switches of the system allow to easily set up the triggering mode of operation. Due to programmability of the system, any special mode of triggering can be set up easily. Depending on the mode of operation, the foot-switches are placed under the heel or toe of both legs. The system can be used to assist people with movement disabilities due to neurological damage including those treated by Odstock stimulator. During sensory-driven mode of operation, the stimulation parameters, i.e., intensity, frequency, rise time, fall time, delay, extension (Fig. 1), can be adjusted using menu-driven user interface.

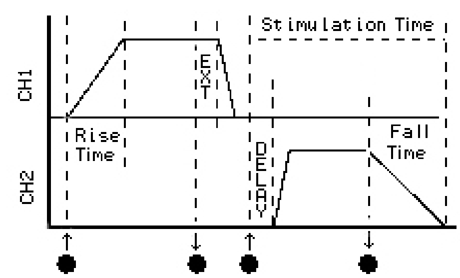

Fig. 1. Stimulation pattern in sensory-driven mode of operation

2.4 Open-loop Mode of operation

During open-loop mode of operation, the system stimulates the paralyzed muscle according to a predefined pattern. The stimulation patterns can be designed using a PC based user friendly graphical programming software and be transferred to the stimulator unit via a serial communication channel.

3. RESULTS

Experiments were conducted on a T7 complete paraplegic subject (9 years post injury) and a 23-

year old man having cerebral palsy (CP) with bilateral dropped foot. An electrogoniometer is fixed on the knee-joint of paraplegic subject to measure the knee-joint position.

The results of fuzzy logic controller during two trials of experiment including standing-up, standing, and sitting down of the paraplegic subject are shown in Fig. 2. The experimental results show that the FLC provides excellent tracking control. The interesting point to note is that the controller generates control signals to compensate the muscle fatigue during standing.

Fig. 3 shows the result of employing the system on a subject with bilateral dropped foot. It is observed that the subject could successfully perform the dorsi-flexion during walking.

4. DISCUSSION AND CONCLUSIONS

In this work, a fuzzy logic controller was implemented by using a portable programmable transcuteneous functional neuromuscular stimulator, Parawalk, for controlling standing up, standing, and sitting down in paraplegic subjects. The results of experiments motivate the use of adaptive fuzzy logic control due to time-varying property of the muscle-joint dynamics.

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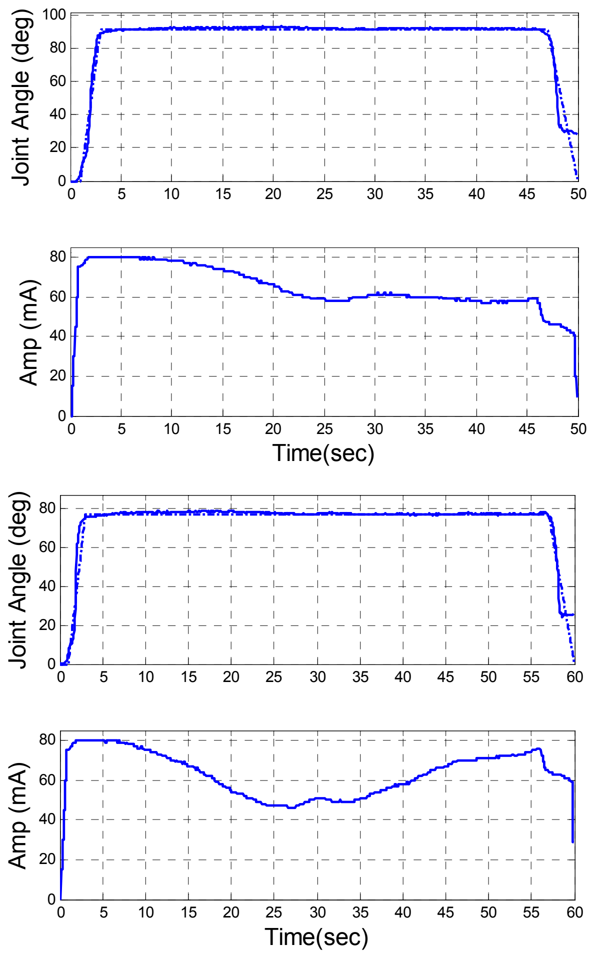

Fig. 2. Fuzzy logic control of knee-joint angle during standing up, standing, and sitting down for two trials experiment.

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Fig. 3. Walking a subject with bilateral dropped foot using Parawalk.