A Portable Programmable Transcutaneous Neuroprosthesis with Built-in Self-Test Capability for Training and Mobility in Paraplegic subjects

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Abstract

In this work, we developed a new eight-channel portable transcutaneous functional electrical stimulation (FES) system called Parawalk for training and mobility in paraplegic subject. The features of the system include completely independent programming stimulation channels, very flexible stimulation pattern and high degree of reliability. The implemented testability scheme makes it possible to test the functionality of the system and the electrode lead connection before and during stimulation. The system has a graphical liquid crystal display for visual interface between the user and the stimulator. The user commands can be entered via thirteen front panel push button switches and hand controlled switches. To date, the Parawalk has been successfully applied to five complete paraplegic subjects. At present, two subjects are able to stand-up and sit-down and three others to walk independently.

1. INTRODUCTION

Motor neuroprostheses has been demonstrated to be effective in restoring hand function in quadriplegia [1] and locomotion in complete [2] and incomplete [3] paraplegia. Several transcutaneous portable functional electrical stimulators have been developed to improve upper and lower limb functions in spinal cord injured [4].

Graupe *et al*. [2] developed a transcutaneous microprocessor-based functional neuro-muscular stimulation system with six stimulation channels, called Parastep, for short-distance ambulation in SCI paraplegia. The system was built into a walkman-size powered by eight AA batteries. The stimulation sequences are controlled by push buttons which are located on a walker's handbars. The Parastep is the first FDA-approved FNS ambulation system and by mid-1997 was successfully applied to approximately 400 patients for standing and short-distance ambulation.

A programmable transcutaneous FES system with four channels, called Compex Motion, developed by Popovic and Keller [5]. By connecting the stimulators, the number of channels can be increased from four to multiples of four. 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.

A portable skin surface 8-channel stimulator, called ExoStim, developed by Simcox et al. [6] for paraplegic muscle training and mobility. The system consists of a portable stimulator powered by 4 AA alkaline batteries and a controller which consisted of a hand-held PC with a custom-designed compact flash interface card.

In this article, we describe a new portable programmable functional electrical stimulator for walking in paraplegics and present its clinical applications on SCI patients.

2. METHODS

2.1. Hardware

The developed system (Fig. 1) is a microcontroller-based (ATmega128) electrical stimulator with eight stimulation channels. Each stimulator channel can deliver current-regulated biphasic stimulation pulses with amplitude in the range of 0 mA to 100 mA with 1 mA resolution, width in the range of 0 μs to 700 μs with 1 μs resolution, and frequency within a range of 1 Hz to 50 Hz with 1Hz resolution. Parawalk can regulate the muscle contraction either by pulse width modulation (PWM) or pulse frequency modulation (PFM), or both of them. The amplitude of each stimulation channel can be adjusted independently.

Fig. 1. Parawalk neuromuscular stimulator

The system has a 240 x 64 dot matrix graphical liquid crystal display (LCD) for visual interface between the user and the stimulator.

The user commands can be entered via thirteen push button switches. The movement commands can be also accepted via hand controlled switches. The reliability of neuroprostheses and patient safety are of great importance. To improve the reliability, the system has built-in circuitry to enable to test the functional operation of the stimulator and lead connections to the patient, before and during on-line stimulation. The built-in self-test scheme continuously monitors the waveform of the stimulation pulses and electrode lead connections. During abnormal operation or lead disconnection, visual and audible alarm indicate the fault condition and detected fault will display on the LCD.

Parawalk is powered by five AA rechargeable NiMH batteries enclosed within the stimulator case. The battery status icon continuously displays the battery life remaining on the LCD.

The stimulator is enclosed in a 174.5 × 98 × 42.5 mm portable case.

2.2 Microcontroller Software

The microcontroller software was written using C programming language. The microcontroller was programmed by using ImageCraft C Compiler (i.e., ICCV7) and a starter kit and in-system programming tool (i.e., STK500 AVR). The software is responsible for reading the user commands, menu-driven user interfacing, monitoring the functional operation of the system and electrode lead connections, displaying appropriate message on the LCD during a fault condition, serial port communication, and stimulation pulse generation.

2.3 Stimulation Pattern Software

A graphic user interface was designed for generating any arbitrary stimulation patterns by using either PWM or PFM or both of them. The stimulation sequence is generated by moving and clicking the mouse. The main screen of the software and an example of generated stimulation patterns are shown in Fig. 2. The designed stimulation pattern is transferred to the stimulator unit via a serial communication channel.

3. RESULTS

Parawalk is now employed for training and ambulation in paraplegic subjects. To date, the Parawalk has been successfully applied to five complete paraplegic subjects. The subjects were selected for FNS training program according to medical criteria in [4]. A typical FNS gait cycle of a paraplegic subject is demonstrated in Fig. 3. The subject is a 19-year-old man with complete T10_T11 spinal cord injury (five years post injury). Two channels are used to stimulate the quadriceps muscles bilaterally, two channels to the peroneal nerves bilaterally, and two channels to stimulate the gluteus maximus/minimus muscles bilaterally. At present, the subject can walk distances up to 100 m (Fig. 3).

4. DISCUSSION AND CONCLUSIONS

In this paper, we described a new portable, flexible 8-channel microcontroller-based functional electrical stimulator for training and walking in paraplegic subjects. The system is easy to use and can generate any arbitrary stimulation sequences. The built-in self-test provides continuous monitoring of the stimulation waveforms and electrode lead connections before and during stimulation..

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Acknowledgements

This work was supported by Industrial Development and Renovation Organization (IDRO) of IRAN under Grant 48-2894.

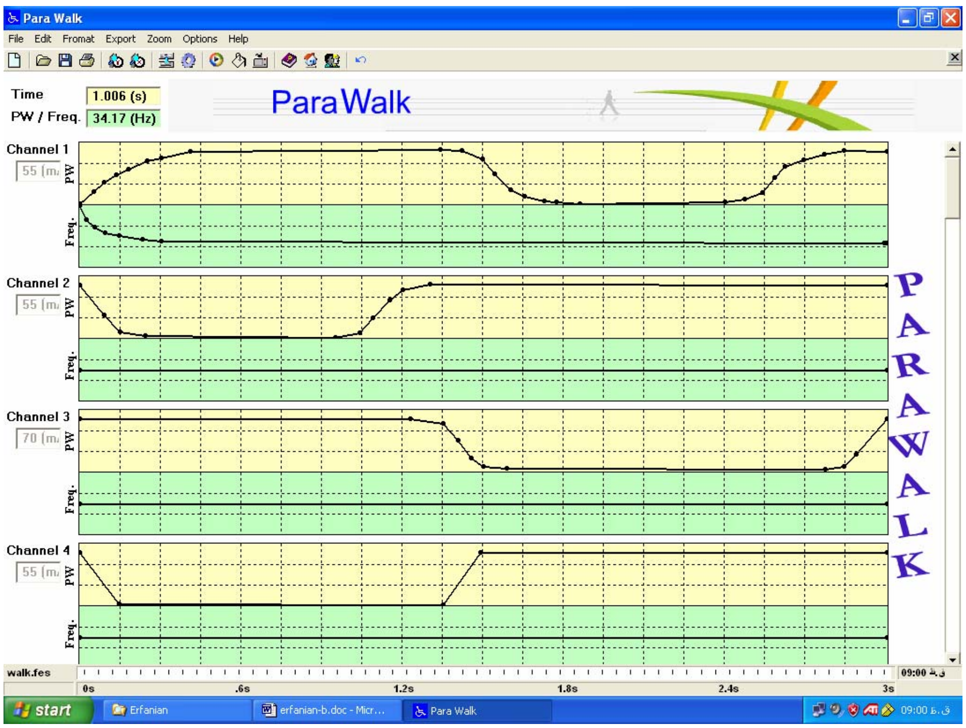

Fig. 2. Main screen of the stimulation pattern software

Fig. 3. A complete paraplegic subject (T10-T11) walking with Parawalk.