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Transcutaneous Electrical Stimulation Technology for Functional Electrical Therapy Applications

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Abstract—**Key to a successful application of functional electrical stimulation as a rehabilitation therapy (also termed functional electrical therapy or FET) is modular, portable, programmable, and versatile transcutaneous electrical stimulation technology. In this article a hardware platform, Compex Motion, that has been used successfully to develop numerous FET systems for walking, reaching and grasping is presented. The Compex Motion stimulator can be programmed to generate any arbitrary stimulation sequence, which can be controlled or regulated using any external sensor or sensory system. The stimulator has four current regulated stimulation channels that can be expanded to multiples of four channels (8,16,20,…). The stimulation sequences are stored on readily exchangeable memory chip-card. By replacing the chip-card the function of the stimulator is changed instantaneously to provide another function or FET treatment. The Compex Motion system was used as a FET device with more than 60 acute and chronic stroke and spinal cord injured (SCI) patients.**

I. Introduction

In recent years functional electrical stimulation (FES) has been applied successfully by a number of researchers world wide in a form of short-term therapy that generates long-term functional improvements in stroke and SCI patients. In particular, FES systems have been used to generate functions such as grasping and walking in repetitive fashion for a number of weeks. After the therapy was completed, stroke and SCI patients who participated in these trials have experienced significant improvements in their functions [1]-[5]. This form therapy has been termed FES therapy or functional electrical therapy (FET).

FET presents a departure from the conventional use of FES technology. Since the 1960s when the first FES system was developed, these devices were primarily used as "orthoses" to artificially generate limb movements and thereby substitute missing function. They have been envisioned as systems patients have to use all the time and would depend on them for the rest of their lives. FET is new and conceptually different approach to use of FES technology. Here FES is used as a short-term intervention to generate lasting improvements in voluntary function and the user does not have to depend on this technology for the rest of his/her life. Our group has been applying FET to acute and chronic stroke and SCI patients for more than 5 years. To date we have demonstrated that this therapy can improve voluntary reaching, grasping and walking functions in stroke and SCI patients [1]-[3].

For this therapy to be successful, one needs to apply modular, portable, programmable, and versatile transcutaneous FES technology. To date very few such systems can be found. In this article Compex Motion FES system is presented as one of the most advanced hardware platforms for developing FET systems. In this article the main features of the Compex Motion system are described followed by an example of its practical implementation as and FET device for grasping. In addition, three useful techniques are disclosed which helped our team facilitate use of Compex Motion stimulator in FET applications.

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II. Compex Motion: Modular Transcutaneous Functional Electrical Stimulation System

A. Concept

The Compex Motion stimulator was designed to serve as a hardware platform for diverse FES applications requiring transcutaneous (surface) stimulation technology (Fig. 1) [6]. The main features of the system are:

1. Easily programmable
2. Allows FES practitioners to apply the same device to a number of different patients requiring unique stimulation protocols
3. Patients with very different FES protocols can be treated one after the other with virtually zero transition time between treatments

To satisfy these needs, the stimulator is programmed with graphical user interface (GUI) software, which is installed on a personal computer (PC). User can program the stimulation sequence using a PC and transfer the complete stimulation protocol to the stimulator by means of a serial port connection. During the transfer, the stimulation protocol is programmed on a chip-card which is inserted into the stimulator. Once the transfer is completed, the chip-card contains all the relevant information required to execute the stimulation protocol. By simply exchanging the chip-card, the stimulator's function is instantaneously changed to provide a different function or FES treatment.

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The main hardware and software features of Compex Motion stimulator include: 1) portability; 2) each unit has four stimulation channels, and any number of stimulators can be combined to form a multiple unit with a greater number of stimulation channels (8,12,16, …); 3) the pulse amplitude, duration and frequency are independently controlled and can be changed during the stimulation in real-time; 4) the stimulation channels are galvanically separated; 5) the stimulator is powered by a rechargeable battery, thus the total stimulation duration is limited to approximately eight hours of continuous stimulation; and 6) the stimulator can be interfaced and controlled with any external sensor, sensory system or laboratory equipment.

Fig. 1. Compex Motion stimulator

B. Hardware

The Compex Motion electric stimulator is a microcontroller-based system with four stimulation channels, two input channels A and B, and a special purpose port C. The stimulation channels are current regulated and have 3 µs rise time for pulses with 125 mA amplitudes (pulse amplitude range 0-125 mA, resolution 1 mA; pulse width range 0-16 ms, resolution 500 ηs - long pulse widths such as 16 ms may be used to stimulate denervated muscles; and stimulation frequency 1-100 Hz, resolution 1 Hz). The input channels A and B can be configured as analog or digital input channels (maximum sampling frequency 8 kHz, voltage range 0-5 V and resolution 20 mV). The special purpose port C is used to interconnect the stimulators, to serially communicate with a PC, and to trigger the stimulator using a push button. By interconnecting stimulators via port C, one can expand the number of stimulation channels from four to multiples of four channels. In such a configuration, one stimulator is designated as a master stimulator while all other stimulators are designated as slaves. The master stimulator paces the stimulation of all connected stimulators and ensures that all stimulators are synchronized and maintain the same "bus frequency" during the entire stimulation protocol.

C. Software

The Compex Motion software consists of two independent, but related software packages. The first software package is a graphical user interface (GUI) developed with LabView software and installed on a PC. The GUI is used to program stimulation protocols, which are later downloaded via serial port connection (port C) to a programmable chip-card inserted in the stimulator's "card read-and-write" module. The second software package was developed using assembler for the Motorola HC11 microcontroller. This software package is imbedded in the microcontroller's external memory and is used to execute stimulation sequences programmed on the chip-card. By inserting a programmed chip-card, and by turning on the stimulator, the software written in assembler reads the content of the chip-card and without a delay, executes the stimulation protocol.

1) Microcontroller's software

The microcontroller's software was developed using the timer controlled multitasking features of the Motorola HC11 microcontroller. This software was written using assembler because of the limited memory space and computational power of the microcontroller. With the exception of the display routines and the serial communication routines, all other subroutines were controlled using timers in real-time. Three different timers were used to control execution time for every subroutine. The timer concept allowed the stimulator to process multiple tasks in real-time using a single processor. Special care was taken to ensure that all tasks were completed before time elapsed on the timer. Hence, all subroutines were executed in a predefined time period. In Table I, main subroutines and corresponding timer frequencies are provided.

TABLE I
PROCESSING TIME AND TIMER RATES FOR SUBROUTINES

Routine	Timer freq.	Called every
battery scan	1 kHz	1 ms
watchdog		10 ms
control frequency		100 ms
slow A/D scan		10 ms
pulse sequence interpreter (timed mode)		100 ms
look-up table routine (timed mode)		10 ms
battery check		1000 ms
stimulation frequency	1-100 Hz	8-1000 ms
pulse sequence interpreter (pulse mode)		8-1000 ms
look-up table routine (pulse mode)		8-1000 ms
fast A/D scan	8 kHz	250 µs
EMG processing		100 ms

2) Graphical user interface software

The GUI software applies a "drag-and-drop" technique to program the stimulation sequences. This is done by sequentially placing icons called primitives on a time line that describes the chronology of the tasks that will be carried out by a single stimulation channel (an example provided in Fig. 2). There are four such time lines, and each time line defines tasks that will be executed by a corresponding stimulation channel. 59 primitives describe tasks that can be carried out by the stimulator. These 59 primitives are sorted out into the following main groups: pulse width primitives (12 primitives), pulse amplitude primitives (6 primitives), pulse frequency primitives (6 primitives), sequence control primitives (10 primitives), user interface primitives (17 primitives) and general purpose primitives (8 primitives). These primitives are either *global* or *local*. The *local primitives* represent tasks that affect only channels in the time lines they appear. One can distinguish local primitives from other primitives by their dark blue background color. In general, *global primitives* represent tasks that affect all active stimulation channels. The global primitives are subdivided into *global primitives that need to appear in all active time lines* (GPA) and *global primitives that need to appear in only one time line* (GPO). GPAs can be distinguished from other primitives by their dark green background color. GPAs are used to synchronize activities carried out by all active stimulation channels. GPOs can be distinguished from other primitives by their violet background color. GPOs are used to execute a task that affects all active stimulation channels or the stimulator.

It is important to mention that the stimulation channels and their time lines were designed such that each channel is executed independently. In other words, a stimulation protocol carried out in one time line does not have to be related to a stimulation protocol in any of the remaining three time lines. However, in certain instances it is necessary that the stimulation channels execute their programs simultaneously and in a synchronized fashion. In these circumstances, a user can apply one of the following GPAs to synchronize stimulation protocols performed by different stimulation channels: *synchronize*, *user interaction*, *user branch*, *fast trigger*, or *synchronized push button triggering*. The main property of GPAs is that once one of them appears in any of the four time lines, the simulator "freezes" the stimulation parameters for that channel and waits until the identical GPA appears in all four time lines. Once the same GPA is reached in all four time lines, the stimulator is allowed to proceed with the following stimulation primitives in all four time lines, if the condition indicated by the GPA is satisfied. An example how the user interaction and user branch GPAs are used to synchronize muscle contractions to generate hand opening and closing functions is provided in Fig. 3, items ①, ②, ④ and ⑤. To learn more about main features of the GUI software please consult [6].

III. Example of Compex Motion Application

To date, more than 100 SCI and stroke patients have used the Compex Motion system. The system was primarily used as a neuroprosthesis for reaching, grasping and walking. In want follows a typical neuroprosthesis application for grasping is presented. This system was applied to a C5 complete SCI patient as part of FET therapy. Other successful applications of the Compex Motion stimulator can be found in [1]-[3], [6].

A neuroprosthesis for grasping had been developed for a 22-year-old, C5, complete, SCI male patient. The patient sustained SCI two months prior to joining our program. The patient's left arm was chosen for the neuroprosthesis application since muscles in his left arm were not denervated and the patient was also able to place his left hand in almost any point in the arm's work space. The patient had good voluntary control of the left shoulder and biceps muscle, while his left triceps muscle was graded level 3. The patient had significant difficulty using his right arm and could voluntarily cover only 30 to 40 % of the right hand's workspace. Prior to his SCI, this patient was right handed. When the patient was admitted to the FES program he had ASIA score A.

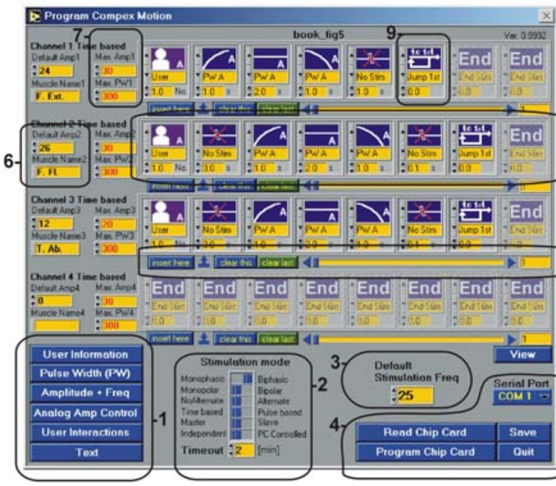

Fig. 2. Main screen of the GUI software: 1) setup functions, 2) stimulation mode functions, 3) default stimulation frequency setting, 4) memory chip-card functions, 5) time line editing functions for stimulation channel No. 3; 6) default pulse amplitude for stimulation channel No. 2, 7) upper limits for pulse width and amplitude for stimulation channel No. 1, 8) time line for stimulation channel No. 2, and 9) primitive "jump to first" in time line No. 1.

The patient was fitted with a neuroprosthesis that allowed him to perform both lateral and palmar grasps on demand (Fig. 3). Channel No.1 was used to stimulate the *flexor digitorum superficialis muscle* and the *flexor digitorum profundus muscle* to generate finger flexion. Channel No.2 was used to stimulate the *flexor pollicis longus muscle* to generate thumb flexion. Channel No.3 was used to stimulate the *median nerve* to produce thumb opposition (two small self-adhesive electrodes placed on the skin along the tendon of the flexor carpi radialis muscle were used to generate this function; distance between electrodes was 2 cm). Channel No.4 was used to stimulate the *extensor communis digitorium muscle* to generate hand opening. The patient used a push button to command the neuroprosthesis. By continuously pressing a push button for less than 0.5 s, the patient would issue user interaction A command (UI-A in Fig. 3). By holding the push button longer than 1 s continuously, the patient would issue user interaction B command (UI-B in Fig. 3). The user interaction A was used to command the lateral grasp, while the user interaction B was used to command the palmar grasp. By generating the user interaction A or B command, the neuroprosthesis would instantaneously produce the lateral or palmar grasp, respectively. Once the hand was closed, it remained closed until the patient pressed the push button for the second time. By generating the user interaction A command while the hand is closed, the patient produces hand opening.

IV. RELEVANT FET TECHNIQUES

In this section three techniques will be disclosed that could be of help to potential FET practitioners.

A. FES-assisted Walking

When our team develops a FET walking system/intervention it generally refrains from using flexor withdrawal reflex as means to generate locomotion function [6]. Instead, we stimulate only muscles responsible for walking. Flexor withdrawal reflex tends to habituate (despite pulse randomization that generally prolongs effectiveness of this stimulation technique) and it generates awkward and non-physiological gait. However, when one stimulates only muscles using transcutaneous stimulation technology one cannot stimulate hip flexors, which are essential for successful gait execution. To circumvent this problem our team applies walking therapy on a declining treadmill. The treadmill has to be declined at least 10° to allow for hip flexion to occur as a result of passive leg dynamics. With this technique one can generate natural looking gait for prolonged periods of time without a need to stimulate hip flexors. Curiously, even though the hip flexors are not stimulated during this FET protocol, the hip flexors tend to become active after 6 to 8 weeks of trice weakly therapy. For more details on this technique please consult [3] and [7].

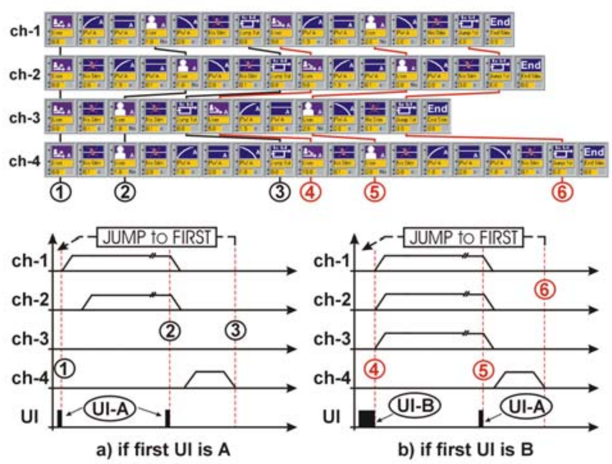

Fig. 3. Grasping protocol that generates both a) lateral and b) palmar grasps on demand. The upper part of the figure presents primitives in time lines and the lower part represents the outputs for channels 1, 2, 3 and 4. UI-A is user interaction A which is generated if the push button is pressed less than 0.5 s; UI-B is user interaction B which is generated if the push button is pressed longer than 1 s; ch-1, 2, 3 and 4 are stimulation channels; and labels ① to ⑥ are used to indicate which primitives in the time lines are responsible for certain stimulation protocol events.

B. FES-assisted Reaching

When training stroke or SCI patients to perform reaching function it is of key importance to engage supraspinatus muscle to generate elbow abduction. However, transcutaneous stimulation technology cannot be used to stimulate supraspinatus muscle because it is too deep and is not accessible by the transcutaneous stimulation technology. Despite this serious limitation, our team has discovered that if one engages both anterior and posterior branches of the deltoid muscle simultaneously, while patient is consciously and voluntarily trying to abduct the arm, the supraspinatus muscle will start being activated voluntarily by the patient after 6 to 8 FET sessions. Note that in this case the supraspinatus muscle will be contracted in synchrony with the anterior and posterior branches of the deltoid muscle, which are contracted using FES. For additional information on this therapy please consult [1].

C. FES-assisted Grasping

Hand opening and finger extension in stroke patients is very difficult to achieve with contemporary transcutaneous FES technology, especially when patient has prominent tone in finger flexor muscles. To address this problem our team has developed a stimulation protocol that first stimulates extensor digitorum muscle *(finger extension)* followed by simultaneous stimulation of lumbricals I, II, III and IV muscles. Stimulation of the lumbricals muscles, which is delayed at least 0.5 sec after the extensor digitorum muscle stimulation, ensures physiological hand opening with fully extended fingers and thumb. Without stimulating lumbricals I-IV muscles the hand opening function does not look naturally and often produces awkward finger extension. For additional information on this therapy please consult [1].

V. CONCLUSIONS

Key to a successful application of FET is modular, portable, programmable, and versatile transcutaneous electrical stimulation technology. In this article Compex Motion electric stimulator was presented that has been used successfully to develop numerous FET systems for walking, reaching and grasping. In addition, some useful techniques are presented that can be used to circumvent some limitations of the transcutaneous electrical stimulation technology when it is applied in the context of FET.

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