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ARTICLE *in* ARTIFICIAL ORGANS · APRIL 2002

Impact Factor: 2.05 · DOI: 10.1046/j.1525-1594.2002.06934.x · Source: PubMed

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Artificial Organs
26(3):219–223, Blackwell Publishing, Inc.

Transcutaneous Functional Electrical Stimulator "Compex Motion"

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Abstract: Research groups in the field of functional electrical stimulation (FES) are often confronted with the fact that existing and commercially available FES stimulators do not provide sufficient flexibility and cannot be used to perform different FES tasks. The lack of flexibility of the commercial systems until now forced various FES research teams to develop their own stimulators. This paper presents a newly developed firmware and graphical programming software for the commercial Compex 2 stimulator which enhances the versatility and capabilities of the stimulator from a medical and therapeutic device to a neuroprosthesis and research tool. The new stimulator, called Compex Motion, can now be used to develop various custom-made neuroprostheses, neurological assessment devices, muscle exercise systems, and experimental setups for physiological studies. It can be programmed to generate any arbitrary stimulation sequence that can be controlled or regulated by various external sensors, sensory systems, or laboratory equipment. By interconnecting two or more Compex Motion stimulators, the number of stimulation channels can be increased to multiples of four channels, 8, 12, 16, 20, and so forth. The stimulation sequences and the control strategies are programmed and stored on exchangeable credit card-sized memory chip cards. The stimulator has four biphasic current-regulated stimulation channels and two general purpose analog input channels that can be configured to measure the output voltage of a variety of sensors such as goniometers, inclinometers, gyroscopes, or electromyographic (EMG) sensors. For real-time EMG control of the stimulation patterns, an EMG processing algorithm with software stimulation artifact blanking was implemented. The Compex Motion stimulator is manufactured by the Swiss company Compex SA and is currently undergoing clinical trials. **Key words:** Electrical stimulator—Functional electrical stimulation—Grasping—Neuroprosthesis—Spinal cord injuries—Walking.

Several portable microprocessor or microcontroller functional electrical stimulation (FES) stimulators for transcutaneous stimulation have been developed to improve upper and lower limb functions in spinal cord injured and stroke subjects (1–4). Most of these systems were built for one specific application and did not have an open architecture. In general, the setup options were limited and device dependent, and the control options were fixed. The preprogrammed stimulation patterns were stored internally. A fixed set of sensors combined with a control algorithm triggered the preprogrammed stimulation sequences. Some systems allowed changes of the stimulation intensity either during the initialization phase or on-line during stimulation . In some cases, a separate software allowed new settings for trigger levels and stimulation sequences to be downloaded from a PC.

In this article, we describe a new generation of transcutaneous electrical stimulators called Compex Motion. This stimulator represents a further evolution and expansion of the already existing ETHZ-ParaCare FES system (5,6). The new Compex Motion portable stimulator exceeds the capabilities and features of other FES systems by providing a user with the flexibility to program subject-specific stimulation sequences and to apply advanced control strategies and by allowing a user to choose the man-machine interfaces.

MATERIALS AND METHODS

Hardware

Compex Motion is a microcontroller-based electrical stimulator with four stimulation channels

Received October 2001.
Presented in part at the 7th Vienna International Workshop on Functional Electrical Stimulation, held September 12–15, 2001, in Vienna, Austria.
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(Table 1) used for transcutaneous electrical stimulation of selected muscles or muscle groups. The stimulator can deliver current-regulated stimulation pulses of maximum 120 mA with a rise time of 3 μs. It has two input channels A and B and a special-purpose port C. A and B can be configured either as analog or digital input channels with a voltage range of 0–5 V. The special-purpose port C is used to interconnect two or more stimulators, to serially communicate with a PC, or to trigger the stimulator using a push button. By interconnecting two or more stimulators, the number of stimulation channels can be increased from four to multiples of four channels, 8, 12, 16, 20, and so forth. In such an arrangement, one of the stimulators operates as a *master stimulator,* and all other stimulators operate as *slave stimulators.* The master stimulator ensures that all interconnected stimulators operate synchronously.

The Compex Motion stimulator has a rechargeable NiMH battery that provides 8 h of continuous stimulation and is recharged in less than 2 h. The stimulator also has a dot-matrix liquid crystal display (LCD) display that provides a visual interface between the user and the stimulator. The user can interact with the stimulator via nine push buttons on the stimulator (Fig. 1) or via any other user interfaces that are connected to ports A, B, and C. Currently, electromyographic (EMG) sensors and a push button can be purchased together with the stimulator. These interfaces can be used to control the stimulation sequences and to regulate the stimulation intensities. Additional stimulator features, accessories, and hardware data are provided in Table 1.

Software

The Compex Motion stimulator is programmed with a graphical user interface (GUI) software that is installed on a PC (Fig. 2). The GUI software uses a *drag-and-drop* technique to program the stimulation sequences. This is done by sequentially placing icons, called *primitives,* on a timeline that describes the chronological sequence of the tasks that will be carried out by a stimulation channel. There are four such timelines, one for each stimulation channel. A total of 56 primitives are available in order to take full advantage of the full flexibility of the system (Table 2). There are two classes of primitives: *global* and *local.* Global primitives represent tasks that affect all active stimulation channels while local primitives affect only the specified channel. The drag-and-drop technique allows a user to compose rapidly precisely timed stimulation sequences that can contain customized pulse width ramps, loops, branches, pauses, user interaction rules, and text displays.

The primitives used for user interactions define how a subject must interact with the stimulator and can be customized to individual needs. For example, the user can initiate or terminate a stimulation sequence via a predetermined analog or digital sensor signal curve profile detected at the input ports A or B. Also, two different sensor signal curve profiles can be used to select between two different stimulation sequences. Sensors such as EMG sensors, force sensitive resistors, gyroscopes, foot switches, and push buttons have already been successfully applied with the user interaction primitives.

Continuous regulation of the stimulation intensity can be achieved in real-time using an analog input signal. For example, the pulse amplitude can be made to depend on the voltage level of the input signal. This dependence can be arbitrarily defined by a lookup table that can be imported as an ASCII file and/or can be edited both graphically and numerically. Each stimulation channel has its own lookup table. Thus far sensors such as EMG sensors, sliding resistors, and potentiometers have already been successfully used with this control strategy.

RESULTS

Table 1 shows the specification of the Compex Motion hardware. Table 2 lists the available primitives. Using the drag-and-drop technique, the programmer arranges these primitives in a timeline in any desired chronological order to form the desired stimulation sequences.

DISCUSSION

The new Compex Motion portable and programmable electrical stimulator that can be used for a

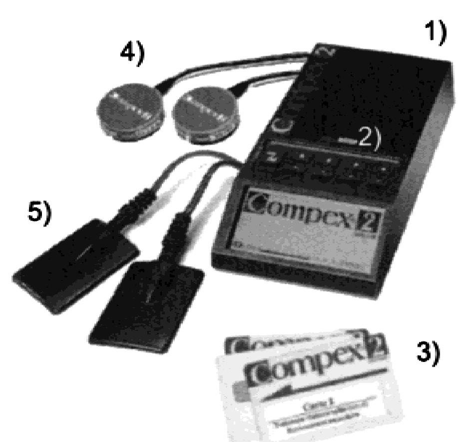


FIG. 1. Shown is the Compex Motion electrical stimulator: 1, stimulator; 2, keypad with nine push buttons; 3, three memory chip cards; 4, two EMG sensors; and 5, two stimulation electrodes.

TABLE 1. *Compex Motion data sheet specifications*

Feature	Characteristics		
Four stimulation channels	Current regulated		
	Pulse amplitude	Range: 0–120 mA	Resolution: 1 mA (8-bit)
	Pulse width	Range: 0–16 ms	Resolution: 500 ns (14-bit)
	Stimulation frequency	Range: 1–100 Hz	Resolution: 1 Hz (8-bit)
Two digital input channels (A & B)		Range: 0–5 V TTL	
Two analog input channels (A & B)	Max sampling frequency: 8 kHz	Range: 0–5 V	Resolution: 20 mV (8-bit)
One special-purpose port (C)	Push button, serial port communication, and stimulator interconnection		
Working regimes	Master/slave		
Stimulation pulses	Monophasic/biphasic; monopolar/bipolar; and alternating/nonalternating		
Microcontroller	Motorola HC11		
Dot-matrix LCD	No. pixels: 165 × 64		Dimensions: 72 × 30 mm
Chip card	Can store up to 255 primitives per channel and all relevant stimulation parameters		
NiMH battery	Rechargeable, 8 h of continuous stimulation		
Stimulator dimensions	148 mm × 80 mm × 30 mm; 420 g		
Accessories	AC/DC adapter, push button, four cables, self-adhesive electrodes, EMG sensor		

wide range of transcutaneous FES applications has been presented. The stimulator can be used to develop various custom-made neuroprostheses, neurological assessment devices, muscle exercise systems, and experimental setups for physiological studies. The Compex Motion stimulator can be programmed to generate any arbitrary stimulation sequence, which can be controlled or regulated using any external sensor, sensory system, or laboratory equipment.

Currently, a number of patients are using the Compex Motion stimulator as a neuroprosthesis for

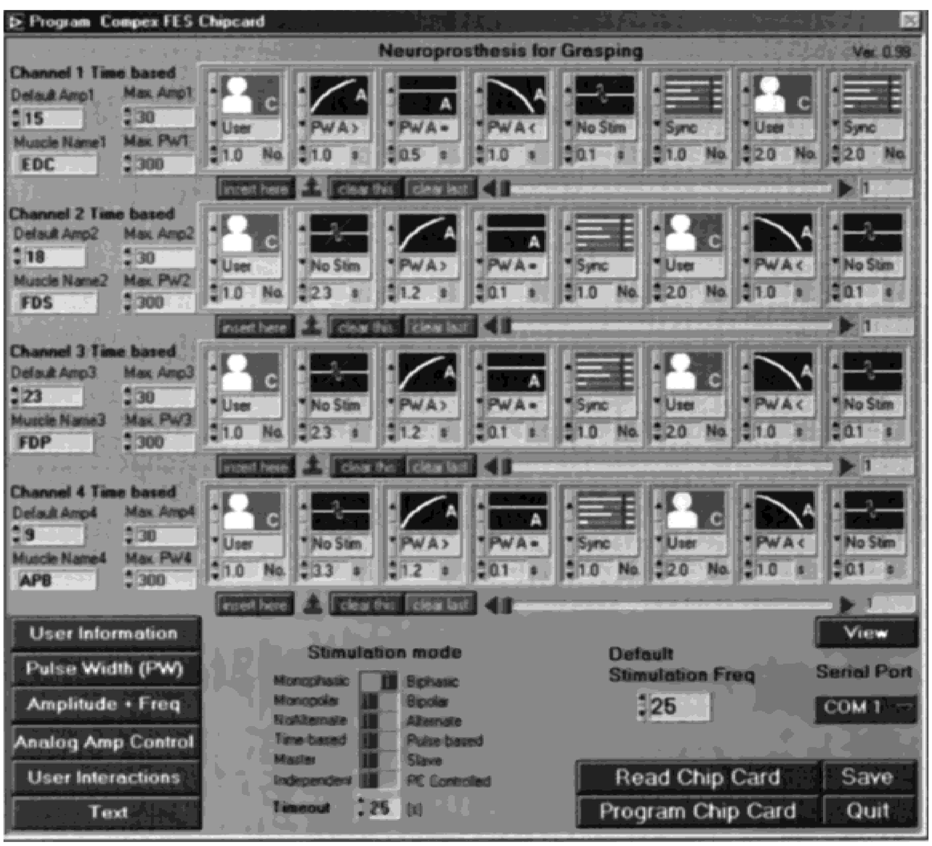


FIG. 2. Shown is the main window of the Compex Motion graphical user interface software. There are four horizontal timelines associated with each stimulation channel **(center and right),** pulse amplitude and pulse width safety limits **(left),** pulse-type settings **(center bottom),** memory chip card functions (right bottom), and setup functions **(left bottom).**

TABLE 2. *List of graphical user interface primitives*

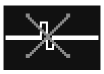
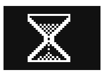
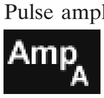
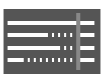
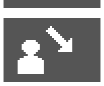
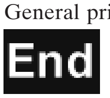
Icon	Name	Description
Pulse width primities		
	Constant pulse width	Generates a pulse train constant pulse width (four different values are available per channel).
	Pulse width ramp-up	Profile for changing the pulse width (two different profiles are available per channel; profiles are described with sixteen values).
	Pulse width ramp-down	Profile for changing the pulse width (two different profiles are available per channel; profiles are described with sixteen values).
	No stim	Pulse width equal to 0.
	Delay	Keeps the actual pulse width at the previous level for the given time interval.
Pulse amplitude primitives		
	Change amplitude	Changes the amplitude from the previous to a new value in a specified time interval (change is linear).
Pulse frequency primitives		
	Change frequency	Changes stimulation frequency (four different values are available, and they apply to all stimulation channels).
Primitive sequence control		
 	Jump back	Program jumps back n times in the sequence to the marker primitive where $n = 1–255$ or infinite ($n = 0$).
	Synchronize	Synchronizes otherwise independent stimulation sequences in all four stimulation channels.
Human interaction primitives		
	User interaction	This primitive waits for a specific user action to trigger a stimulation sequence. Any sensor and triggering criteria can be used.
 	User branch	Two trigger criteria set with the *user interaction* primitive are used to generate branching. If Critrerion 1 is fulfilled the program proceeds with the next primitive in the timeline. If Criterion 2 is fulfilled, the program jumps to a marker in the timeline and proceeds with the next primitive after the marker.
  	User interrupt	One trigger criterion set with the *user interaction* primitive is used to generate an interrupt. If this criterion is fulfilled at any time in the timeline between the ON and OFF primitives, the program jumps to a predefined marker and proceeds with the next primitive after the marker.
General primitives		
	End	Terminates stimulation in the specified channel timeline.
	Turn off	Turns off the stimulator.
	Display text	Displays two text lines with eight characters in each text line.
	Generate sound	Generates a melody (two different short melodies are available).

TABLE 2. *Continued*

Icon	Name	Description
Special primitives		
 	Random frequency	Activates a stochastic variation of the frequency. The frequency varies randomly about the nominal value (±0% to 100%) following a uniform probability distribution function.
 	Random pulse width	Activates a stochastic variation of the pulse width in the specified channel(s). The pulse width varies randomly about the nominal value within a specified range (±0% to 100%) following a uniform probability distribution function.
 	Random amplitude	Activates a stochastic variation of the pulse amplitude in the specified channel(s). The actual amplitude varies randomly about the nominal value within a specified range (±0% to 100%) following a uniform probability distribution function.

grasping or walking at our facilities. Besides walking and grasping, the system was used to treat shoulder subluxation and to strengthen muscles in some patients. Multicenter trials are expected to start by the year 2002.

Acknowledgments: This project was supported by a grant from the Federal Commission for Technology and Innovation, Switzerland (Project No. 4891.1).

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