

A portable, 8-channel transcutaneous stimulator for paraplegic muscle training and mobility—A technical note

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Abstract—This paper introduces an 8-channel transcutaneous neuromuscular stimulator, called ExoStim, which was designed and developed to provide stimulation to the lower-limb muscles of spinal cord injured individuals. The intended purposes of the ExoStim were to act as a skin-surface precursor to an implantable neuromuscular stimulator for the specific tasks of increasing paralyzed leg strength and endurance, enabling the performance of basic lower-limb functional tasks, and familiarizing patients with functional electrical stimulation training. The initial design specifications included portability (~500 g), battery-powered output, constant current control (0–300 mA), 8 channels of biphasic stimulation (charge-balanced, constant current), and microprocessor control of all stimulation parameters. Various tests, including output power characteristics, environmental, mechanical, and battery life, were performed on three prototype units to validate our design specifications. Having successfully passed all tests, the ExoStim is now ready to be deployed to clinical trial sites for further evaluation with spinal cord injured subjects.

Key words: functional electrical stimulation, neuromuscular stimulator, paraplegia.

INTRODUCTION

Functional electrical stimulation (FES) has been used to enhance the mobility of individuals with paraplegia for over 25 years [1,2]. Stimulation technologies have also

evolved from the early developments, with transcutaneous stimulators by Bajd et al. [3] and Kralj et al. [4], to multifunctional implantable devices that restore control to the bladder and bowel, as well as various levels of functional mobility.

In 1991, a 22-channel FES system was surgically implanted into an individual with thoracic-lesion-level paraplegia to restore lower-limb movements [5], and in later years development had begun on new multifunction FES neuroprosthesis (the Praxis FES System, Neopraxis Pty. Ltd., Sydney, Australia) that included an implantable stimulator, controller, and external limb-orientation sensors [6]. Before this multifunction FES neuroprosthesis entered clinical trials, we hypothesized that a simpler, transcutaneous stimulator (later called the ExoStim), employing a shared controller with the implantable system,

Abbreviations: ADC = analog-to-digital converter, CF = compact flash, DAC = digital-to-analog converter, FES = functional electrical stimulation, HV = high voltage, IC = integrated circuit, I/O = input/output, SPI = serial peripheral interface.

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would benefit prospective candidates by providing basic exercise and mobility functions prior to surgical implantation. In addition, a transcutaneous FES system, in its own right, could aid researchers and clinicians with a broad range of FES research interests.

Previous stimulator designs described in the literature portray devices that have successfully enabled standing [7], stepping [8], and lower-limb exercise [9,10] in persons with paraplegia. While standing can be achieved with only two channels of transcutaneous stimulation, four or more channels are necessary for reciprocal gait [11]. Other researchers have employed 6- [10] to 8-channel stimulators to achieve stepping, using the extra channels for better control of the gait cycle [12]. However, despite the inevitable development of improved stimulator technology and the abundance of research projects involving FES systems, there are still only a handful of commercially available skin surface stimulators for home use by paraplegic individuals [13].

Most of the aforementioned FES systems were designed for a particular research application and were not intended for clinical deployment. However, recent attempts have been made to develop clinical stimulators for a broad range of FES applications [14,15]. We considered it vital to incorporate into the ExoStim principles of FES system design appropriate for clinical devices, in an effort to overcome the negative attributes that previously led to poor end-user acceptance, such as—

- Lack of portability: Most stimulators reported in the literature are not portable because they derive their power from a mains connection [16] or, although portable, they rely on direct connection to a computer for programming of stimulation patterns or implementation of closed-loop control [8,12].
- Size: In the past, portable stimulators were large and cumbersome [10,17] and required a large number of batteries for a relatively limited amount of stimulating time.
- Clinician intervention: Most stimulators require input from a PC or other control device to program the operation of the stimulator before deployment, and thus require intervention by a trained professional. Even then, the stimulator cannot act autonomously to modify its stimulation parameters in real time with a user-friendly, robust control interface.

An important design objective of the ExoStim was to overcome some cosmetic and functional limitations apparent in previous neuromuscular stimulators, without

compromising any of the criteria necessary for a multi-purpose device suitable for a variety of FES tasks.

Therefore, the purpose of this project was to apply recent technological advances in the areas of electronics, microcontrollers, and software design to develop a transcutaneous neuromuscular stimulator that was small, lightweight, and portable, with multiple independent output channels and broad flexibility in the control of the stimulating pulse train (**Table 1**). Additionally, it was necessary for the design to provide some degree of backward hardware and software compatibility with an established, implantable FES system (the Praxis FES System, which comprises a Pocket PC controller, implantable stimulator, and orientation sensors) under worldwide clinical trials. Since the Praxis implant system already had an established serial communications protocol between the controller and the sensors, the ExoStim required compatibility with this communications protocol as well. We also wanted to keep system software changes within the controller to a minimum to accommodate the new stimulator, and the ExoStim's firmware had to be compatible with the existing implantable stimulator's software drivers.

This article describes the hardware and software of the ExoStim, and the components of the controller software as they relate to the command interface between the two devices. To verify the hardware design, we compared the calculated maximum power output of the stimulator to experimental results from a manufactured prototype. In preparation for eventual commercialization environmental and mechanical stress testing, we followed Australia Standards guidelines, and also determined the battery life during normal and extreme operating conditions.

METHODS

System Overview

The FES surface system consists of a stimulator, called the ExoStim, limb or trunk orientation sensors, and a controller. The stimulator is enclosed in a $9 \times 6 \times 3$ cm portable case outfitted with two belt clips. The case meets International Electrical Code 60601-1 electrical safety requirements, including prevention of contact with interior electronics. The unit's power is supplied by 4 AA alkaline batteries enclosed within the case. The ExoStim, with batteries, weighs approximately 500 g. There are a total of six input/output (I/O) connectors: two stimulation

Table 1.
Stimulation parameter ranges and technical specifications of ExoStim.

Stimulation Parameter	Range (Resolution)
Number of Channels	8
Current Output per Channel	0–216 mA (1 mA)
Waveform Type	Biphasic, square wave, charged balanced
Pulse Frequencies	17, 20, 25, 33, 50, 100 Hz
Pulse Width	25–500 μ s (2 μ s)
Interpulse Phase Interval	10 μ s
Channel Parameter Update Schedule	Per period
Technical Specifications	
Maximum Electrode Voltage	200 V
Output Characteristics	Constant current
Power Source	4 AA alkaline batteries
Low-Battery Notification	3.6 V

channel connectors (modified RJ45 connectors) for the eight stimulation channels, and four serial peripheral interface (SPI) (Motorola, USA) communication ports. The stimulation channel connectors were specifically designed to accept a 4-channel, custom-made cable, which features no exposed terminal electrodes. The four communication ports provide a direct link to the controller, as well as additional links for body-worn position feedback sensors via the ExoStim communication ports. A low-power LED, visible on the side of the enclosure, continuously flashes at a rate of 1 Hz when the ExoStim is powered and executing its embedded software. To alert the user during stimulation of any of the output channels, the flash rate increases to 2 Hz.

The controller consists of a separate, hand-held PC ($8.5 \times 13.49 \times 2.54$ cm) (Cassiopeia EG-800STG, Casio, Japan) with a custom-designed compact flash (CF) interface card, which together weigh ~ 300 g. The CF card provides the SPI to all the external components (ExoStim or sensors) on the communications bus via three ports. The controller has been modified with two belt clips, so the entire FES system consists of body-worn devices, as shown in **Figure 1**.

Stimulator Hardware

A block diagram of the stimulator hardware is given in **Figure 2**. Descriptions follow of key components, including the microcontroller, high-voltage (HV) power supply, stimulation current control, and the stimulation pulse width and frequency generator.

Microcontroller

The microcontroller chosen for our portable stimulator was a 4 MHz, low-power, 8-bit RISC chip with 128 kB of programmable flash and 4 kB of EEPROM (ATmega103L, ATMEL, California). This microcontroller also includes an on-board, 8-channel, 10-bit, analog-to-digital converter (ADC); 32 programmable I/O lines; master/slave SPI; and two 8-bit and one 16-bit counter.

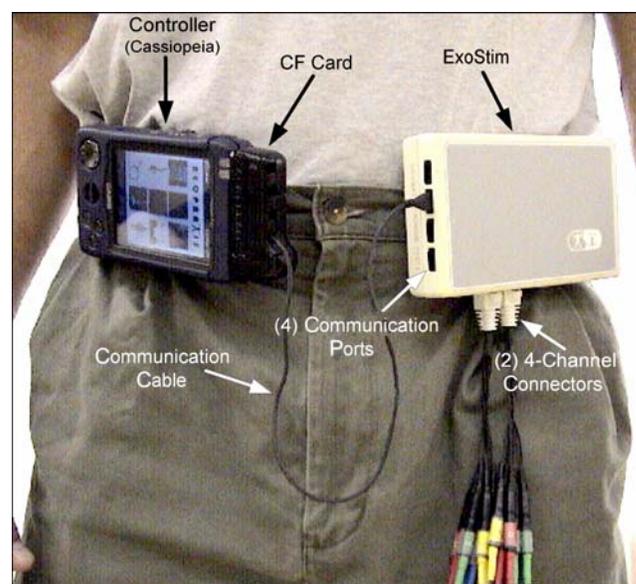


Figure 1.
ExoStim neuromuscular stimulator with its channel electrodes linked to handheld computer controller mounted on belt of user.

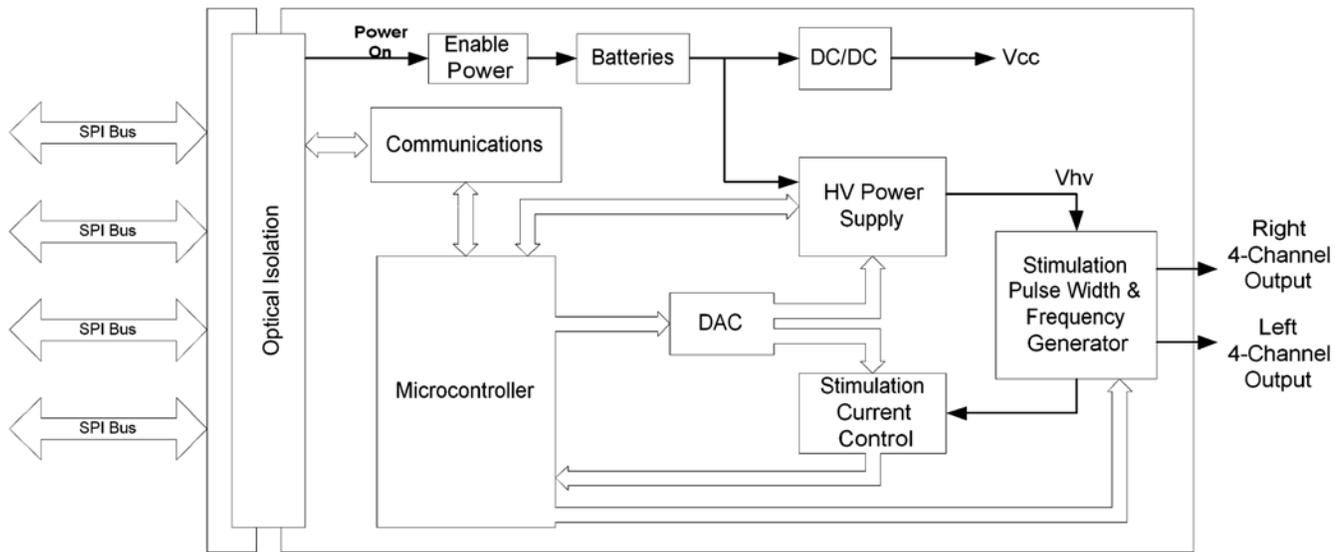


Figure 2.

Block diagram of stimulator components. Outlined arrows represent digital information flow and solid arrows represent power flow. V_{cc} is supply voltage for stimulator electronics and is maintained at +5 V. V_{hv} is high-voltage supply for stimulation channels and is maintained at +200 V.

Signals from the current control module, HV power supply module, and batteries are continuously sampled by the ADC and monitored for errors to ensure that the stimulator is safely operating within predefined parameters. Eight I/O lines to the digital-to-analog converter (DAC) (MAX505ACAG, Dallas Semiconductor, California) provide the analog signals that set the stimulation current and the HV threshold, and an additional nine lines are used to control the stimulation pulse width and frequency generator.

Communications

The communications module within the ExoStim is optically isolated from the controller to shield the user from potential grounding problems that could occur by touching the exterior casing of the controller while stimulating. This module includes a programmable logic device that facilitates the SPI with the controller and provides the means to shut down the microcontroller safely if the stimulator's battery output cannot maintain a nominal voltage for the microcontroller.

HV Power Supply

The HV power supply (5A200S, Pico Electronic, NY) of the HV power supply module is enabled by software

control and maintained at 200 V with feedback control circuitry, as shown in **Figure 3**.

Stimulation Current Control

The stimulation current setting is derived from eight digital lines of the microcontroller feeding into a DAC. The generated analog signal provides the reference point for the operational amplifier (OP162, Analog Devices, Massachusetts) controlled current source. Output stimulation occurs in a time-interleaved manner, meaning that in a given period of stimulation, the eight channels are alternately stimulated in 2 ms intervals. For example, if the stimulating period is set at 40 ms for all eight channels, the software would stimulate channel 1, then 2 ms later stimulate channel 2, etc., until all active channels have been stimulated. The stimulator is then idle for the remaining 26 ms until the sequence is repeated. Therefore, the DAC only has to provide a single analog voltage every 2 ms to control the current for a particular channel, which is easily achievable by the 4 MHz microcontroller.

Stimulation Pulse Width and Frequency Generator

The biphasic output timing characteristics (stimulation pulse width and frequency) of each channel are generated by 3 HV switch ICs (HV20720, Supertex, California) connected in an H-bridge configuration. The

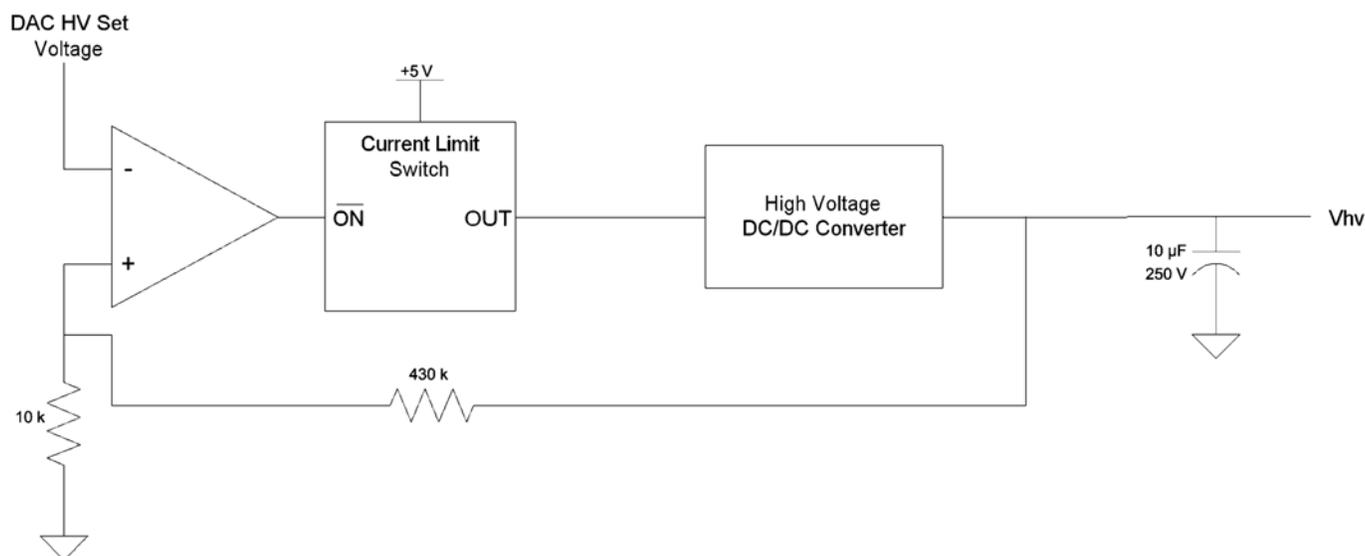


Figure 3.
Schematic of HV power supply module.

three digital inputs (A, B, and CLR) for each IC shown in **Figure 4** control up to 8 HV output switches that operate in tandem (SW1a & SW1b, SW2a & SW2b, etc.). It should be noted that when the CLR line is pulled high, all switches on the IC are open circuit; this is the state the switches are in upon start-up and when no channels are stimulating. Precise control of the switches, and therefore accurate stimulation pulse width and frequency of each channel, is achieved through interrupt-driven timers running in the embedded microcontroller software.

Controller Software

The controller software, Clinix, consists of a graphical user interface driven by C++ embedded software that runs on a Windows CE 3.0™ (MIPS) operating system. Functions are displayed as icons on the touch screen of the controller and represent various FES-related operations and tasks, such as a user-specific “stimulation parameter settings” function, lower-limb exercise (e.g., cycling), sit-to-stand, and stepping tasks. Each function consists of a “strategy,” or multiple strategies, comprising software routines that control the pattern and timing of the electrical stimulation pulses that carry out the FES task; these are configured by a clinician to suit the user.

A set of the strategies is provided with the complete FES system; however, third-party development of strategies is possible and controller software provides interfaces for the stimulator and peripheral devices.

Stimulator Interface

The stimulator interface processes the information from the strategy and sends appropriate commands to the stimulator via the SPI bus. Since the controller may use either the ExoStim or an implanted stimulator, the function calls from the strategy to the interface are identical for either device. This feature allows for a strategy to be developed initially for the ExoStim and subsequently used with a Praxis-implanted stimulator, without the need to reprogram the controller.

Peripheral Device Interface

Communication between the controller and the ExoStim is handled by a multi-layered bidirectional protocol capable of simultaneous communication to multiple peripheral devices on the SPI bus. Commands are concatenated to uniquely identifiable packets, depending on their intended receiving device—multiple orientation sensors or the ExoStim. To prevent transmission errors, a “checksum” is carried out on each packet; if an error is detected, the packet is resent.

Stimulator Software

The ExoStim’s microcontroller executes embedded software written in C language. Its operation can be described in three modes: communications, background, and stimulation.

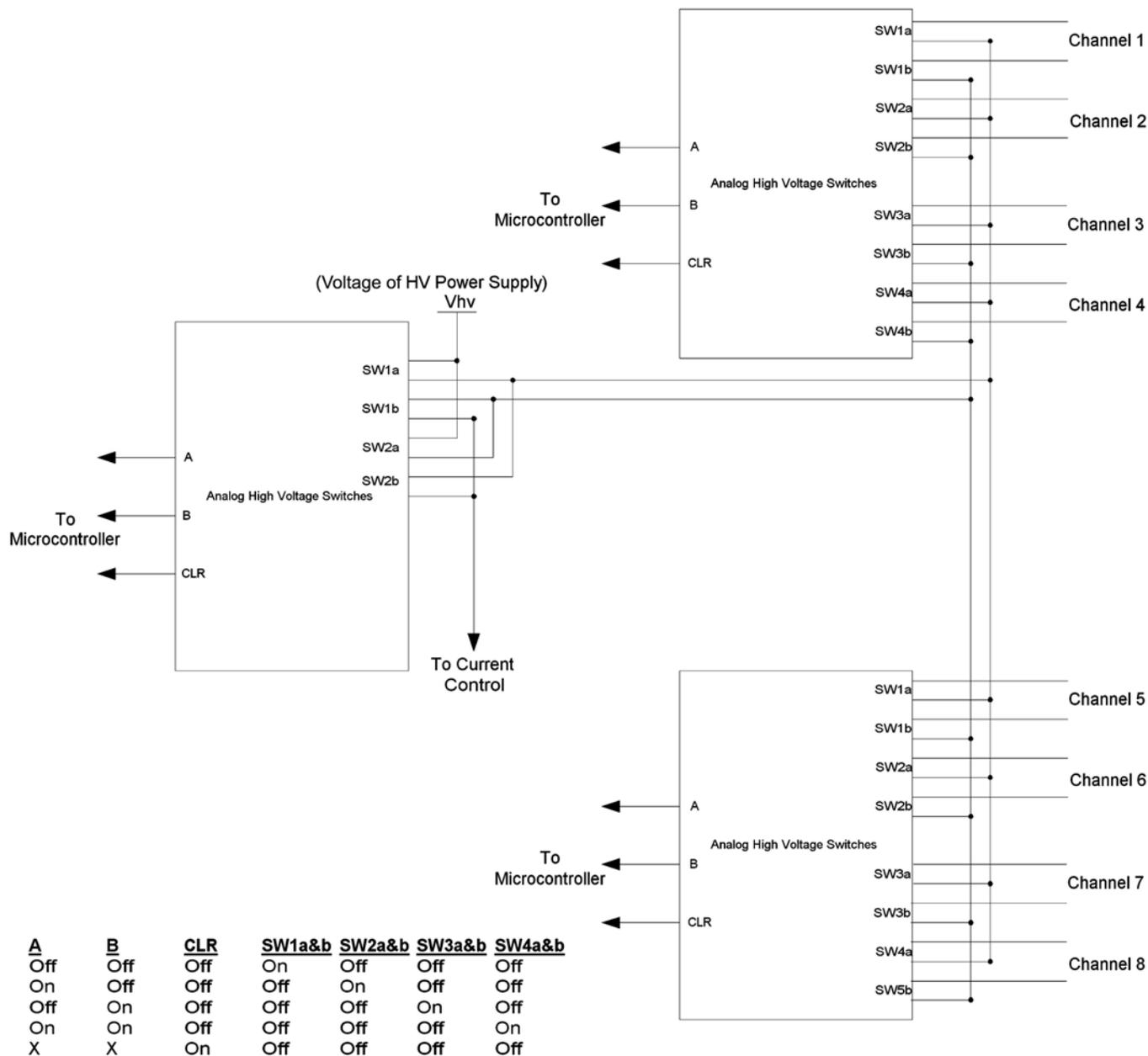


Figure 4. Schematic of stimulation pulse width and frequency generator module. Inset truth table demonstrates how logic inputs (A, B, and CLR) control tandem switches (SW1a&b, SW2a&b, SW3a&b, and SW4a&b) of high-voltage ICs.

In communications mode, commands are sent from the controller as packets that trigger SPI interrupts on the stimulator’s microcontroller when the receive buffer contains a “send” packet. The command is then stripped from the packet and processed. There are more than 20 different commands that deliver and retrieve informa-

tion to and from the stimulator. For example, the SET_STIMULATION_PARAMETER command provides the waveform information for the stimulation output for each channel, such as stimulation period, amplitude, pulse width, pulse width and amplitude slope, and duration of stimulation.

The stimulator enters the stimulation mode immediately after a stimulation command is received. Two software interrupt counters are enabled, one that regulates the stimulation pulse frequency and the other the pulse width of each channel, which execute a routine that opens or closes the appropriate HV switches to accurately establish the requested pulse width and frequency for each channel.

While in background mode, the microcontroller samples various ADC channels to conduct error checks on the stimulation output, batteries, and other electronic components. Data from each stimulation channel are analyzed per period for errors, such as significant impedance changes (open- or short-circuit conditions) and output compliance of the stimulation parameters (channels maintain the requested current level). A single ADC channel is all that is required to collect the output channel impedance data for all 8 channels. Also monitored, but on a less frequent schedule, are low battery voltage ($V_{\text{batt}} < 3.6 \text{ V}$) and over voltage of the HV power supply ($V_{\text{hv}} > 220 \text{ V}$). When an error condition arises, the stimulator software autonomously handles the error. For example, if a stimulation pad is removed from the user while stimulating, the software will detect the impedance change and deactivate that channel. All detected errors are written to an error register that is transmitted to the controller in the “return” packet after a command is sent to the stimulator. The controller alerts the user of the error condition and subsequently sends a command back to the stimulator to clear the error.

The ExoStim software can also be updated by the controller. If a software update is required, a controller utility can be executed that places the stimulator’s microprocessor in programming mode and then transmits the new software to its flash memory. Software modifications can be downloaded from a PC to the controller or directly from the Internet, thus eliminating the need to return the stimulator to the manufacturer for software updates.

Design Specification and Validation Testing

Power Compliance

The limitations of the stimulator power output were calculated based on the capabilities of the HV power supply and the duty cycle of the stimulation parameters. The maximum available power (P_{max}) provided by the power supply is

$$P_{\text{max}} = VI_i = (200 \text{ V})(18.75 \text{ mA}) = 3.75 \text{ W} , \quad (1)$$

where V is the constant power supply voltage and I_i is the total output current of the power supplies.

The total output power (P_o) of the stimulators channels is related to the current amplitude of each channel and the pulse train duty cycle:

$$P_o = (V) \sum_{n=1}^m (I_n) (PW_n / \tau_n) , \quad (2)$$

where m is the number of stimulating channels, I_n is the current amplitude of channel n , PW_n is the pulse width of channel n , and τ_n is the period of channel n .

To maintain voltage compliance the requested power to the stimulation channels cannot exceed the available power of the HV power supply’s output. Therefore, the duty cycles of the pulse train and current amplitude are bounded in order to sustain the desired power output of the stimulator.

To experimentally measure the power compliance of the ExoStim, we stimulated all eight channels through a $1 \text{ k}\Omega$ resistive load at set pulse amplitude and period. The pulse width was then increased from $50 \mu\text{s}$ in $2 \mu\text{s}$ intervals until the output voltage of the HV power supply decreased 5 percent from its regulated value of 200 V . This procedure was repeated for pulse amplitude/period combinations of $175 \text{ mA}/20 \text{ ms}$, $125 \text{ mA}/20 \text{ ms}$, $100 \text{ mA}/20 \text{ ms}$, and $175 \text{ mA}/30 \text{ ms}$.

Stress Tests

Three ExoStim units were evaluated under environmental and mechanical stress conditions according to specifications outlined by Australia Standards 1099 (1990), for basic environmental testing procedures for electrotechnology. The environmental testing was limited to the ability of components to be used or stored at the environmental extremes described in each test. All environmental tests were conducted in an environmental chamber (1020S, TestEquity, California) programmed to conditions specified in **Table 2**. At least 20 min were allowed for the test units to stabilize to ambient temperature ($23 \pm 3 \text{ }^\circ\text{C}$) before an operational electrical test, described in **Table 2**, was conducted on each unit. An external testing facility conducted the shock and random vibration mechanical tests. The free-fall test was conducted in our laboratory. Following mechanical testing, an operational electrical test was again carried out on all units.

Table 2.

Results and test conditions of ExoStim stress and battery tests.

Test	Condition	Referenced Australia Standard	Result
Environmental			
Cold Temperature	5 ± 2 °C for 16 h	AS1099.2.1 Aa	Pass
Dry Heat	55 ± 2 °C for 16 h	AS1099.2.2 Ba	Pass
Thermal Cycling	60 ± 2 °C to -20 ± 2 °C for 30 min in each of 5 cycles	AS1099.2.14 Na	Pass
Cyclic Damp Heat	95% relative humidity 55 ± 2 °C for 12 hr, then 25 ± 2 °C for 12 h	AS1099.2.30 Db	Pass
Mechanical			
Random Vibration	10–150 Hz @ 0.1 g ² /Hz 30 min/axis on 3 orthogonal axis	AS1099.2.34 Fd	Pass
Shock	15 g for 11 ms, half sine, 3 shocks per face on all 6 faces	AS1099.2.27 Ea	Pass
Free Fall	1.0 m drop per face onto all faces	AS1099.2.32 Ed	Pass
Battery			
Idle	0.45 W, continuous	N/A	>12 h
Medium	1.25 W, continuous	N/A	4 h
Heavy	3.75 W, continuous	N/A	45 min

Note: Three stimulator units were tested under each test condition. A “pass” result was given if all test units successfully performed an operational electrical test that consisted of these tasks: established communications with controller, enabled and maintained high voltage, and stimulated a 100 µs pulse width, 100 mA amplitude, and 33 Hz frequency pulse train on all 8 channels.

N/A = not applicable

Battery Life Tests

Three ExoStims were used to measure the battery life during three operating conditions; idle, medium, and heavy stimulation. Software running on the controller recorded the time elapsed before a low battery ($V_{\text{batt}} < 3.6 \text{ V}$) was detected while an ExoStim was operating in one of three selectable states: idle, no channels stimulating and HV power supply is off = 0.45 W; medium stimulation, power output = 1.25 W; and maximum stimulation, power output = 3.75 W. The output power from the batteries was measured with a digital voltmeter. For each condition the power output was continuous. For each test, fully charged, off-the-shelf alkaline batteries were used.

Waveform Traces

To illustrate the output characteristics of the ExoStim driving a real load, a single channel was applied to the leg of a healthy, able-bodied volunteer. Self-adhesive gel electrodes (Oval, 2.75 × 5 in., 6000 Series, Empi, MN) were placed across the rectus femoris while a stimulation waveform of 100 mA, 100 µs, and 25 Hz was applied. The voltage was measured by an oscilloscope (Tektronix, Beaverton, OR) with the probes connected directly across

the electrodes, while the current was measured as the voltage across a small (100 Ω) series resistor.

RESULTS

The experimentally measured points of compliance limit corresponded well with the calculated compliance curves, as portrayed in **Figure 5**. Empirically derived points of compliance failure for 125, 150, and 175 mA at a 20 ms stimulation period, and 175 mA at a 30 ms stimulation period, were all on or slightly below their respective calculated parameter limits.

Table 2 displays the results of the environmental, mechanical, and battery tests. All three units satisfactorily passed environmental and mechanical stress testing. It should be noted that there was negligible cosmetic damage as a result of the free-fall test; however, this did not affect the normal mechanical or electrical operation of the stimulator. The battery test demonstrated the ExoStim battery life to be greater than 12 h for idle, 4 h at medium load, and 45 min at maximum load.

The current and voltage characteristics of a pulse train of stimulation applied to the quadriceps of an able-bodied

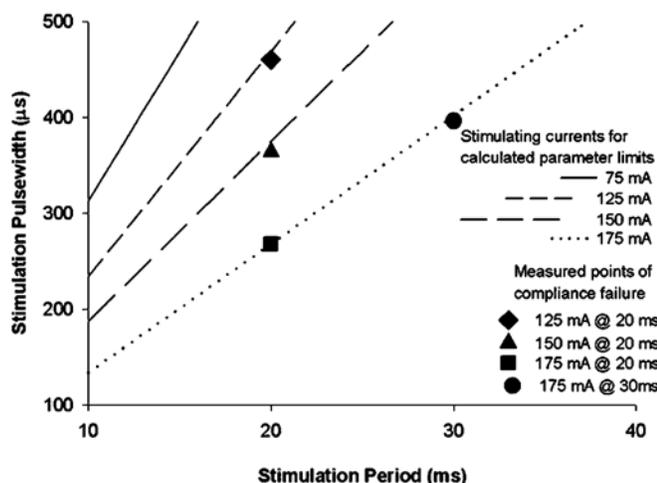


Figure 5.

Stimulator power output capabilities of 8 channels simultaneously stimulating 1 k Ω resistive load. Line plots represent theoretical power output of stimulator at various stimulating currents. Solid symbols represent measured stimulator output parameters that cause 5-percent decrease in power supply output.

volunteer are shown in **Figure 6**. The current trace demonstrates the ability of the stimulator to maintain balanced, rectangular pulses while driving a transcutaneous load.

CONCLUSIONS

This article describes the design, development, and validation of a new, portable, eight-channel transcutaneous FES system intended for a wide variety of clinical and research functions and eventual commercial deployment. During the design stage, we relied on input from FES researchers and investigation of the current state of surface FES stimulator technologies found in the literature. Although similar in many characteristics to earlier presented FES systems, the ExoStim FES system incorporates several unique features. First, its portability allows the stimulator to be used outside the laboratory without the need for a PC or large battery pack. Both the ExoStim and controller are belt-worn devices, and this enhances their cosmesis for clinical or home use by clients. Second, the ability to modify stimulus parameters (e.g., pulse amplitude, width, frequency, and duty cycle) in real time on a period-by-period basis across all eight channels may be used to optimize muscle performance

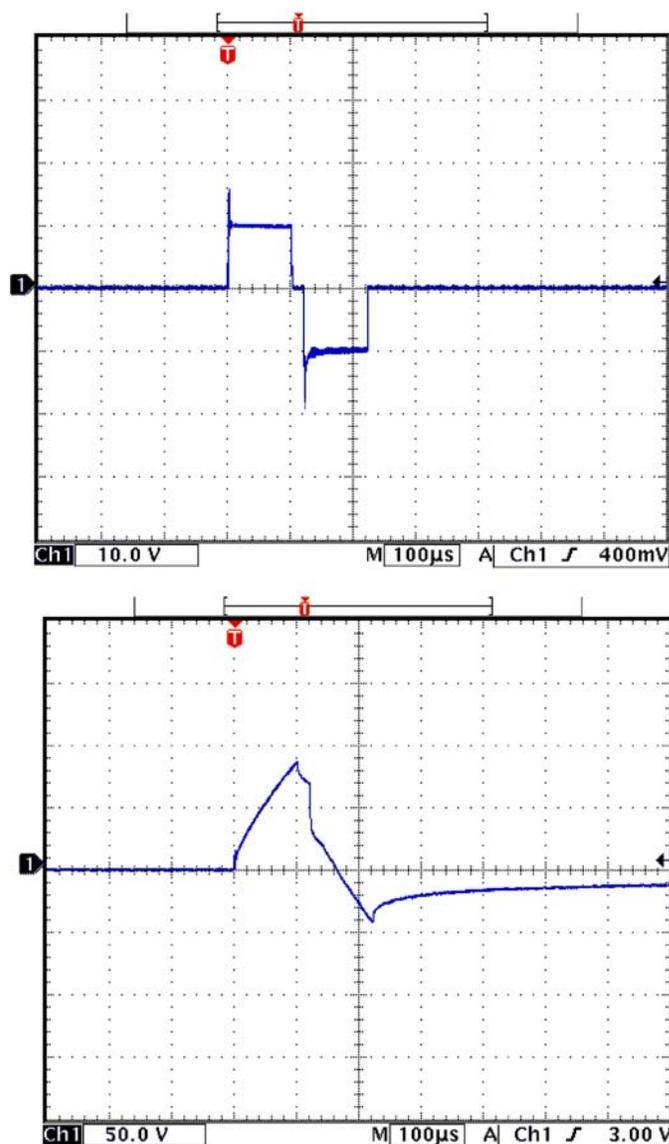


Figure 6.

Upper trace is single biphasic current pulse across single channel applied to real transcutaneous load. Lower trace is voltage through same load.

during a movement task. For example, in performing a sit-to-stand maneuver, the pulse frequency and duration might be altered in real time to recruit new muscles or change muscle performance near the end range of movement (e.g., near full-stance position). Third, the ExoStim's firmware was capable of acting autonomously to accomplish a multitude of stimulation and error-handling tasks, such as identifying batteries installed with

reversed polarity, low battery voltage, and “open circuit” electrode impedance, all without the need to communicate with the controller.

The ExoStim’s electrical performance behaved as expected. The results of the power compliance tests demonstrate that the theoretical expectations closely matched the experimental findings. Also encouraging are the results of the stress testing, demonstrating that our design and manufacturing processes meet independent standards for electronic devices, which is a basic requirement for future commercialization.

As with any device, certain compromises were necessary to maintain the design specifications that had been established at the onset of the project. One such compromise was the size of the stimulator versus its battery capabilities. To condense the size of the stimulator, the number and size of the batteries were reduced, with the knowledge that this would also reduce the time between battery supply changes, especially during heavy stimulation workloads. Nonetheless, a vital attribute of the stimulator was its cosmesis and portability, and these considerations were more important than the alternative of carrying unwieldy battery packs. Additionally, a battery pack of 4 AA alkalines was adequate to carry out a number of FES functional mobility or exercise tasks across multiple sessions. For example, the stimulator’s power output, at its maximum of 3.75 W, yielded a battery life of 45 min. However, under normal operating conditions, where the stimulator’s power output was only 1.25 W, the battery life was shown to be approximately 4 h. Well-trained individuals who perform FES-induced leg cycling have been shown to maintain 30 min of exercise involving 6 muscle groups at power outputs of 12 to 18 W [18], which translates to 8 to 10 training sessions per set of batteries.

Another design compromise was limiting the number of available stimulation frequencies to 100, 50, 33, 25, and 20 Hz (or 10, 20, 30, 40 and 50 ms stimulation periods) per channel, while gaining the advantage of having each channel individually stimulating at any of these frequencies. A contrasting approach would have allowed the stimulation of all channels at any frequency between 10 and 100 Hz (with a 1 Hz resolution); however, all channels would then be constrained to the same frequency. To justify the former design, most transcutaneous FES tasks involving the lower-limb use stimulation frequencies of 20 to 50 Hz, and for the control of fatigue it is desirable to individually modify the period of stimulation for vari-

ous muscle groups [19]. So, for prolonged FES activities, muscle fatigue might be reduced by dynamically changing the stimulation frequency to certain stimulating channels to recruit fatigue-resistant muscle fibers. This approach will soon be deployed in a strategy using the ExoStim for prolonged leg-cycling exercise.

Currently, the ExoStim is undergoing final hardware validation and preliminary human trials before it is deployed as a complementary device to the implantable Praxis FES system. The stimulator is also being repackaged into a smaller, custom-designed housing, providing enhanced cosmesis. Future research with the system is also under way at several research sites to deploy it for FES-evoked leg-cycling exercise (using fatigue-minimization strategies) and for stepping, using six channels of FES muscle contractions (with the 2 additional channels stimulating erector spinae for trunk stabilization). Long-term uses of the ExoStim may involve reducing “foot-drop syndrome” in hemiplegic stroke patients and assisting with arm cranking for C7–C8 lesion-level tetraplegic individuals who desire to undertake upper-body exercise.

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