Portable Neuromuscular Electrical Stimulator

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Abstract—Neuromuscular electrical stimulation is useful for restoring the movement of extremities in the treatment of some neurological disorders. A portable neuromuscular stimulator was developed for rehabilitation, Functional Electrical Stimulation (FNS) and for experimentation. The device is battery powered and can be controlled wirelessly. The adjustable current output is one of the advantages of this stimulator, because it can deliver several waveforms and it is possible to change every parameter on the stimulation signal. Power consumption, high selectivity, patient comfort and portability are important terms for medical electronic devices. Several setups were developed for the neuromuscular stimulator in order to perform different experiments.

Index Terms—neurostimulation, neuromuscular stimulation, electrical stimulation, portable stimulator, stimulation waveform.

I. INTRODUCTION

NEUROMUSCULAR electrical stimulation (NMES) and functional neuromuscular stimulation (FNS) are important bio-medical methods in modern medicine. They are useful for restoring the movement of immobile or immobilized extremities [1] or reducing symptoms of some neurological diseases [2]–[4].

Due to neurological disorders, like spinal cord injury, multiple sclerosis, cerebral palsy or stroke, people can be partially or completely disabled in their freedom of their movement. Damages at the central nervous system or particular nerve pathways can lead to severe consequences and a failure or disorder of muscles can occur.

The use of electronic devices allows to bypass the neuronal pathways from central nervous system, to stimulate directly the motor neurons which are electrically excitable and produce the muscle contraction.

The electronic devices are used to perform such electrical neurostimulation for rehabilitation [5], support in daily life [6], [7], for alleviating some types of chronic pain [8] or muscle training [9].

The NMES can be performed either by voltage or current signals. Voltage stimulation is non-preferred, because of changes in the electrode-tissue impedance, which can affect the stimulation threshold. The stimulation current is mostly a pulsed current, which consist of stimulation pulse trains, separated by interpulse intervals.

For achieving high selectivity it is favored to use small electrodes in order to stimulate small groups of neurons, e.g. in case of wrist and hand stimulation it is desired to control each finger apart to obtain natural pattern of movement. Due to the small area of electrodes the electrode-tissue impedance is higher, therefore greater voltage is required. On the other hand greater voltage between the electrodes can lead to skin burns in case of transcutaneous stimulation or hydrolysis and metal corrosion in case of invasive stimulation.

An unidirectional, monophasic stimulation pulse is able to fire the action potential and results in neuronal activation. In practice biphasic stimulation pulses are applied to provide a charge balance between negative and positive phases of the waveform. Charge balanced stimulation is important for safe stimulation to prevent damage at neural structures caused by electrochemical species on the electrode-tissue interface. It is particularly important with the use of implanted electrodes, because a mistaken use could be harmful [10]. Electrode implantation is currently more challenging than transcutaneous electrode use.

Totally implantable stimulators are more complex in fabrication and technology. The tendency is to have the whole system on a single chip, so they have to be small, low powered and hermetically sealed [1]. Because of the implantation, the chip is normally powered by an inductive link with a limited energy transfer.

In practice the rectangular pulse is the most utilized waveform for neurostimulation. Electrical stimulation devices mainly use this pulse form for the neuronal activation. However, other researchers have already shown through simulations that non-rectangular pulse forms can reduce the necessary energy used for neuromuscular stimulation [11]–[13] and also reduce the required voltage to fire the action potential [14]. We performed an in vivo experiment getting similar results [15]. The pulse width of the applied pulses and the frequency of the signal have likewise certain influence on the performed neurostimulation [9], [16].

In the document we describe the developed device. The system is programmable and can deliver current signals, it can be completely adjusted to perform several experiments or it can have fixed parameters to be used in rehabilitation and in daily use for FNS. Stimulation current signals formed by pulse trains can be defined, parameters like waveform, amplitude, pulse width, interphase interval between positive and negative phase or time between pulses can be configured by the user.
II. MATERIAL AND METHODS

A. System Description

The system can be divided into three components: the first one is a portable stimulator, which performs the electrical stimulation; the second one is graphical user interface, which enables the user to control and monitor the stimulation; the third one is the USB base station (hereinafter referred to as base or base station), which functions as an intermediate and communicates the PC and the portable stimulator.

B. The Portable Stimulator

The device is powered by a battery. On one hand the battery is important because of the safety reasons, so the stimulating device, which comes in contact with the human body, is not connected to the power grid, on the other hand because of the mobility and the flexibility of the portable stimulator.

A microcontroller (PIC18F46J50, Microchip) was used as a processing unit and programmed for the portable stimulator. The core of the stimulator is an application-specific integrated circuit (ASIC) developed in our facilities [17]. This ASIC behaves like a 9 bit DAC. It generates an analog signal from a digital data which is received in serial way and stored in an internal memory. The ASIC has one bipolar current output channel. An amplifier is connected directly at the output of the ASIC in order to deliver a current signal with amplitudes up to ±100 mA.

Due to the low voltage supply and the necessity of higher voltages to perform transcutaneous stimulation a voltage booster was implemented, it receives 9 V at its input and delivers ±100 V at its output.

Several electrodes can be used to conduct electrical current to the skin. Two universal 4 mm bunch pin plugs terminate the cable line of the portable stimulator in order to connect the electrodes.

In case of experimentation an external three-axial accelerometer (LIS344AL, ST) is attached to the stimulator. By locating it on any joint it enables the measurement of the muscle reaction or even the angle change of the joint because of the stimulation.

The control is effected either by the PC via the wireless interface or by the control panel. The control panel is compose by four push-buttons. The buttons can be programmed individually to perform individual tasks, i.e. to change the stimulation waveform, change the intensity of the output current, change the pulse width, etc.

A wireless transceiver module (MRF24J40MA, Microchip) based on the IEEE Std. 802.15.4 is implemented to establish the link with the PC through the base station.

C. USB Base Station

The base station (PIC18 Explorer Board, Microchip) is the bridge between the PC and the stimulator. It is connected to the PC through its USB port. A daughter card (MRF24J40MA PICtail, Microchip) is attached in order to establish the wireless link with the stimulator. Its core (PIC18F87J11, Microchip) was programmed to perform the corresponding tasks.

D. Graphical User Interface

Different graphical user interfaces (GUI) were developed to perform different tasks.

The first version program was developed for manual control over the portable stimulator. Visual Basic was used as application development tool. The user can manually generate the current signals, it is possible to choose the waveform, amplitude, interphase interval and time between pulses. It is also possible to perform either a single or a continuous stimulation.

Another version of the user interface was developed with LabVIEW especially for performing different experiments, see Fig. 2. This GUI enables precise experimentation due to its ability of loading a preconfigured file. The file should contain the number of signals to deliver on every experiment. All the parameter can be adjusted individually for every signal, e.g. it makes possible to perform an experiment by sweeping only a parameter or a combination of all of them. The signals can be single pulse or continuous. Fig 3. shows the adjustable parameters.

The interface also controls a data acquisition card (DAQ M PCI-6289, National Instrument) on the PC. The card is connected to the electrodes to perform the voltage and current measurements.
III. RESULTS

The portable stimulator is enclosed in a plastic box (16x8x2.5 cm³) and is be powered by a 9 V rechargeable battery. The weight of the portable stimulator is 272.60 g with the battery.

The device can deliver a signal with a maximum amplitude of ±100 mA, but by changing the gain resistor of the amplifier the output was limited to ±60 mA because of safety reasons. The output voltage will depend on the electrodes impedance, the device is able to handle up to ±100 V.

By stimulating with a continuous signal the current consumption of the system was found to be around 130 mA. For the measurement the stimulator was programmed to deliver continuously a sinusoidal signal. The parameters were: 33.5 mA amplitude, 290 µs pulse width, without interphase and 22 ms interpulse. At its output the two electrodes were connected at the forearm of a person.

According to the manufacturer the wireless control has a range of 400 ft (121.92 m). We tested the connection indoors for short distance communication without problems.

A. Experiments

An in vivo experiment was performed with the stimulator [15]. The study shows the difference of single pulse stimulation with four different waveforms (rectangular, sinusoidal, linear increase and linear decrease). For the experiment two electrodes (FLAB PG473 45x80 mm²) were placed on the right forearm, on the elbow over the ulnar nerve and over the motor point of the extensor muscle. The accelerometer was attached on the proximal phalanx of the middle finger. The amplitude was varied in order to know the muscle reaction for a certain amount of current, the experiment included the use of the four waveforms at different pulse widths (from 128 µs to 1024 µs).

The current and voltage at the electrodes by stimulating with a 256 µs pulse width signals are shown in Fig. 4.

Fig. 4 shows the energy that is necessary to apply in order to get the same muscle reaction (1.2 g) with four waveforms at different pulse widths.

IV. DISCUSSION

The size and weight of the stimulator make it suitable for daily use as FES. However, its autonomy is too short for the application, e.g. according the measurements it sinks around 130 mA. If we consider the use of a rechargeable battery which is commercially available, 9.6 V with a capacity of 200 mAh, it would function continuously around 1.5 hours without a change of battery. However, as shown its flexibility makes the device suitable for perform experimentation with changing waveforms sinusoidal, linear increase and linear decrease showed higher energy efficiency than the rectangular pulse. The optimal stimulation pulse width was found to be around 256 µs because of its balance between energy, current and voltage required. Among these four waveforms and with a 256 µs pulse width: the linear increase requires the lowest amount of energy (84.33% of the rectangular); linear decrease the minimum voltage peak (86.30% of the rectangular). The non-rectangular waveforms needed higher current amplitudes, between them the sinusoidal required the minimum current (140.93% of the rectangular).
parameters.

The results of the study [15] encourage to perform further experimentation in order to find the very optimal waveform for NMES. The use of lower voltages and necessity of less energy lead to smaller designs. The device presents the required characteristics and flexibility for performing such experiments.

The portable neuromuscular electrical stimulator can be combined with EMG/EEG biosignal acquisition methods, in order to perform the bypass in patients which the neuronal pathway is broken or interrupted by any disease or accident [18].

V. CONCLUSION

The developed neuromuscular stimulator is portable, flexible and battery powered.

The device is useful in some cases of FES, and rehabilitation, it able the physicians to select the required parameters.

Due to the fully programmable output signal it is possible to analyze the muscle reaction against the change of several stimulation parameters.

REFERENCES