# Enhancing Functional Electrical Stimulation for Emerging Rehabilitation Robotics in the Framework of Hyper Project

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**Abstract.** This paper presents the development of a novel functional electrical stimulation (FES) system. New approaches in emerging rehabilitation robotics propose the use of residual muscular activity or limbs movements during the rehabilitation process of neuromotor. More ambitious projects propose the use of FES systems to restore or compensate motor capabilities by controlling existing muscles or subject limbs. These emerging approaches require more sophisticated FES devices in terms of channels, signals controls and portability. In the framework of HYPER project, such devices are being developed to support the main objective of the project: the development of neurorobots and neuroprosthetics to restore functional motor capabilities in patients who suffered cerebrovascular accidents or spinal cord injury. The presented portable FES system includes novel electrostimulator circuits and improved channel switching capacities to enable emerging approaches in rehabilitation robotics.

### 1 Introduction

Cerebrovascular accidents (CVA) is the second leading cause of death worldwide, the third one in industrialized countries. In fact, it is considered as the main cause of long-term disability causing a tremendous economical and societal burden. Each year, about 795,000 people suffer a stroke in US. Nowadays, stoke death rate is about 13.5%. Approximately the 75% of all strokes occur in people over the age of 65 causing important motor impairments, affecting their quality of life, and struggling the chance of independent living.

Spinal Cord Injuries (SCI) can be considered as the second leading cause of long term motor disabilities. In numbers, approximately 11,000 new injuries occur each year in US. In the EU, an estimated 180,000 to 230,000 people suffer from spinal cord injury and there is an incidence of about 12,000 new cases each year. Unlike CVA, almost the 50% of SCI population is between the ages of 16 and 30, causing an even deeper impact in social structure and important economical burdens, [1]. Together with physiological and pathological tremors [2], CVA and SCI are the most important causes or motor impairments.

In many cases, motor capabilities affected by CVA can be rehabilitated. The use of robotics systems for this goal is almost a common approach in developed countries. Current approaches are focused on robotic exoskeletons that  $\mathbf{2}$ 

replicate the characteristic movements of a rehabilitation session driven by a therapist. In this approach, potential capabilities of smart robotic systems are not exploited, since the role of the robot is very passive, and moreover, the human-robot cognitive interaction is scarce. In the case of SCI, rehabilitation is quite more complicated. Many scientific works are aimed at developing solutions for the well-known problem of neural tissue and motor function restoration [3]. Cutting edge approaches propose brain-neural computer interfaces (BNCI) as an integrated tool to get a deep and natural human-robot interaction, both physical and cognitive, to expand the limits of neuromotor rehabilitation after CVA, [4], or to compensate neuromotor disorders like tremor, [5]. These novel human-robot interaction experiences include augmented reality to motivate user, bioinspired and optimal actuators to facilitate the rehabilitation process or to soft the physical interface and make the exoskeleton lighter and portable, among other new features.

In this context, Hyper project was conceived. Hyper is an initiative of several spanish research centers in field of robotics, biomechanics, neurology, braincomputer and human-computer interfaces, advanced power management and battery systems for portable devices. The project intends to represent a breakthrough in the research of neurorobotic and motor neuroprosthetic devices in close cooperation with the human body, both for rehabilitation and functional compensation of motor disorders in activities of daily living. The main objectives of the project are to restore motor function in SCI patients through functional compensation and to promote motor control re-learning in patients suffering from CVA by means of an integrated use of neurorobotics and neuroprosthetics. The project will combine biological and artificial structures in order to overcome the major limitations of current rehabilitation solutions for the particular case of CVA and SCI. The project addresses key questions at the frontier of knowledge in various scientific and technological disciplines. these questions are investigated in six research tracks with horizontal interrelationships: the systems will deal with variability in the human neuromuscular structures, with dynamical adaptations according to the latent motor capabilities of the users.

The ambitious objectives of Hyper can only be achieved with the support of adequate technologies. In this matter, the project dedicates efforts to specific technological developments, such as improved batteries, exoskeletons, sensors, control architectures, and novel actuators. Moreover, Hyper project collaborates with other satellite projects like TERERE, which is aimed at the development of electronic devices and systems for emerging rehabilitation robotics.

The work presented in this paper is focused on development of a Functional Electrical Stimulation system in the framework of the Hyper. Previous experiences in wearable exoskeletons demonstrated the difficulty of getting adequate performance of classic actuators in terms of power, portability and weight, in order to replace, replicate or compensate the function of human muscles, [6]. Hyper looks forward to contributing to the state of the art in modern actuators. These actuators should enable the development of the proposed portable exoskeletons. In this regard, the use of existing actuators is crucial. The muscles, that cannot be controlled anymore due to the motor impairment, will be the robotic actuators. By means of advanced BNCI and novel electrostimulators, the users could control their own muscles to provide the needed torque to joints to generate the desired forces and movements of limbs. However, to achieve this is a reliable manner, new FES systems should be able to tackle current limitation of the technologies, such as the provoked fatigue and coarse movements.

The paper provides a short review of FES technology and existing devices, and presents the enhanced solution designed in Hyper project.

# 2 Functional Electrical Stimulation Systems

Functional Electrical Stimulation (FES) consists in the excitation of muscle fibers or nerves by means of electric impulses to provoke a movement of organs or limbs. The electrodes used as an interface between the tissue and the electric impulses source can innervated the muscles, be attached to a nerve or placed externally over the skin. Thus, these systems can be invasive or non-invasive. The presented development was designed considering a non-invasive approach.

FES is not a novel technique, but it was rather restricted to labs as a research tool, or to clinics for rehabilitation sessions of paralyzed limbs. In 1985, the use of FES for restoring walking in SCI patients was already proposed by Bajd et al. [7], [8]. Later, some researchers combined FES with orthoses or exoskeletons to compensate the coarse movements provoked by existing FES technologies, [9]. Currently, FES is a more common and accepted technology. In the literature, many applications can be found such as the compensation drop foot after CVA, [?]. Veltink et al. developed smart sensors to be integrated into a implantable FES device to for drop-foot, [?]. The trend in walking restoration after SCI clearly points toward the use of FES systems in combination with modern exoskeletons, [10], [11]. However, classic FES problems remain in most of these application, such as user fatigue, [12], poor energy efficiency, lack of autonomy, scarce selectivity, of muscles, [13], and limited joint torques exerted by FES. By means of more optimal FES systems in combination with external light exoskeletons actuators, Hyper plans to tackle all the commented problems.

## 2.1 Key aspects of FES

FES technique directly interacts with living tissues. A FES system must know and respect the limitations and characteristics of the tissue. Otherwise, common problems will rapidly appear, like tissue damage, pain, fatigue, interface or electrode corrosion and poor selectivity.

The first decision that designers of non-invasive FES devices have to make is the type of signal that it is going to be applied to the skin. The delivered energy to contract the muscles can be in the form of current or voltage pulses. At first sight, both have the same effect. However, based on the neurophysiology of muscles current pulses look more natural, since that neural signal path is based of electric charges transmission. Moreover, in transcutaneous or noninvasive FES systems, the interface impedance can easily change and provoke different contraction levels that directly depend on the electric charges applied to muscle fibers. This is avoided if current pulses are applied. In terms of electronic design, a current source capable of handling the skin-electrode impedance is more complex to obtain, even more when considering a portable design for wearable rehabilitation robotic scenarios.

Another very important issue is the waveform of the applied current pulses. Figure 1 depicts several waveforms that have been studied, [14]. Waveforms can be monophasic (a,b) or biphasic (c, d, e, f). Some FES systems apply balanced charge biphasic stimulation patterns, which means that the applied energy to skin, in terms of charges, is the same during the positive and negative cycles, as occurs in waveform (c, d, e, f). It has been demonstrated that balanced waveform reduces the muscle fatigue. Regarding the shape of the waveforms, most of the depicted ones are based on rectangular pulses. Studies demonstrated better cell and fiber, [14], recruitment results comparing to triangular and other functions.

The electrostimulated plant (electrodes-skin-muscle) can be modeled as an electric resistance in parallel with a capacitor, and this arrangement in series again with another resistance, [15]. If rectangular voltage pulses are applied, RC charge-discharge curves appears in current waveforms, affecting the recruitment of muscle fibers and cells. This justifies the use of a current source instead of a voltage one.

Frequency, amplitude and duty cycle are other aspects that have to be considered when designing a FES device. Moderns electronic devices allows the fulfillment of most requirements in this regard. Amplitude of current signals can vary between 10 mA and approximately 150 mA depending on the muscle groups stimulated, the electrode-skin interface and the pain threshold of the user. Frequency range between 5 and 50 Hz. Muscle fatigue is also related with the frequency. It increases with frequency. Regarding the duty cycle, rectangular pulse width is usually between 100  $\mu$ s and 3 ms, [16].

#### 2.2 Open Challenges

Modern FES points towards the use of distributed electrodes to stimulate muscles. This approach is twofold. First, it is desired to reduce the amount of the current used to contract the muscles at each electrode-skin contact point. This would reduce pain and fatigue. Second, with more contact points and electrodes, muscle selectivity can be improved, [13].

The distributed concept also demands new stimulation algorithms and patterns to reach the desired goals. In this matter, flexible waveforms generators and multichannel systems are required. Some previous works have proposed techniques for optimization of spatial selectivity of multi-pad electrodes, [17] and their potential application in enabling functional movements, [18].

These former requirements are directly related with the electronic design of the FES device. Voltages at the electrode-skin interface can easily reach above 100V considering a 100 mA current pulse and an impedance of  $1 \text{ k}\Omega$ . Distributed



Fig. 1. Common current waveform used in FES systems. X-axis correponds to time represented in seconds.

electrodes mean dozens of electrodes that a have to be connected to the stimulator and moreover stable current stimulator cannot be obtained so easily using compact electronic components unless using a complete microelectronics system design, in which the power management and dissipation could be one of the major concerns.

Emerging rehabilitation robotic solutions, like the one proposed by Hyper project, need flexible, portable, controllable, robust and multichannel FES devices. This can only be achieved by means of new advances in portable current sources with high voltage electronic switching.



Fig. 2. Basic biphasic transconductance amplifiers or voltage controlled current source.

### 2.3 Current approaches

The most basic electrostimulator circuit is the one shown in figure 2. It can provide a monophasic or biphasic output waveform, similar to those shown in figure 1 (a), (b), and (c).

The amplitude of the current pulses is proportional to the amplitude of the voltage V1 and V2 applied to base pin of the transistor near the voltage source. The symmetric arrangement of two transistors, the one connecter to the voltage source and the other connected to collector the former one, work as a transconductance amplifier. The other two transistors act as single switches. The problem with this simple circuit is that it works in an open loop fashion and the transconductance gain,  $g_m$ , depends on each transistor and cannot be controlled.

In a previous section, the importance of balanced charge biphasic waveform was stated. To achieve this goal, Keller proposed a two staget circuit with two different working phases, [19]. During the first phase, the phase of active stimulation of the system, an operational amplifier controls the current across the load connected to a high voltage source. During the second phase, a passive discharge circuit, which appears in the upper part of figure 3, removes the electric charges from the electrodes-skin-muscle interfaces, previously inserted during the active phase. This is a very interesting solution but it struggles the chance of modifying actively the waveforms of the discharging periods.



Fig. 3. The biphasic current source circuit with balanced charge proposed by Thierry Keller, [19].

### 2.4 Existing solutions

There are many FES devices available on the market. However, as a result of an extensive literature survey, three models, two of then portable, are the most adequate for rehabilitation robotics and scientific purposes.

The first one is the Compex Motion, developed by T. Keller et al. in 2002. The Compex Motion was developed to control a hand neuroprosthesis, [20]. It is a current controlled stimulator, with a current range between 0 and 120 mA, pulse width between 0-16 ms, and a pulse frequency up to to 100 Hz. The device provides four channels for stimulation and some other digital and ADC inputs. The battery is rechargeable. The inventors claim that monophasic and biphasic waveforms can be obtained, [21].

The second reviewed model is the UNAFET8, [22]. This device provides a USB connection to connect to the PC. The Compex Motion provided a RS-232 interface. The UNAFET is similar to the Compex since it provides a current controlled output. The voltage output can be up to 150 depending of the electric load. The pulse amplitude goes from 0 to 50 mA and the pulse width can be set between 0 and 1 ms. The frequency rage is between 5-80 Hz. The inventors refer to the output as monophasic charge compensated. This means a waveform output similar to that shown in figure 1(e) and it is similar to the provided by the Compex Motion device. They probably called it this way because the discharging period is achieved passively, and not by the current source. The main advantage of this device comparing to the Compex Motion is the number of channels that in the case of the UNAFET8 is eight.

The third and last reviewed FES device is the RehaStim. It was developed by Hasomed GmbH, [23]. It can stimulate up to 8 independent channels. The current amplitude ranges from 0 to 126 mA. The waveform is biphasic. The frequency



Fig. 4. The TEREFES block diagram.

range is between 0 and 180 Hz. The communication interface is based on USB technology. This FES device is the most flexible one, but it is not portable.

# 3 The TEREFES design

The design proposed in the framework of Hyper and TERERE projects look forward to providing a high number of electrostimulation channels driven by controlled and stable current sources. The design has to be portable and flexible. This means that the generated waveforms could be modified to explore novel stimulation algorithms and patterns to support this emerging rehabilitation robotic field.

The proposed architecture Is depicted in figure 4 and its called TEREFES. Four AA batteries power the device. It includes USB communication interface by means of a FTDI232BL IC. This allows the configuration by an external software application. The stimulation circuit is controlled by an Atmel Atmega128 microcontroller. All the digital circuit is isolated and digital to analog convertors are used to control, by means of a voltage signal, the amplitude of current pulses used for stimulation.

The amplitude of the current pulses is between 0 and 120 mA (256 steps), with a maximum voltage of 250 V. The frequency can be configured with values between 0 and 100 Hz. It provides up to 32 channels, in two independent groups of 16 channels each, and driven by two different electrostimulators. The pulse width can vary from 10 to 5,000  $\mu$ s. It also includes some general purpose TTL digital I/O tfor synchronization with other devices and if required for external sensors signal acquisition.

There are two main components in the novel device: the electrostimulators and the switching circuits.



Fig. 5. The basic circuit of the TEREFES electrostimulator.

#### 3.1 Electrostimulators

Hyper proposes a more stable current source acting as the core of the novel FES device. The source current is based on a close loop voltage to current, or transconductance, amplifier. The basic circuit diagram is depicted in figure 5. A high voltage operational amplifier, the APEX PA78, enable this circuit. Within the proposed circuit, by choosing adequate values of R1, R2 and Rs, the transconductance gain,  $g_m$ , can be set.

The microcontroller provides a low voltage signal that is transformed to a current signal that crosses along the load. By proper switching of the loads, fully controlled monophasic and biphasic signals can be obtained. Since it is current source, when the electric load is high, meaning an open circuit, the voltage of the electrodes reaches its maximum value (250 V). Special techniques were developed to minimize this voltage when switching the loads to obtain biphasic waveforms.

The technical specification of the high voltage OPAMP allow fast rising times. Comparing to the two different current sources previously reviewed, the basic circuit based on transistors and the Keller's approach, the Hyper proposal has two main advantages. First, the  $g_m$  value remains constant within the range of operation. The second advantage is that the load is connected at a 0 V point when the controlling signal is equal to cero. This does not happen in the circuit depicted in figure 3. In this case, the load is always connected to a high voltage point.

#### 3.2 Channels switching

The second key component of the TEREFES design is the switching circuit. The aim of this circuit is to provide in a small form factor the capabilities of applying a unique excitation signal source to multiple electrodes. The solution comes from the field of microelectronics for piezoelectric arrays. The TEREFES uses the MAX14802 that is a 16-channel high voltage analog switch IC, controlled by a serial bus. The microcontroller generates the adequate signals to control the



Fig. 6. Basic switching circuit of the TEREFES electrostimulator. The switches are part of the MAX14802, a 16 high voltage anlog switches IC.

used scheme, depicted in figure 6, enabling the implementation of monophasic and biphasic waveforms. The TEREFES uses 4 ICs to get the full functionality of two stimulator with 16 channels each. The configuration uses a common cathode scheme for each 16-channel group. The setup is adequate to control two different muscle groups in a distributed manner simultaneously.

# 4 Implementation and results

Implementation of TEREFES design resulted in a 190 x 138 x 45.5 cm device. The weight is approximately 300 grams. The autonomy could be measured under different conditions, but early results indicate an autonomy of approximately 4 hours under normal conditions. The complete design is divided in three different interconnected printed circuit boards. The first one includes the power circuit. The second one includes the digital controller, isolators, and switching circuit. The high voltage operational amplifiers are located in different printed board circuits.

Figure 7 depicts a basic high voltage waveform obtained with the TEREFES electrostimulators and the switching circuits with a pure resistive load.



**Fig. 7.** Basic waveforms obtained with a pure resistive load and the TEREFES electrostimulator.

# 5 Future work

In the framework of HYPER project the system will be validated with normal subjects and with CVA and SCI patients. Ad-hoc designs will be implemented to get optimal configuration in terms of number of channels and stimulators.

The TEREFES is not only a flexible FES device, but also a modular architecture. Future works will be focused on the development of alternative switching modules in order to get different configurations, resulting from the trade-off between the number of channels and muscle groups. For instance, for other rehabilitation robotics scenarios, a more adequate configuration of the TERFES could be one with two stimulators but for eight different muscle groups, each one with up to four electrodes. This would require eight different cathodes, unlike the current configuration, which has only two.

# 6 Conclusions

This paper presents a novel FES device system. The system was conceived in the framework of Hyper project, which proposes ambitious rehabilitation neurorobotic and neuroprosthetic systems for SCI and CVA patients.

The developed electrostimulator is based on a novel current source that represent a step forward in current state of the art in FES devices. It represents a robust designed based on a linear closed loop transconductance amplifier.

The FES system, called TEREFES, also provides enhanced switching capacities to support multiple electrodes. In the described design with up to 32 channels are obtained in a portable device. The electrostimulator can drive in each channel a 120 mA biphasic waveform. 12 F. Brunetti, A. Garay, J.C. Moreno and J.L. Pons

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