FUNCTIONAL ELECTRICAL STIMULATION FOR UPPER LIMBS FLEXION-EXTENSION AND PREHENSION MOVEMENTS IN REHABILITATION

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ABSTRACT

Functional Electrical Stimulation (FES), is a technique that uses low-energy electrical pulses to artificially generate muscle contractions, in individuals with damages regarding the central nervous system. The application of FES in clinical environment involves both patients care and rehabilitation. Aim of this work is to introduce a clinical FES protocol for upper limbs rehabilitation, in order to assist and train the execution of complex movement, such as flexion- extension of wrist and fingers and palmar prehension. The new FES protocol has been tested on a cohort of five subjects with different upper limb neuromotor deficits, during their rehabilitation. The benefits deriving from the application of the new FES protocol have been evaluated by comparing specific quantitative electromyographic parameters assessed before and after the treatment. Results show effective improvements in performances of 4 patients out of 5.

INTRODUCTION

Functional Electrical Stimulation (FES) is a technique based on the application of low-energy electrical pulses to neuro-muscular structures in order to achieve movements or sensations. FES is used in individuals who have been paralyzed due to injury to the central nervous system, but maintaining a residual peripheral neuro-muscular innervation.

FES is typically provided through the application of regular pulse waves made of monophasic or biphasic pulses. Monophasic waveforms consist of repeated identical pulses (Fig.1), usually cathodic. Biphasic waveforms (Fig. 2) are made of repeated biphasic pulses, each one composed by a cathodic phase followed by an anodic phase. The second phase pulse is aimed at reversing the electrochemical processes triggered by the first phase pulse, which can occur at the tissue-electrode interface damaging the skin.

Pulse waveform has to be chosen considering the following: the desired physiologic effect (action potential), any potential damage to the tissue and the potential degradation of the electrode. Biphasic waveforms are more used than monophasic in FES, and they are typically made of square pulses. Brief rise time in pulses can avoid the accommodation of the muscle fibers. An inter-phase time delay should be applied between the cathodic and anodic pulses, in order to allow the complete propagation of the action potential along the nerve. Moreover, the limitation of second pulse amplitude can prevent the electrode potential

and its corrosion.

The application of FES in clinical environment involves both patients care and rehabilitation. FES can be used in patient with damages regarding the central nervous system, presenting an interruption of stimuli propagation towards peripheral structures due to injuries or cerebral palsy. In order to achieve results, the stimulated muscle and nerve have to be intact and totally healthy.

The principal purpose of FES is to keep training healthy muscles and voluntary functions by inducing physiological changes [1-3]. The principal results achieved with FES are: reduction of spasticity and pain associated with it; improvement of local blood circulation; mobilization of local soft tissues; stress of the bones; stopping atrophy and increasing muscle mass; improvement of the limb posture.

FES intervention is aimed to complement functions, both sensitive and motor, altered and damaged by neurological pathologies. It stimulates neuronal reorganization for the recovery of motor control, exploiting the plasticity of the cerebral cortex. In the case of the upper limbs, for example, the aim of FES is to restore to the patient (typically hemiplegic or who has suffered a spinal cord injury at C5 and C6 level) the ability to grasp, manipulate and release objects and tools of various shapes, thus restoring his self-sufficiency in daily activities.

Aim of this study is to set up a clinical FES protocol to follow in upper limbs rehabilitation, in order to assist

Fig. 1 - Monophasic waveform, The application of FES in clinical environment involves.

Fig. 2 - Biphasic waveform.

and train the execution of complex movement, such as flexion- extension of wrist and fingers and palmar prehension. The benefits deriving from the application of the new FES protocol have been evaluated by comparing specific quantitative electromyographic parameters assessed pre and post treatment.

METHODS AND MATERIALS

A. Study Population

A group of five subjects with different upper limb neuromotor deficits and different muscle degeneration, without previous experience with FES training, were recruited from the Neurology Unit of ICS Maugeri Institute of Care and Scientific Research, Telese Terme (BN, Italy). Written informed consent was obtained from each of the subjects prior to their participation in the study.

Subjects' features are summarized in Table I.

Despite their different diagnosis, all patients are characterized by spastic muscles in the impaired upper limb treated.

Subject	Age	Sex	Diagnosis
1	42	M	Right hemiplegia
2	25	M	Left spastic hemiparesis
3	17	F	Spastic tetraparesis
4	16	M	Spastic tetraparesis
5	74	F	Neglect syndrome - Left spastic hemiparesis

Tab. 1 - Study Population.

Fig. 3 - MotionStim8 device.

B. Functional electrical stimulator- MotionStim 8

MotionStim8 from Medel Medicine Electronics is a device designed for FES as a supplemental therapy after impairments of the central nervous system (Fig. 3). The system is designed to integrate movement therapy with FES, for damaged and/or paralyzed muscles in order to activate trophic recovery and muscle effort and restore lost functionalities.

The device has 8 channels, to each of which 2 electrodes can be connected. It measures 186 x 38 x 155 millimetres, weighs 550 grams and contains an internal battery for wireless operation, which ensure the supply and removal of the current. The treatment time is adjustable from 0 to 10 hours. The stimulation is done by a biphasic square pulse. Current pulse amplitude can be set from 1 up to 125 milliamperere, with frequency from 1 to 99 Hertz and a pulse width of 10 - 500 μ seconds [4]

MotionStim8 can be supplied with Motionsoft, the PC software dedicated to creating functional electrical stimulation protocols. The software development environment is equipped with intuitive interfaces that make learning to use very fast for the user. These, by means of an editor for the creation of electrical stimulation protocols, can effectively develop customized FES programs.

C. BTS FREEEMG 300

BTS FREEEMG 300 is a diagnostic device for surface dynamic electromyography analysis. Based entirely on wireless technologies, BTS FREEEMG 300 uses 16 miniaturized probes (Fig. 4) with active electrodes weighting less than 9 grams for signal acquisition and transmission. The probes amplify EMG signals, digitize them and communicate with the compact and light receiving unit, consisting of a Pocket PC based on Microsoft Windows.

BTS FREEEMG 300 is supplied with Myolab, the smart and easy to use software that BTS has developed for EMG signal acquisition, visualization, and a first level of processing.

Fig. 4 - BTS FreeEMG probe.

Channel	Muscle	Pulse Amplitude [mA]	Pulse Width [us]	Time Delay [s]	Pulse Frequency [Hz]
Ch1	Extensor Carpi Ulnaris	23	500	-	20
Ch2	Extensor Digiti Minimi	25	500	0,1	20
Ch3	Flexor Carpi Ulnaris	23	500	5,0	20
Ch4	Flexor Digitorum Superficialis	25	500	5,0	20

Tab. 2 - Muscles involved and Parameters of the First Trial.

Channel	Muscle	Pulse Amplitude [mA]	Pulse Width [us]	Time Delay [s]	Pulse Frequency [Hz]
Ch1	Extensor Carpi Ulnaris	22	500	-	20
Ch2	Extensor Digiti Minimi	8	500	0,1	20
Ch3	Flexor Digitorum Superficialis	10	500	2,0	20
Ch4	Flexor Digitorum Superficialis	8	500	2,0	20
Ch5	Lumbrical (II and III fingers)	6	500	2,5	20
Ch6	Lumbrical (IV and V fingers)	5	500	2,7	20
CH7	Flexor Carpi Ulnaris	5	500	3,0	20

Tab. 3 - Muscles involved and Parameters of the Second Trial.

D. Clinical FES Protocol

We developed a new clinical protocol to assist and train the execution of complex movement of the upper limbs, based on the asynchronous FES. The protocol is made of 2 trials

1. The first trial is aimed at the re-education of the upper limbs muscle in flexion-extension movements of the wrist and fingers.
2. The second trial is aimed at the re-education of the upper limbs muscle in palmar prehension movements.

In Table II muscles involved in the first trial are reported. For each muscle the following information are reported: channel of the MotionStim8 to which the muscle is connected, current pulse amplitude, current pulse width, delay time from the first pulse given on channel 1 and stimulation frequency. Pulse amplitude and width are the parameters used to adjust the number of motor units involved and the muscle contraction strength. The increasing of one of these parameters produces the growth of the energy provided to the muscle, causing the activation of a greater number of motor unit, and a consequent greater muscle strength. Otherwise pulse frequency does not affect muscle contraction strength. Values of pulse frequency below 15 Hz can cause muscle tremors, values above 50 Hz cause rapid muscle fatigue, while frequency values between 15 Hz and 50 Hz have little or no effect on muscle strength. Therefore the stimulus frequency is set at a constant value (20 Hz) as low as possible to avoid premature muscle fatigue and minimize skin discomfort.

Transcutaneous electrodes have been used in FES protocol. They have been placed on muscle motor points, which is the stimulation site that produces the most isolated and strong contraction, at the lowest level of stimulation. The advantages of surface electrodes are their non-invasiveness, low cost and relative technological simplicity. However, the disadvantageous

aspects are not lacking: it is problematic to reach isolated contractions or activate muscles in depth; the repeated placement of electrodes is difficult to replicate; finally, electrical stimulation on sensitive skin can cause painful sensations due to the activation of the skin pain receptors. Fig. 5 shows electrodes' placement. In this trial Flextrode oval electrodes (4x6 cm) have been used for all the involved muscles.

First trial's duration is 22 minutes, with an initial warm-up time of 2 minutes, during which the amplitude of current pulses is gradually increased up to the value chosen for the stimulation. During the following 20 minutes, 10-second stimulation phases alternate with 5-second pause phases, in which pulses are not supplied. Stimulation phase begins with the activation of the extensor carpi ulnaris on channel 1, followed from extensor digiti minimi on channel 2 after 100ms. This kind of stimulation allows fingers and wrist extension and is kept active for 5 seconds. After this, channel 3 and 4 simultaneously activate flexor muscles, causing wrist and fingers flexion during the last 5 seconds of the stimulation phase.

In Table III muscles involved in the second trial are reported. Fig. 6 shows electrodes' placement. In this trial 6 Flextrode oval electrodes (4x6 cm) and 8 Flextrode round electrodes (Ø25mm) have been used. Second trial's duration is 22 minutes, with an initial warm-up time of 2 minutes, During the following 20 minutes, 11-second stimulation phases alternate with 5-second pause phases, in which pulses are not supplied. Stimulation phase begins with the activation of the extensor carpi ulnaris on channel 1, followed from extensor digiti minimi on channel 2 after 100ms and flexor digitorum superficialis from both channels 3 and 4 after 1.9 seconds. This kind of stimulation allows the prehension hand closing phase. Following this, channels 5 and 6 activate sequentially the lumbrical palmar muscles to have better control of the movement. Lastly, after 300ms, the flexor carpi ulnaris is activate on channel 7 to hold the grip. All invol-

Fig. 5 - Electrodes placement in the first trial.

Fig. 6 - Electrodes placement in the first trial.

ved muscles are kept active for 8 seconds, after which the extensor muscles first start to release and then the hand and flexor muscles follow.

Patients performed FES protocol once a day, for at least one week during their rehabilitation treatment in Neurology Unit of ICS Maugeri Institute.

E. EMG Acquisition Protocol

Electromyographic assessments on patients have been conducted before and after the FES treatment to evaluate the rehabilitation outcome. Electromyography (EMG) has been performed by using BTS Free EMG system, on the following muscles: Extensor Carpi Ulnaris (ECU), Extensor Digiti Minimi (ECM), Flexor Carpi Ulnaris (FCU), Flexor Digitorum Superficialis (FDS). Before the application of the probes, patient's skin has been shaved and cleaned with alcohol. The bipolar electrodes on each muscle have been applied with an inter electrode distance of 20mm, and with the orientation parallel to the muscle fibers. Fig. 7 shows EMG probes' placement.

EMG measurement session is made of 5 consecutive phases, each one lasting 1 minute, for a total duration of 5 minutes. In each phase patient has been asked to

perform a different task:

1. Rest
2. Maximum wrist extension (MWE)
3. Maximum wrist flexion (MWF)
4. Maximum fingers extension (MFE)

Each subject has performed at least 2 sessions. EMG signals have been post-processed using Matlab. Signals have been detrended and then filtered using band-pass Butterworth filter (cut-off frequencies 10-500 Hz). The Root Mean Square (RMS) of the signal has been assessed for each muscle and for each task of the recording. In order to compare RMS values of the different phases and muscles, they have been normalized to the RMS value assumed from the same muscle of the same subject during the rest phase. This way RMS values are expressed as percentage of the correspondent rest phase.

■ RESULT AND DISCUSSION

EMG measurements have been performed to assess the rehabilitation outcome induced by the FES protocol. In Table IV results are expressed in terms of RMS range, that is the range between the minimum and the maximum values assessed. Results are reported for each patient and for each active task phase of the EMG acquisition protocol. RMS ranges are expressed as percentage of the correspondent RMS value assessed during the rest phase. For each task, results have been divided into RMS ranges of the agonist and antagonist muscles. A cohort of 3 healthy subjects performed the same EMG protocol in order to assess *normative ranges* for the evaluated measurements. Normative ranges are reported in the last row of the table. Significant differences between pre and post RMS ranges have been highlighted with bold font.

The first task involves the wrist extension. In all the patients, significant differences have been assessed between pre and post measurement, both for agonist and antagonist muscles. RMS ranges for agonist muscles assume greater values after the rehabilitation, pointing out an increase in muscle tone. Antagonist muscles have tighter RMS ranges after rehabilitation, which means a better control of muscle activation.

In the second task, regarding the wrist extension, similar results have been pointed out. RMS ranges in agonist muscles get higher values and closer to nor-

Fig. 7 - Electrodes placement for EMG acquisition protocol.

	Maximum Wrist Extension				Maximum Wrist Flexion			
	Agonist Muscles (ECU, ECM)		Antagonist Muscles (FCU, FDS)		Agonist Muscles (FCU, FDS)		Antagonist Muscles (ECU, ECM)	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Patient 1	92% - 119%	127% - 215%	120% - 131%	189% - 353%	178% - 254%	227% - 359%	144% - 233%	216% - 230%
Patient 2	122% - 782%	468% - 1201%	248% - 1217%	415% - 929%	1797%-4531%	620%-2880%	200% - 310%	343% - 344%
Patient 3	144% - 186%	475% - 1223%	869%-2007%	416% - 927%	243%-298%	630%-2920%	117% - 240%	348% - 352%
Patient 4	118% - 261%	620% - 771%	297%-1641%	478% - 666%	122%-369%	1084%-2200%	119% - 996%	207% - 328%
Patient 5	198% - 209%	476% - 1229%	160% - 184%	407% - 865%	209%-222%	632%-2929%	212% - 245%	349% - 351%
Normative Range	390% - 1490%		110% - 500%		250% - 1780%		190% - 590%	

	Maximum Fingers Extension				Maximum Fingers Flexion			
	Agonist Muscles (ECU, ECM)		Antagonist Muscles (FCU, FDS)		Agonist Muscles (FCU, FDS)		Antagonist Muscles (ECU, ECM)	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Patient 1	117% - 140%	111% - 155%	129% - 175%	246% - 252%	175% - 300%	169% - 170%	233% - 428%	126% - 191%
Patient 2	115% - 240%	281% - 288%	1324%-1514%	530%-2495%	224% - 319%	475% - 971%	1041%-2679%	328% - 723%
Patient 3	127% - 141%	280% - 287%	722%-1603%	526%-2471%	104% - 192%	476% - 974%	238%-350%	328% - 724%
Patient 4	113% - 298%	146% - 198%	285%-1457%	862%-1050%	118% - 823%	229% - 255%	109%-266%	240% - 609%
Patient 5	233% - 258%	279% - 287%	154% - 167%	523%-2452%	217% - 242%	480% - 982%	173%-226%	328% - 727%
Normative Range	400% - 1910%		180% - 700%		370% - 1300%		210% - 790%	

Tab. 4 - RMS Ranges of Pre and Post Surface Electromyography Acquisition.

mative values in post measurements. A better control of antagonist muscles is pointed out by the tighter ranges assumed after the rehabilitation. In fingers extension no significant differences have been carried out. Finally in fingers flexion 4 patients out of 5 have improved their performances thanks to FES rehabilitation. Due to the severe pathological condition and the state of minimum consciousness characterizing Patient 4, no significant finger flexion or extension were observed. According to the presented results, it can be stated that the new asynchronous FES protocol proposed has carried out effective improvements in 4 patients out of 5. It should be underlined that the numerical limitation of the study population makes this work a preliminary study and an explorative investigation with bioengineering value. In order to point out significant clinical results, it would be desirable to extend the study towards a largest cohort of patients.

REFERENCES

1. H. Ring, h. Weingarden and r. Nathan, “the handmaster – benefits of intensive functional electrical stimulation in cva”, proc irma 8th world congress, kyoto, japan, 1997.

2. H. Weingarden, r. Nathan, r. Kizony and h. Levy, “upper limb functional electrical stimulation for walker ambulation in hemiplegia – a case report”, am j of phys med rehab, vol. 76, no. 1, pp. 1-5, 1997.

3. H. Weingarden, g. Zeilig, r. Heruti, y. Shemesh, a. Ohry, a. Dar, d. Katz, r. Nathan and a. Smith, “hybrid functional electrical stimulation orthosis system for the upper limb: effects on spasticity in chronic stable hemiplegia”, am j phys med rehab, vol. 77, no. 4, pp. 276-281, 1998.

4. Simon, c. (2017). Drahtlose pc-anbindung des muskelstimulators motionstim8 und realisierung einer steuersoftware zur kopplung mit dem thalmic myo armband (doctoral dissertation, hochschule heilbronn).

CONCLUSION AND PERSPECTIVE

In conclusion, two important aspects emerged from this work. The method performed demonstrated the effectiveness and usefulness of a Functional Electrical Stimulation protocol in the therapeutic treatment of particular neuromotor pathologies. On the other hand, although simple devices for FES are commercially available, their concrete implementation in the rehabilitation protocols of clinical practice is difficult to establish. The main obstacle lies in the gap between bioengineering skills and the needs of doctors, physiotherapists and neurophysio-pathology technicians. Overcoming this obstacle is possible by aiming at a high integration and synergy among the professional figures involved; the engineer must have the ability to establish a profitable relationship of intermediation and mutual collaboration with doctors, physiatrists and therapists, promoting and allowing the configuration of the technology in the clinical protocols of the rehabilitation program.