IMPROVING FUNCTIONAL ELECTRICAL STIMULATION DRIVEN CYCLING BY PROPER SYNCHRONIZATION OF THE MUSCLES

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Our aim is to define optimal stimulation patterns for controlling lower limb movements of spinal cord injured patients. Here we report on a study about cycling movements of healthy subjects under regular conditions and spinal cord injured patients whose cycling movement was generated by functional electrical stimulation.
The stimulation pattern required for coordinated activities of lower limb muscles of spinal cord injured patients was improved by using the observations what we gained from measuring and analyzing cycling movements of 42 young healthy subjects.
Kinematical parameters (joint angles) and muscle activities (EMG) were recorded simultaneously by an ultrasound based movement analyzing system.
We replaced the cycling program of the commercially available stimulator with a new one that we developed on the basis of the measured healthy cycling movements. We present that our new stimulation patterns provided a great increase in the performance of our spinal cord injured patients.

Keywords: *muscle stimulation, functional electrical stimulation cycling, EMG, spinal cord injury*

A FUNKCIONÁLIS IZOMINGERLÉS HAJTOTTA KERÉKPÁROZÓ MOZGÁS TÖKÉLETESÍTÉSE AZ IZMOK MEGFELELŐ SZINKRONIZÁLÁSA ÁLTAL

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Célunk a gerincvelősérültek alsó végtagi mozgását megvalósító optimális ingerlési mintázat meghatározása. A jelen közleményben az egészségesek normális körülmények közötti kerékpározásának, illetve gerincvelősérültek funkcionális elektromos ingerlés által létrehozott kerékpározó mozgásának vizsgálatáról számolunk be.
A gerincvelősérültek összehangolt lábizom-aktivitásához szükséges ingerlőmintázatot 42 egészséges fiatal kerékpározó mozgásának méréséből és elemzéséből nyert megfigyelések segítségével tökéletesítettük.
Ultrahangalapú mozgáselemző rendszerrel egyidejűleg rögzítettük a kinematikai jellemzőket (ízületi hajlásszögeket) és izomaktivitásokat (EMG-t).
A kereskedelmi forgalomban is kapható stimulátor kerékpározó programját új – a mért egészséges kerékpározó mozgás alapján fejlesztett – változatra cseréltük. Bemutatjuk, hogy az új ingerlőmintázatunk nagy teljesítménybeli javulást eredményezett gerincvelősérült betegeink esetében.

Kulcsszavak: *izomingerlés, FES-kerékpározás, EMG, gerincvelő-sérülés*

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Since the eighties functional electrical stimulation (FES) have become a viral topic of medical researches. Despite this fact there were no real breakthroughs till now which can be traced back to many theoretical and technical reasons. For example by surface electrodes one cannot stimulate all the muscles that the nervous system can. The main issue is that there is a high number of muscles and plenty of motoneurons innervating the muscles whose activities must be orchestrated for a proper motor function. Finding appropriate control algorithms is essential and the theoretically defined stimulation patterns[1–3] must be transferred to the motor nerves innervating the muscles or their motoneuron pools[4, 5]. Thus, modeling technique must be combined with new bioengineering results.

On the other hand far not every motor function of the nervous system has been properly discovered yet. The relation of excitatory, inhibitory neurons influences the effect of given stimulation patterns. Thus new results from neuroscience research are also advantageous for developing functional electrical stimulation methods. Presently most FES studies are based on applying surface electrodes for muscle stimulation. Different kind of movements as standing up, walking[6], grasping[7] and cycling[8–12] are controlled by the application of surface electrodes.

The proper stimulation patterns for this motor functions might be defined by tuning the timing of the stimulation pulses sent to the different muscles. Even this method may give nice results especially in cycling where the role of the balance and the bodyweight are not significant.

We started our work in the field of functional electrical stimulation cycling on the basis of the research and support of dr. Johann Szecsi from the Sensorimotoric Institute of the Ludwig-Maximilians University, München[10, 12]. The present results are gained in the measurements performed in National Institute for Medical Rehabilitation in Budapest.

In this paper we will present an observation that we conclude from two series of measurements. In the first series we investigated the cycling motion of 42 healthy subjects by measuring joint angles and muscle activities. In the second part of our work we have improved functional electrical stimulation cycling methods based on earlier observations.

Methods

In the first experiment we measured 42 healthy subjects, aged 16–33, while they were cycling on a recumbent stationary bike. The measurement protocol has been approved by the Ethical Committee of the National Institute for Medical Rehabilitation. Each subject signed an informed consent.

They were asked to drive the pedal with two different speeds – about 45 and 60 rounds per second (rpm), besides the level of load was also changed from light to heavy in three steps. Therefore we recorded six phases of cycling at each subject. We used a ZEBRIS CMS70P motion-analyzer system to record kinematical data and EMG signals. With this measurement system we could measure only one lower limb during a session therefore only the left lower limb was measured. Ultrasound emitting markers were mounted above the left hip, knee, ankle and one on the left pedal.

EMG was measured on left quadriceps, hamstrings, tibialis anterior and soleus using surface electrodes. The synchronization of the two kinds of data was made by the motion-analyzer system. In the case of the ultrasound markers and the EMG electrodes the sampling frequency was 50 and 1000 Hz respectively. Therefore the number of recorded samples of marker positions was twenty times less than the recorded samples of muscle activities (EMG) during a given time.

We recorded about 15 seconds in each of the six phase from which 12 sec was processed after exporting them into text files with the software of ZEBRIS.

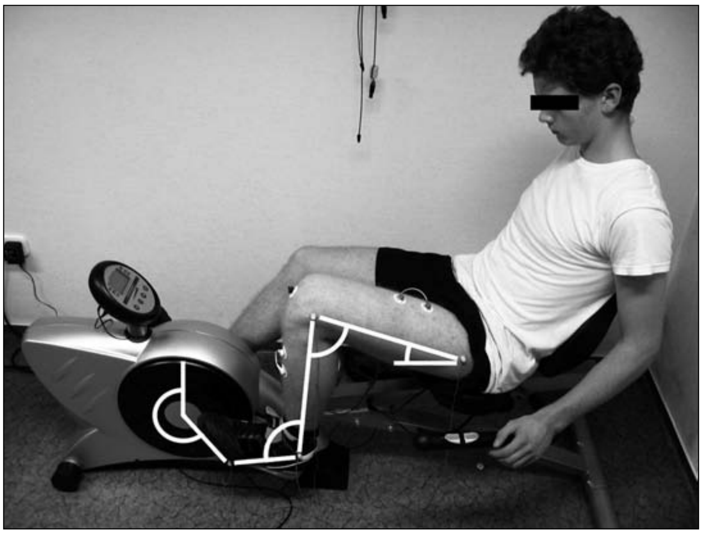

Figure 1. *The measurement setup as it was "seen" by the ultrasound-sensors of the motion-analyzer system. The vectors and angles that were defined from the marker positions are also presented*

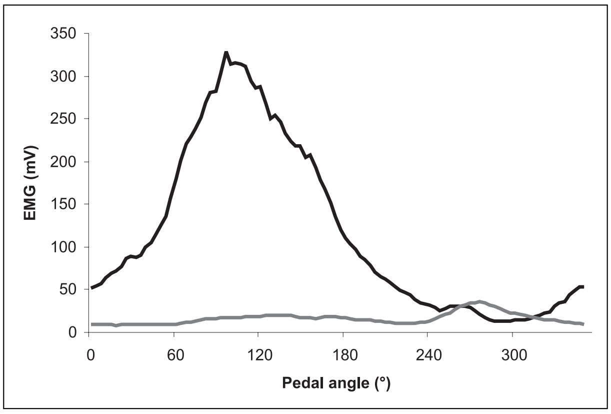

Figure 2. *The filtered quadriceps (black) and hamstring (grey) activities of a healthy subject are shown: the averaged EMG values of 10 consecutive cycles as a function of pedal angle*

Table 1. *The main properties of our patients, who trained on the functional electrical stimulation cycling system regularly*

Patient No.	Sex	Age	Lesion	Months post-injured	Training count
1	M	23	C5	25	37
2	F	24	Th7-8	8	50
3	M	17	C5	2	21

Figure 3. *Functional electrical stimulation cycling measurement setup. Stimulator, electrodes with a patient, who is cycling on an ergometer*

After this series of measurements we have got a database containing all the spatial coordinates of the markers and the EMG values, too.

Since the cycling motion remains mainly in the sagittal plane we simplified the processing by neglecting all of the deviations in other planes. We defined vectors between the recorded marker positions and computed joint and pedal angles (**Figure 1**). This procedure had to be automated due to the high number of measurements and for this we developed software in Visual Basic. Each recording was divided into as many separate files as many cycles the subject did. The subjects kept a speed of approximately 60 rpm in the fast cycling, thus we have got usually 10 cycles during the processed 12 sec time-interval (the first and last cycles were not used for analysis). EMG signals were filtered in MATLAB by Butterworth filter with cutting frequencies of 50 and 400 Hz (**Figure 2**). Finally all of the kinematical and EMG data were time normalized using cubic spline interpolation. After all processing we have got almost 20 000 files.

In the second experiment measurements were made with the participation of three spinal-cord injured people (**Table 1**).

All of our patients were completely informed about the measurement procedure which was actually an active training of their paralyzed thigh-muscles. After that they participated in numerous trainings by means of functional electrical stimulation driving the pedal of an ergometer usually twice a week (**Figure 3**). As for the stimulation we used a Motionstim8 device made by the Krauth and Timmermann Ltd.

This stimulator has got a built-in cycling program for our Motomed VIVA 2 ergometer that was capable to give information about the position of the legs by sending the actual pedal position to the stimulator via serial port. It must be emphasized that the stimulator uses only the pedal angle as input to activate the muscles in the predefined order. The ergometer also measured the average performance of the pedal motion generated by the patient during a whole training.

We have also acquired the programming software (MotionSoft) for the stimulator. In this program we could make custom stimulation patterns in the function of the pedal angle. The MotionSoft considers the zero degree as the uppermost position of the left pedal. The pedal angle is measured relative to this position; positive angles presented clockwise (**Figure 4**). In this respect the default cycling program stimulated the left quadriceps from –70 to 100 degrees with biphasic square-impulses, while the frequency and pulse-width was 20 Hz and

300 μs respectively. As for the amplitudes, only the maximum values could be given in the MotionSoft, since the actual amplitudes had to be adjusted manually on the device every time we used it. This was a bit uncomfortable but also useful since the necessary amplitudes varied among the measurements and the subjects.

In the beginning we applied this built-in stimulation program and in the course of some measurements the proper impulse-amplitudes were determined for each patient. We found that at most of them the two legs developed different performances for equal stimulation; therefore an asymmetric stimulation (e.g. 80 vs. 60 mA) was required for generating a symmetric occupation of the muscles. Due to this adjustment a slightly smoother motion could be generated compared to the symmetrical stimulation.

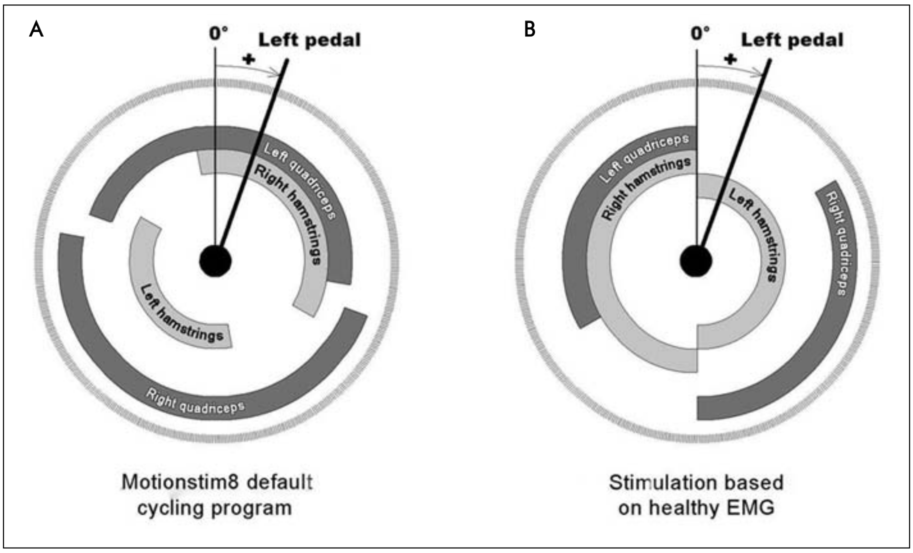

Figure 4. *The relation of muscle activations and pedal angle ranges. The default cycling program of the stimulator* (**A**) *has fundamentally been altered by replacing it with our new stimulation pattern* (**B**)

Later we realized that the default stimulation program was not proper in the timing of the muscle-activations, so we have started to improve the stimulation pattern. Using our empirical observations we improved the built-in stimulation pattern by changing the timing of the muscle activations. After some attempts we could generate somewhat smoother motion, but at last we introduced a quite different stimulation pattern that resulted in a much better performance and smoothness.

Results

Observing the cycling of the healthy people we found that the maximal quadriceps activity was measured when the pushing of the pedal began, but the activity started to increase much earlier. We also noticed that the quadriceps activity decreased in the same rate as it had increased, hence at the top position of the pedal the quadriceps activity on the same side approached zero.

These findings helped us to define a new stimulation pattern (**Figure 4.B**) in which the activations were applied earlier compared to the default cycling program (**Figure 4.A**). The quadriceps activation was brought backward with 50 degrees and become shorter with 50 degrees too, while the hamstrings got almost the opposing activation range as in the old program.

The muscle-activations in this program differed basically from the stimulation patterns that were

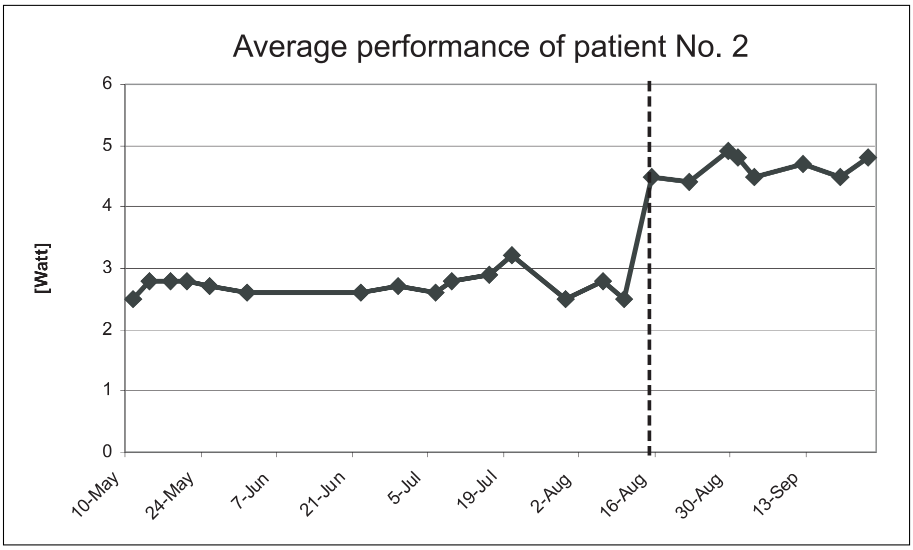

Figure 5. *This figure presents one patient's performance-graph. The positive effect of the new stimulation program can be clearly seen. The subject started to use the new program in the second week of August 2007 (dashed line) and a sudden improvement of her performance occurred*

Table 2. *The average performance of the three patients who used both the default and our new stimulation program. The "before" values are the averages of performances reached on the last three trainings with the old program, while the "after" values are the averages of first three trainings with the new program*

Patient No.	Average performance (W)		
	Before	After	Increase
1	4.87	6.6	+35.52%
2	2.6	4.6	+76.92%
3	2.34	3.96	+69.23%

used previously but the improved performance of the patients proved the advantage of our new sequence of stimulation. Due to this new program our patients' performance increased by 60% in average (**Figure 5** and **Table 2**); meanwhile the smoothness of their motions also became more natural.

Conclusion

The results showed that if we would like to produce well synchronized and therefore smooth cycling motion by means of functional electrical stimulation, the above mentioned observations should be taken into account. We reckon that preliminary EMG measurements of healthy people can give a solid basis for functional electrical stimulation procedures in most cases, since it can give more reliable information about the muscle functionalities than generalized theoretical models.

In the future we plan to measure other motor tasks to reveal that either the cycling motion was a special motion or the presented results may be applied to other non-periodical motions. For this reason we will make even more measurements investigating the relation between the EMG and actual muscle contraction reflected in joint angle changes.

The found stimulation pattern is sufficiently good for each of our patients but it was based on averaged values of healthy people, therefore we will investigate our database more deeply to classify the healthy subjects in order to find individual (and therefore more optimal) stimulation pattern for each patient.

Ultimately stimulating muscles by surface electrodes would not necessarily give the best results. It is desirable to get closer to the muscle fibers or spinal motoneuron pools without damaging them. In the future our stimulation patterns may be used by currently developed new stimulation techniques[4, 5, 13].

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