FES driven lower limb cycling by four and eight channel stimulations – a comparison in a case study

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Abstract: *FES driven lower limb cycling has been studied and the results here presented are from the case of a complete spinal cord injured participant. Two stimulation patterns were applied. In the first one, two muscle groups were stimulated, the hamstring and the quadriceps. In the second stimulation pattern, four muscle groups were stimulated on each leg: three parts of the quadriceps separately (vastus lateralis, vastus medialis, rectus femoris) and the hamstrings. We compare the parameters of the two stimulation patterns and present differences in power output and mechanical energy. The cadence of cycling was on average 47-48 rpm (revolutions per minute) in both stimulating conditions. We note that when stimulating four muscles per limbs, lower current amplitude (per muscles) was sufficient to reach a higher power output compared to the stimulations with two muscles per limbs. The participant preferred to cycle longer when only two muscles (per legs) were stimulated. The power output was lower in this case but the total energy (during the training) did not differ significantly in the two examined stimulation conditions.*

Keywords: *stimulation pattern, power output, current amplitude*

Introduction

In Hungary, FES driven cycling training is available at 2 locations - at the National Institute for Medical Rehabilitation (NIMR) and at the University of Physical Education in cooperation with the University of Pecs, the Pázmány Péter Catholic University (PPCU) and the Wigner Research Centre for Physics. During the application of FES assisted training the stimulation device and the stimulation patterns have been continuously developed [1,2,3] and applied to generate cycling movements for Spinal Cord Injured (SCI) individuals. Here we compare the efficiency of two stimulation patterns through the results obtained during the training of one SCI person who participates twice a week in FES driven cycling training in NIMR. The Ethical Committee of the NIMR approved the procedures.

The power output produced during FES cycling by SCI people depends on many factors. Such factors are cycling cadence, crank resistance and the current amplitude, pulse width and frequency of the stimulating current. Here we examine the dependence of power output on the amplitude of the stimulating current. Current amplitude varies among FES cycling protocols. We report on results obtained with stimulation applying low current amplitudes, 20-45mA per muscles, and led to a power output of 7-11W depending on the number of stimulated muscle groups. The aim is to check if the power output is higher when more separate muscle groups are stimulated. In particular we stimulated the quadriceps muscle group as a whole with one pair of electrodes in one stimulation pattern (SP) and in the other SP 3 parts of the quadriceps (vastus medialis, vastus lateralis, rectus femoris) were stimulated separately by three separate pairs of electrodes.

Material and Methods

For the trainings we used a MOTOMED Viva 2 ergometer and an 8 channel stimulator developed at the PPCU in Budapest, Hungary. The hamstring and quadriceps muscle groups of both legs were stimulated through bipolar surface electrodes (PG473W TENS ELEC 45x80mm). The adjustable stimulation parameters were current amplitude, pulse width and pulse frequency. Pulse width (rectangular, monophasic) was set to 300 µs, stimulation frequency was 30 Hz in each training. Current amplitude varied among trainings. The participant sat in a wheelchair in his usual sitting position. At the front of the wheelchair a MotoMed Viva 2 cycle ergometer was placed. The distance between the wheelchair and the ergometer was established keeping in consideration that the wheelchair should not prevent the motion of the pedal and allows appropriate knee extension. The participant's feet were placed on the pedals in pedal boots fixed to the pedal and their shanks were strapped to the boots.
The stimulator was connected to a rotation sensor that recorded the ergometer's crank position (100Hz sampling frequency). The stimulator device allowed the selection of a reference crank position and the direction of cycling and then received the crank angle value during cycling.
The training started with a warm up period while the ergometer's motor rotated the cranks and carried the legs. Then we started stimulating the muscles. The current amplitude for each muscle was increased until the muscles started to generate the cycling and the cranks were rotated at 30rpm, at this time the motor stopped and didn't work during the active cycling period, this is the time interval in which the participant cycled by his own stimulated muscles without the assistance of the motor. The stimulating current was further increased until the cadence reached an approximately constant value

between 45-50 rpm. When this cadence was reached then the current amplitude remained constant during the active cycling period for each muscle. In pattern H2 the same current was applied to all muscles. In pattern H4 the 3 parts of the quadriceps were stimulated with the same current amplitude but the hamstrings' stimulation current was further increased in the 5th-10th training (Table 2). The active cycling period was finished when the cadence fell below 40 rpm or when the participant wanted to stop cycling. He was free to stop cycling at any time when he wanted to finish even when the cadence didn't drop below 40 rpm. The active cycling periods varied among trainings and lasted for about 20-40 minutes (Table 1.) The finishing part of the training is a cool down when the ergometer's motor generated the cycling movement without electrical muscle stimulation and physiological parameters of the participant reverted to the default levels.

The product of angular velocity and crank resistance (torque) gave the cycling power output and it was averaged across time during the active period in each training. The energy output was calculated as the product of average power output and active movement time.

Heart rate and blood pressures were measured with a blood pressure monitor 5 times during the training: before the warm up, after the cool down period and 3 times between these measurements (with intervals of 8-9 minutes) within the active cycling period. Mean arterial pressure (MAP) was calculated from measured systolic and diastolic blood pressure values (SBP and DBP respectively) by the following formula:

$$MAP = (SBP - DBP)/3 + DBP$$

We applied 2 stimulation patterns. We name these patterns as H2 and H4 referring to the number of muscle groups stimulated on one leg. With the H2 pattern we applied 2 pairs of surface electrodes on each leg, one for the quadriceps and one for the hamstring muscle groups. With the H4 pattern three parts of the quadriceps muscles - vastus medialis, vastus lateralis and rectus femoris - were stimulated separately, and the hamstrings. Training set up is presented in Figure 1. and figure 2 for cycling with H2 and H4 stimulation patterns.

Stimulation patterns were based on data obtained during cycling of able-bodied people [1,4]. They performed cycling movements on the stationary ergometer and their muscle activities (EMG) were recorded by surface electrodes, while the crank position and crank angle respect to the top dead position was computed from marker coordinates recorded by a ZEBRIS movement analyzer system. Ranges of crank angles in which a muscle was active, were established for each muscle. First the quadriceps and hamstrings activity was recorded applying pairs of electrodes for each of these muscle groups. The electrodes were placed on the muscular belly with an inter-electrode distance of approximately 50 mm. In a separate measurement the activity of three parts of the quadriceps (Vastus lateralis, vastus medialis and rectus femoris) were measured and the hamstrings. The angular ranges of crank positions, in which a particular muscle was active, were established. A muscle was considered active when its EMG amplitude exceeded the 35% of its mean EMG amplitude. These ranges of muscle activities were used to define H2 and H4 stimulation patterns.

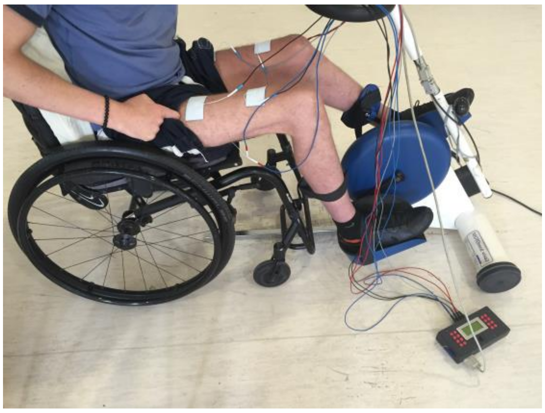

Figure 1: Training setup with the H2 stimulation pattern.

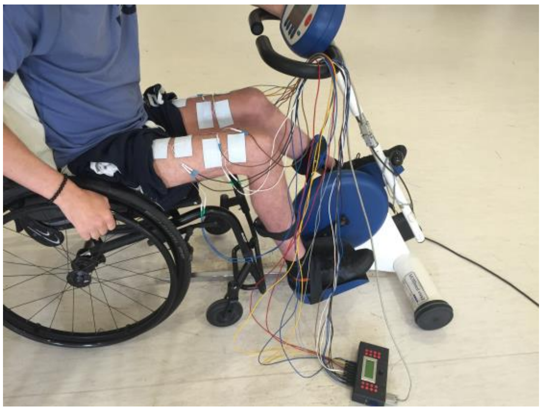

Figure2: Training setup with the H4 stimulation pattern. Three parts of the quadriceps are stimulated.

A 34 years old participant with complete spinal cord injury used both SPs. His level of injury was at Th8 and he started to participate in FES cycling training four years after the injury. Using H2 the participant had 27 training sessions, and then he started to use the H4 pattern. We compare the last 10 sessions performed with H2 and the first 10 performed with H4. Thus the participant had already practiced (17 trainings) and was experienced in FES cycling when we started to include data into this comparison. We compared statistically the power output, the mechanical energy and the cycling time during the FES assisted cycling with H2 and H4 patterns. The differences between values obtained applying the two SPs were assessed with Student's T-test (p=0.05).

Results

Comparison of the total energy during the cycling with two different stimulation patterns didn't show significant difference (p=0.559). However, the power output is significantly higher and the active cycling time is significantly shorter applying H4 comparing to the application of H2 (p=0.001).

Table 1: Comparison of the averaged parameters and standard deviations of the two stimulation conditions

	H2	H4
Cycling time (min)	27.1±3.6	22.3±2.6
Cadence (rpm)	47.4±1.17	48.5±1.3
Current amplitude (mA)	35±7.45	25.9±3.7
Energy (kJ)	12.82±1.82	13.41±2.08
Power output (W)	7.91±0.75	10.08±1.4

The power and energy output, obtained in each training is presented in Figure 3. When H2 stimulation pattern was changed for H4 a significant increase of power output occurred. This change didn't have a significant effect on mechanical energy.

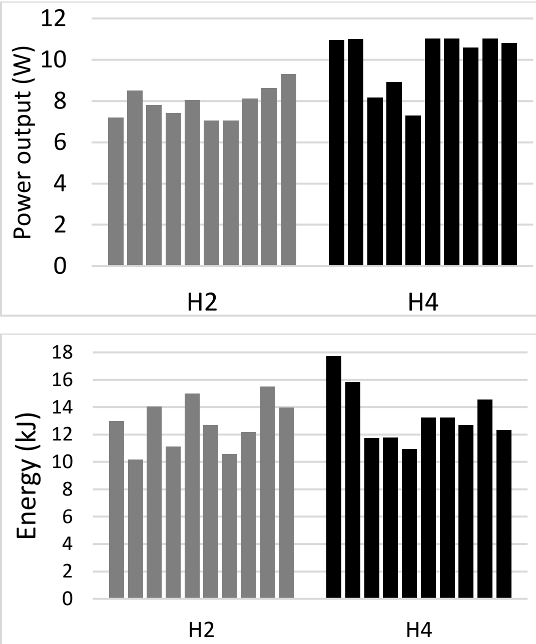

Figure 3. Power output (upper diagram) and mechanical energy (lower diagram) in 10 trainings with H2 (grey bars) and consecutive 10 trainings with H4 (black bars).

In H2 quadriceps and hamstrings muscle groups were stimulated. In H4 three parts of the quadriceps - vastus medialis, vastus lateralis and rectus femoris - were stimulated separately and the hamstrings.

The mean arterial pressure increased during the active cycling period and dropped after the training (Figure 4.). The heart rate remained approximately constant during the training and dropped after the training (Figure 5)

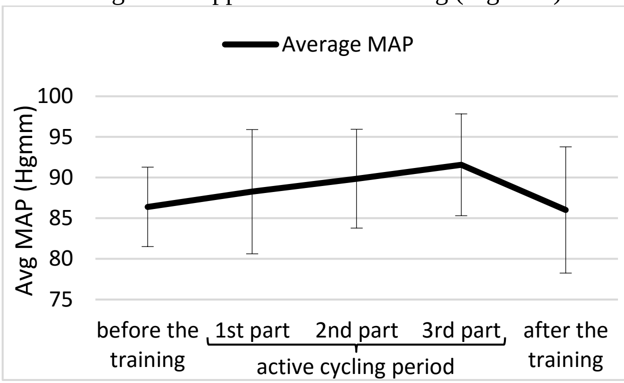

Figure 4: Averaged (across trainings) Mean Arterial Pressures and their standard deviations in five phases of the trainings performed by H2 stimulation pattern: before the warm up period, in the 1st, 2nd and 3rd parts of the active cycling period and after the cool down period.

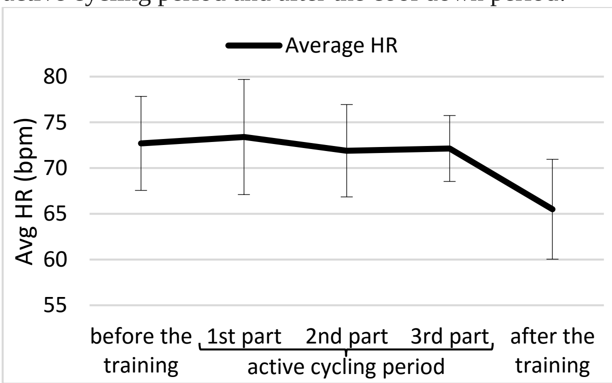

Figure 5: Averaged (across 10 trainings performed by H2 stimulation pattern) heart rates and their standard deviations in five phases of the trainings.

Table 3 shows the relation between cycling time, current amplitude and power output in each individual training.

Table 3. Cycling time, current amplitude (per muscles) and power output in trainings by H2 and H4 stimulation patterns. In the 5th-10th trainings with H4, the hamstrings' stimulation current was higher than that of the 3 parts of the quadriceps.

H2 (training's serial number)	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	Mean
Cycling time (min)	30	20	30	25	31	30	25	25	30	25	27.1
Current amplitude (mA)	35	45	45	35	45	30	30	30	30	25	35
Power output (W)	7.20	8.48	7.79	7.42	8.05	7.05	7.05	8.11	8.61	9.30	7.91

H4	1.	2.	3.	4.	5.	6.	7.	8.	9.	10	Mean
Cycling time (min)	27	24	24	22	25	20	20	20	22	19	22.3
Current amplitude (mA) (Quad/Ham)	25	20	25	25	30/40	25/35	20/25	25/30	25/30	25/35	24.5/29
Power output (W)	10.94	10.98	8.15	8.92	7.29	11.02	11.02	10.58	11.02	10.80	10.08

Discussion

By stimulating three parts of the quadriceps separately instead of stimulating the quadriceps by one signal, our SCI participant was able to reach a higher power output. This was gained by lower stimulation current amplitude per muscle groups. When instead of 2 muscle groups 4 separate muscle groups were stimulated, the total stimulation current (the sum of the currents applied in all of the channels) was of course higher, although, lower current amplitude per channels may be favourable for the muscles. While the participant reached a higher power output, he preferred to cycle for a shorter time with H4 stimulation pattern, thus the total mechanical energy per session didn't differ comparing the two SPs. The order of the applied SPs in consecutive sessions was not randomized, but because the participant was already a trained person (having 17 sessions before we involved his results in this study) the training may had similar effect on the results gained applying the 2 different SPs. In spite of many studies and application of various SPs [5], effective fatigue control is not well known yet. The cardiovascular effect should also be further investigated. We highlight that we applied relatively low current amplitudes (20-40mA) per muscles. The average current amplitude applied in FES driven cycling of SCI individuals used to be at least around 50-70 mA per muscles and it varies in a wide range [6]. In some protocols current amplitude was increased until 120-140 mA to achieve power output around 10W [7] in extreme cases 20W [8]. Szecsi and coworkers stimulated hamstrings and quadriceps muscles with frequency as we did (30 Hz) but with a higher current amplitude (70-90 mA) and wider pulse width (500 μs) when they reached a power output around 30W [9]. In these works the quadriceps stimulation was not distributed to stimulation of 3 parts of the quadriceps as it was in our case.

Conclusions

We presented the results of a new stimulation pattern for FES cycling by data obtained during the training sessions of one participant. This case study shows that applying more stimulating channels with lower current amplitudes per channel can result in a higher power output. Particularly, stimulating 3 parts of the quadriceps separately, allowed the SCI participant to increase power output in average by 27%. Further studies can investigate this recommendation and may lead to new stimulation protocols applied in rehabilitation of SCI individuals.

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