OPTIMIZATION OF A FES CYCLING NEUROPROSTHESIS ON STROKE PATIENTS BY MEANS OF THE LEFT AND RIGHT CRANK MEASUREMENTS

Ferrante Simona[1], Comolli Lorenzo[2], Pedrocchi Alessandra[1], Bocciolone Marco[2], Ferrigno Giancarlo[1] and Molteni Franco[3]

[1]*Bioengineering Department, NITLab - TBMLab, Politecnico di Milano, Via Garofalo 39, Milano, Italy*

[2]*Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 34, Milano, Italy*

[3]*Valduce Hospital, Villa Beretta Rehabilitation Center, Via N.Sauro 17, Costamasnaga (LC), Italy*

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Abstract: The use of functional electrical stimulation (FES) is a well established method in the rehabilitation of stroke patients. In particular, a bilateral movement such as cycling induced by FES would be crucial for these patients who had an unilateral motor impairment and had to recover an equivalent use of the limbs. To improve the rehabilitative effects of the FES cycling, a metrologically qualified cycle-ergometer was used, so that the left and right crank torque values are measured in real-time. Three protocols were evaluated. First, healthy subjects performed voluntary pedaling. Second, healthy subjects were stimulated one muscle individually to study the contribution of each single muscle to the cycling. Third, stroke patients executed a complete FES cycling trials. Results demonstrated that the proposed sensors could be successfully used to monitor online the unbalance of the cycling. Single muscle tests showed that only the quadriceps and the hamstrings provided a significant contribution to the crank torque. Patient trials confirmed the difficulty for stroke subjects to carry out symmetrical cycling. The use of the proposed sensors, hence, could offer a good signal for biofeedback neuroprostheses and for closed loop controllers.

1 INTRODUCTION

A neuroprosthesis is defined as a functional electrical stimulation (FES) device used as a substitute for lost neurological function. The use of a neuroprosthesis is a well established method in the rehabilitation of individuals with spinal cord injuries and stroke (Kralj, Acimović & Stanic, 1993, Petrofsky, 2004). Among all the existent neuroprostheses, the cycling movement induced by the stimulation of the major muscles of the lower limbs is now becoming a spread application (Hunt et al., 2004, Trumbower, & Faghri 2005, Szecsi et al., 2007). In the following this artificial movement will be named FES cycling.

One of the most difficult and appealing improvements in FES research is the integration of hardware and software and the development of control systems for the neuroprosthesis in order to enhance the clinical benefits for the patients. Some of the rehabilitation objectives for spinal cord injured patients are an increase in muscular tone, an improvement in the peripheral and cardiac circulation avoiding the occurrence of decubitus ulcera and the prevention of joint rigidity (Hunt et al. 2004). In stroke patients, the neuroprosthesis also becomes therapeutic and in fact, it permits one to learn new motor strategies for Central Nervous System (CNS), exploiting residual capacity (Lee & van Donkelaar, 1995, Sheffler & Chae, 2007). Indeed, FES cycling providing the complete afference of the task to the stroke patients could re-educate the synaptic controls needed to produce a well organized movement. Because of the laterality of the pathology, one of the rehabilitation aims is the recovery of walking and particularly the recovery of the symmetry of the movement. Therefore, the use of FES cycling was investigated as a method to re-learn the bilateral and symmetrical use of the legs.

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The feasibility of applying FES cycling to stroke patients was analyzed in a previous study and encouraging results were reached (Ferrante et al., 2006). The stimulation strategy delivered to the quadriceps, hamstrings, gluteus maximus and tibialis anterior of the two legs was exactly the same for both the legs, but shifted of 180° in respect to the crank angle. The patient was asked not to voluntary contribute to the motor task. In this study the total motor torque produced at the crank was measured. Therefore, it was possible to quantify the performance obtained in terms of power output but not in terms of unbalance at the pedals which is a crucial aspect in the rehabilitation of individuals with stroke.

The aim of this study is to develop and test sensors able to measure the torque at the right and left crank in order to provide a step forward in the application of FES cycling on individuals with stroke. In fact, monitoring these signals during the movement would be a crucial starting point in the design of an automatic time variant controller for symmetry.

2 METHODS

2.1 Experimental Setup

A current–controlled 8-channel stimulator and a motorized cycle-ergometer were used for the experiments. It was possible to control the cycle-ergometer by changing the resistant torque and the angular velocity or by directly setting the motor voltage.
As shown in Figure 1, the cycle-ergometer was equipped with instruments able to measure the bending moments and the radial forces at the right and left cranks, so that the torque can be computed (Gföhler et al., 2001). Four Wheatstone full bridge made up of electrical resistance strain gauges were used to measure the strain on the right and left crank during the cycling task. The strain gauge bridges are conditioned through a four-channel wireless device, which allows to transmit the signal from the rotating shaft to the acquisition system. The angular crank position was measured through optical encoders mounted on the main wheel of the ergometer. More details on the instrumentation, the acquisition chain and the metrological characterization of the cycle-ergometer can be found in Comolli et al., 2005 and Bocciolone, Comolli and Molteni, 2008. The cycle-ergometer was equipped with two ankle foot orthoses fixed to the pedals and used to stabilize the legs and to constrain the movement to the sagittal plane.

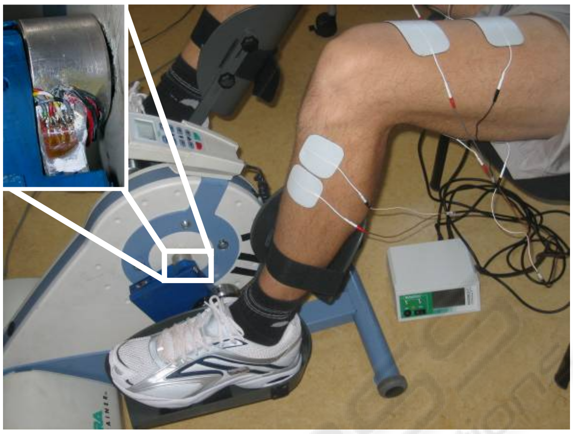

Figure 1: The instrumented cycle-ergometer, the wireless device is in the box on the crank.

All the transducers were connected to a PC for data acquisition and stimulation device control. The real-time acquisition and control system is shown in Figure 2. The stimulation controller set the stimulator parameters according to the crank angle measured in real time. Therefore, each muscle used is activated in a particular angular phase of the cycling movement as explained in the following.

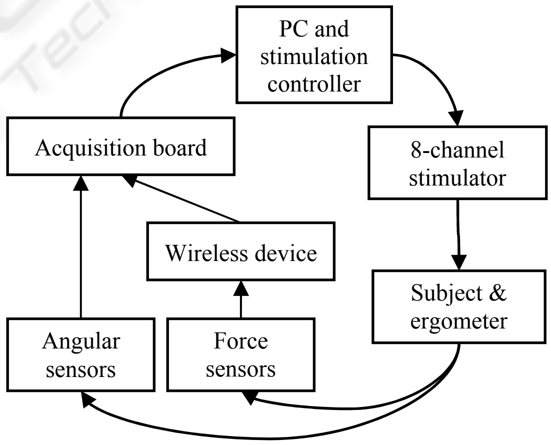

Figure 2: The experimental setup.

2.2 Experimental Protocol

Written informed consent was obtained from all the subjects who took part in the experiments. Three different experimental sessions were performed and are explained in the following paragraphs.

2.2.1 Tests During Voluntary Pedaling

First, the developed sensors were tested during voluntary pedaling of healthy subjects. The protocol required the subject to perform one trial lasting 8 min. The first 2 min the motor of the cycle-ergometer was used and the subject was cycling only passively at 30 rpm. Then, the subject carried out a normal cycling for 2 min, trying to keep the former velocity. After that, 2 min in which the subject was asked to pedal using only the right leg and 2 min using only the left one were performed.

2.2.2 Stimulation of the Muscles Individually

Once tested the sensors, a specific FES cycling experimental protocol was carried out on a healthy subject. Once the subject was sat on the ergometer and the electrodes were placed, an initial trial to choose the stimulation current of each muscle was carried out. The chosen stimulation currents were set at a value that produced a tetanic contraction using a pulse width of 400 µs. The crank angle was set at 0° in correspondence to the point of maximum flexion of the left hip. During the trials 8 muscles, 4 per each lower limbs (quadriceps, hamstrings, gluteus maximus and tibialis anterior) were stimulated. The stimulation strategy, i.e. the choice of the cycling phases in which each muscle was stimulated in respect to the crank angle, were selected following Ferrante et al., 2005. An ON-OFF pulse width profile was used: for all the muscles the pulse width value was fixed at 400 µs during the ON phase and at 0 µs during the OFF phase. The stimulation frequency was set at 20 Hz and all the torque signals were gathered at 500 Hz.

The subject performed a trial with a resistant torque value of 3 Nm. The angular velocity was maintained by the motor at a minimum value of 30 rpm during all the trials.

The trial lasted 10 min: during the initial and final 60 s, the subject was pedaling passively. In the intermediate part of the test, each muscle group was individually stimulated for 60 s within its stimulation range.

2.2.3 First Tests on Stroke Patients

Finally, a feasibility test was carried out on 2 post-acute stroke patients at the beginning of their rehabilitation. Both the patients performed a complete FES cycling trial according to Ferrante et al., 2006.

2.3 Data Analysis

The measured bending moments and radial forces were used to compute the torque at the right and left crank. The torque was expressed as a function of the crank angle. The median and the 5^{th}-95^{th} percentiles of the right and left active torque were computed in each test condition of the trials. Then the left and right active torque at the crank were computed as the difference between the torque produced during the active phases and the one generated during passive pedaling. The total torque was obtained adding together the right and left torque.

3 RESULTS

3.1 Tests During Voluntary Pedaling

Figure 3 shows the results obtained by an healthy subject during the voluntary pedaling protocol in terms of the right and left active torque measured at the crank.

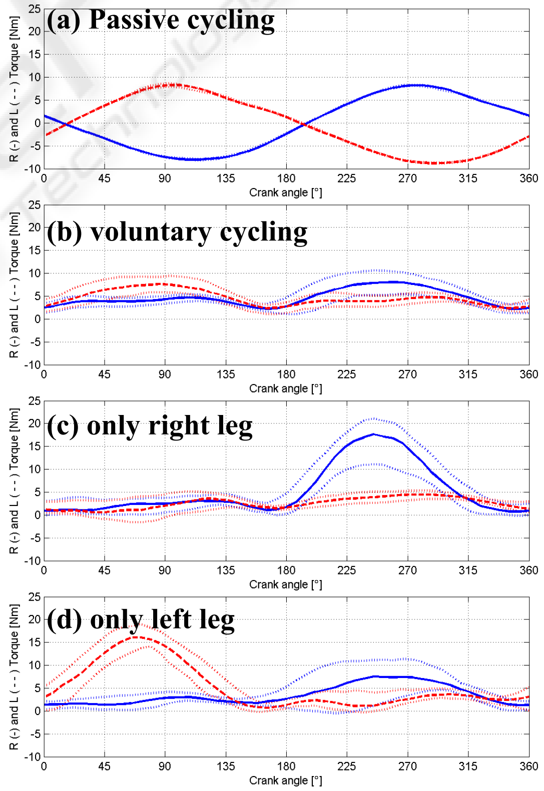

Figure 3: Measurement of the right (solid line) and left (dashed line) passive (a) and active (b,c,d) torque; the median on 15 revolutions are shown. In dotted lines the 5^{th} and 95^{th} percentiles are reported.

In panel (a) the repeatability of the signals during passive cycling is noticeable. In panel (b), the subject was performing a normal pedaling. The effect of the two legs on the right and left active torque was quite similar in amplitude but it showed a shift of 180° in phase. The asymmetrical cycling presented in panels (c) and (d) highlighted a dual behaviour. When only the left leg was cycling actively (c), only the left active torque had a positive peak and the right torque was quite zero during the whole revolution. The peaks of the active torque in panels (b), (c) and (d) were produced when the right quadriceps was pushing. This behaviour agrees with the fact that during a voluntary pedaling the quadriceps muscle gives the greatest contribution to the movement.

The results obtained in the same trials in terms of total torque are reported in Figure 4. The panels are referred to the same working conditions of Figure 3. The total torque seems to be a good signal to distinguish an asymmetry in the cycling movement.

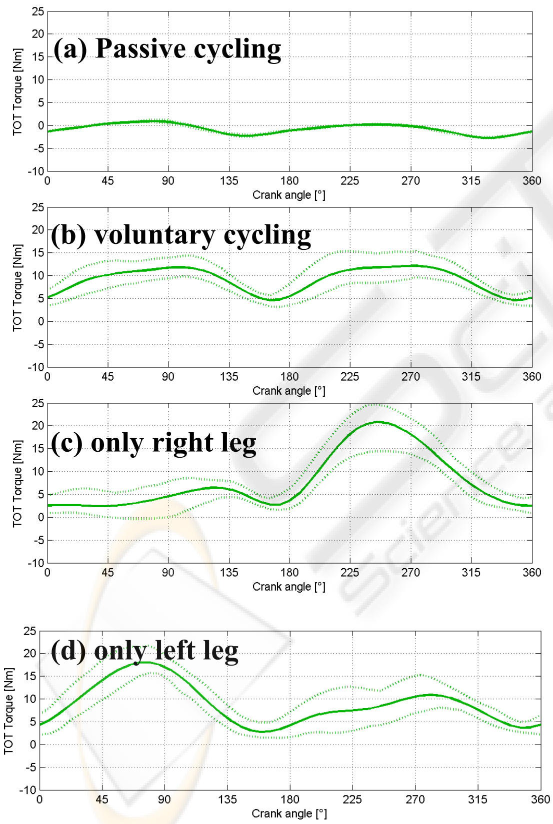

Figure 4: Measurement of the total passive (a) and active (b,c,d) torque; the median on 15 revolutions are shown in solid line. The 5th and 95th percentiles are reported in dotted lines.

3.2 Stimulation of the Muscles Individually

Figure 5 shows the results obtained by the healthy subjects during the FES protocol when only the right quadriceps (a), hamstrings (b), gluteus maximus (c) and tibialis anterior (d) were selectively stimulated. In all the panels of Figure 5 the grey area represent the angular range in which the muscle was stimulated.

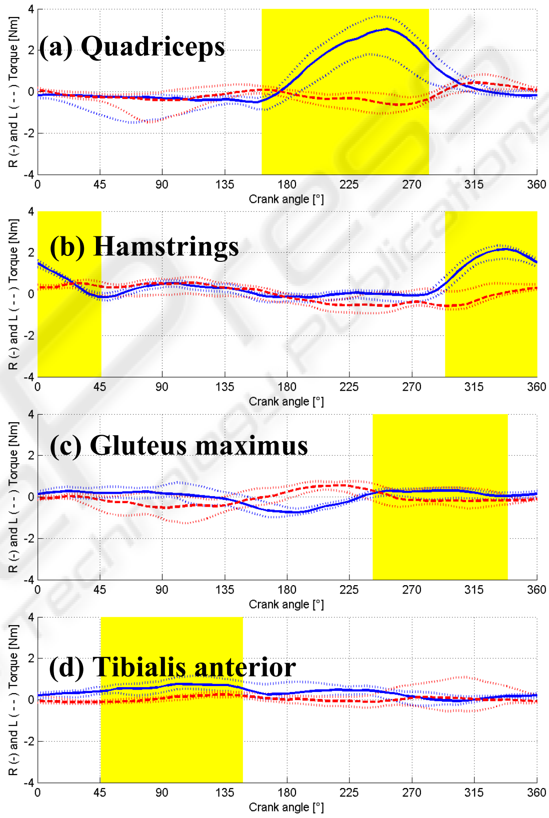

Figure 5: Measurement of the right (solid line) and left (dashed line) active torque; the median on 15 revolutions are shown. The 5th and 95th percentiles are reported in dotted lines.

In panels (a) and (b), a positive peak of the right active torque can be noticed exactly in correspondence to the muscular stimulation range.

This confirms that the muscles were stimulated in their functional range, i.e., when they were assisting the cycling motion.

The active left torque was nearly zero during the whole revolution because the left leg was pedaling passively. The gluteus and the tibialis anterior instead did not produce an effective right active torque at the crank, thus their contributions to the drive torque were negligible. Such a result was expected because the gluteus, as a proximal muscle acting only on the hip, can transfer a low contribution to the crank, while the effect of the tibialis anterior is limited by the use of the ankle foot orthosis.

These results are confirmed by the total torque shown in Figure 6.

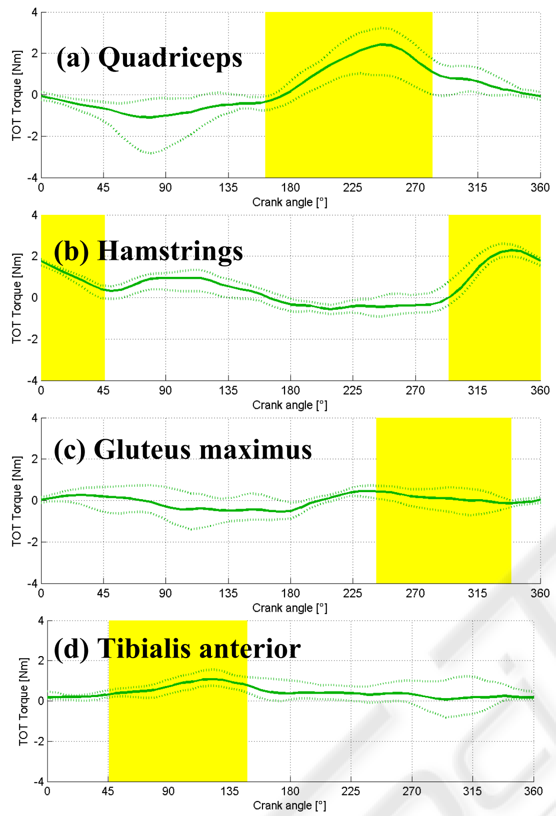

Figure 6: Measurement of the total torque; the median on 15 revolutions is shown in solid line. The 5^{th} and 95^{th} percentiles are reported in dotted lines.

3.3 First Tests on Stroke Patients

Figure 7 reports the results obtained by a post-acute stroke patient during a FES cycling trial performed, stimulating 8 muscles following the stimulation strategy described in Ferrante et al., 2006. As it is shown in panel (a) the positive peak of the left torque is the 40% greater then the one of the right torque, which was correspondent to the pushing of the impaired leg.

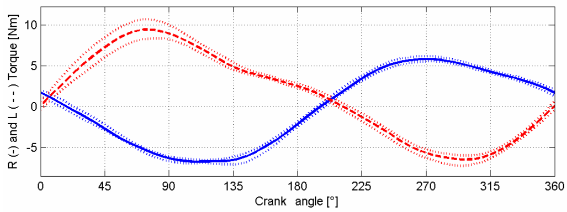

Figure 7: The right (solid line) and left torque (dashed line) are reported. Results are shown in terms of the median torque of 50 revolutions obtained by a stroke patient during an FES cycling trial. This result suggests the idea to use these signals as control signals for a real-time automatic controller to minimize the asymmetry of the movement in stroke patients.

4 CONCLUSIONS

The possibility of using a rhythmic and bilateral movement such as cycling induced by a stimulation pattern delivered in both legs seems to be a good rehabilitative method for post acute stroke patients. These patients, having an unilateral motor impairment, need to be re-educated to the correct use of both the lower limbs together in order to recover the motor control symmetry in more complex and demanding task, such as walking.

The aim of this study was to develop and test sensors designed for a FES cycling neuroprosthesis specific for stroke patients. Custom designed sensors able to measure independently the torque produced by the right and the left leg during cycling were tested both on healthy subjects and stroke patients.

To understand the effect of the stimulation of each muscle on the signals, a proper protocol was defined. Each muscle was stimulated individually in the phase of the revolution in which his action was functional to the movement (Ferrante et al., 2005, Ferrante et al., 2006). The results obtained suggested that the developed sensors allowed to distinguish the effect of the stimulation of the quadriceps and hamstrings during the movement. Instead, the active torque produced by the gluteus maximus and by the tibialis anterior were quite negligible. Other experimental trials using this second protocol presented are now ongoing in our laboratory on more subjects.

This study was crucial to verify that the signal to noise ratio of the torque measurement is sufficient to discern the torque induced by the stimulation of the single muscle, which are an order of magnitude lower than the ones induced by the voluntary active pedaling.

The possibility to monitor the torque at the right and left crank represents an important step forward in the application of FES cycling on stroke patients. It would be possible to use the acquired torques to monitor the unbalance of the movement on line. The unbalance could be used as a biofeedback signal to the patient. Thus, looking at a display where the asymmetry is shown, he could correct the exercise on line giving a voluntary contribution. Alternatively, starting from this unbalance signal it would be possible to develop a closed loop controller aiming at the maximization of the symmetry during the movement. The achieved results also suggest that a simplified first version of the controller could act only on the stimulation of the hamstrings and quadriceps and not on the gluteus maximus and tibialis anterior, which shown a quite negligible effect on the right and left torque.

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