Design of a symmetry controller for FES cycling - Preliminary results on post-acute stroke patients
Emilia Ambrosini, Politecnico di Milano, Bioengineering Department, Italy
Simona Ferrante, Politecnico di Milano, Bioengineering Department, Italy
Thomas Schauer, Technische Universität Berlin, Control Systems Group, Germany
Alessandra Pedrocchi, Politecnico di Milano, Bioengineering Department, Italy
Giancarlo Ferrigno, Politecnico di Milano, Bioengineering Department, Italy
Franco Molteni, Valduce Hospital, Villa Beretta Rehabilitation Center, Italy

Abstract
The aim of the present study was to develop an automatic controller for FES cycling able to assure a symmetrical pedalling. The controller is therefore exploitable in the rehabilitation of hemiplegic patients. Starting from a measurement in real time of the bending moments produced at right and left crank, the controller tries to reduce the unbalance of the movement and then to maintain a symmetrical pedalling. To reach this goal the controller updates the stimulation pulse width of the two legs independently. Specific FES cycling experiments were carried out on two healthy subjects and two hemiplegic patients to test the controller. These trials showed that the controller was able to reach and then to maintain a symmetrical pedalling. In particular, the controller took less than 1 minute to achieve a stable condition. The symmetry controller developed could accelerate the recovery of motor symmetry, crucial aspect in the rehabilitation of stroke patients.

1 Introduction
In industrialised countries, stroke represents the first cause of long term disability. Subsequently, the demand of new rehabilitation treatments able to accelerate and improve motor recovery is increasing. Clinical studies on central motor neuroplasticity demonstrated that goal-oriented, active, repetitive tasks in the training of the paretic limb are crucial in post-acute stroke patients motor relearning [1]. The applicability of Functional Electrical Stimulation (FES) for therapeutic purpose in hemiplegic patients has been investigating [1]. FES-induced exercises offer the patients the complete afference of the task. This could enhance the synaptic controls, facilitate the reorganization of the motor schemes and accelerate the process of functional recovery. Among all FES induced tasks, the FES cycling, seems to be an interesting treatment in the lower limb rehabilitation of stroke patients. A previous work showed that a rehabilitation treatment including FES cycling was more effective in increasing muscular strength and motor recovery of the legs than standard rehabilitation alone [2].

Because of the laterality of the pathology, the recovery of the motor symmetry is crucial in the rehabilitation of stroke patients. Therefore, the main goal of the present study was the design of an automatic symmetry controller for FES cycling. The controller, starting from a real time measure of the unbalance between the bending moments produced at the two cranks, modifies the stimulation parameters of the legs independently in order to achieve a symmetrical pedalling.

2 Methods
2.1 The design of the symmetry controller
Fig. 1 shows the structure of the symmetry controller. It includes two parallel branches to control two systems at the same time: the left and right leg. The inputs (control signals) of the systems are the values of pulse width ($PW$) used to stimulate the selected muscles of the left ($PW_L$) and right ($PW_R$) leg; while the outputs (controlled signals) are the bending moments, $M_{b,R}$ and $M_{b,L}$, produced at the right and left cranks.

Fig. 1 Structure of the symmetry controller. The dotted line encloses the whole controller.

The definition of the reference signals of the two controllers is not unique. There are two possibilities to nullify the difference between $M_{b,R}$ and $M_{b,L}$:
1. increasing the $PW$ of the weaker leg;
2. decreasing the $PW$ of the stronger leg.

In the design of the controller, it has been chosen to stimulate as much as possible the weaker leg till the maximum value ($PW_{\text{max}}$), which is fixed at 500 $\mu$s. Then, if an unbalance is still present, the $PW$ of the stronger leg is decreased. The design of the controller is summarised in the flow diagram reported in Fig. 2. In each revolution, the mean value of $M_{b,L}$ and $M_{b,R}$ ($M_{h,L}$ or $M_{h,R}$) are compared in order to define the reference signal and, consequently, to obtain the two error signals, $e_i$ and $e_R$.

\[
PW(k) = PW(k-1) + k_c e_i(k), \quad \text{with } i = R, L
\]  

(1)

The values of $PW$ are updated each revolution. $k_c$ is set at the same value for both the controllers (30 $\mu$s/N). This value assures the stability of the closed-loop system according to a stability analysis performed in simulation [3]. The controller is implemented with an integral anti-windup design so that the $PW_i$ is constrained between 0 and $PW_{\text{max}}$.

The symmetry controller was implemented in Matlab/Simulink.

### 2.2 Experimental setup

The experimental setup developed includes a current-controlled 8-channel stimulator (Rehastim$^\text{TM}$, Hasomed GmbH, Germany) and a motorized cycle-ergometer (THERA-live$^\text{TM}$ Medica Medizintechnik GmbH, Germany) equipped by resistance strain gauge sensors able to measure the bending moments at the left and right crank. These signals are transmitted from the ergometer to a desktop PC via wireless, providing a measure of the unbalance between the two legs during cycling. More details on the unbalance between the two legs during cycling. More details on the setup, especially on the sensors used, can be found in [4].

### 2.3 Stimulation protocol

An FES cycling protocol has been defined in order to test the controller both on healthy subjects and stroke patients, who had signed a written informed consent. Subjects details are reported in Table 1.

### 2.4 Data analysis

Results of the testing trials of the controller have been analysed in terms of initial and stationary conditions. The initial conditions consist in the value of $PW_i$ and $PW_R$ and in the difference between $M_{h,R}$ and $M_{h,L}$ in the first revolution in which the stimulation is on. The stationary conditions are defined as the mean value and the standard deviation of $PW_i$, $PW_R$ and $M_{h,R}$, $M_{h,L}$ computed in the 10 s successive to the achievement of symmetry. Pedalling is considered symmetric when $|M_{h,R} - M_{h,L}|$ is less than 0.1 Nm, corresponding to a difference between the forces at the right and left crank less than 1 Nm. The controller is also evaluated by the time to achieve symmetry.

### 3 Results

The symmetry controller developed have been tested in experimental trials, first on two healthy subjects (S1, S2) and then on two stroke patients (P1, P2). The stimulation currents used in the testing trials are reported in Table 2.

### Table 1 Details on the subjects involved in the trials.

<table>
<thead>
<tr>
<th>Sub</th>
<th>Sex</th>
<th>Age</th>
<th>Ictus Origin (I)</th>
<th>Plegic Side (L/R)</th>
<th>Months Post-Ictus</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>F</td>
<td>25</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>S2</td>
<td>F</td>
<td>30</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>P1</td>
<td>F</td>
<td>32</td>
<td>H</td>
<td>L</td>
<td>5</td>
</tr>
<tr>
<td>P2</td>
<td>M</td>
<td>51</td>
<td>I</td>
<td>L</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 2 Stimulation currents (right in grey and left in white) used in the trials. The values are in mA.

<table>
<thead>
<tr>
<th></th>
<th>Quadriceps</th>
<th>Hamstrings</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>30 20 25</td>
<td>30</td>
</tr>
<tr>
<td>S2</td>
<td>35 30 35</td>
<td>30</td>
</tr>
<tr>
<td>P1</td>
<td>40 45 50</td>
<td>55</td>
</tr>
<tr>
<td>P2</td>
<td>30 30 30</td>
<td>30</td>
</tr>
</tbody>
</table>
Panel (a) reports the values of $PW_L$ and $PW_R$; panel (b) reports the values of $M_{b,L}$ and $M_{b,R}$. Only the phase (60 s – 180 s) in which the stimulation was on is shown.

Fig. 3 shows the results of the trial performed by P1. It can be noticed that, at first, the values of $M_{b,L}$ are lower than the mean value of $M_{b,R}$, although the amplitudes of current used in the stimulation of the left leg are bigger than those used in the stimulation of the right one (see Table 2). Thus, the $PW_L$ starts to increase from the initial value (300 µs) till the maximum value (500 µs); then, because an unbalance is still present, the value of $PW_R$ starts to decrease. In less than 1 minute, starting from a difference of 0.65 Nm, i.e. of about 7 N, the controller is able to achieve and to maintain the symmetry. It can be noticed that after 10 s of stimulation the increase of $PW_L$ do not produce an increase of $M_{b,L}$ because the torque production of that leg is already saturated.

Table 3 summarizes the results of the trials

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>Stationary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PW_L^0$ [µs]</td>
<td>$PW_R^0$ [µs]</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>S1</td>
<td>200</td>
</tr>
<tr>
<td>S2</td>
<td>200</td>
</tr>
<tr>
<td>P1</td>
<td>300</td>
</tr>
<tr>
<td>P2</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 3 Results of the trials: $PW_L^0$, $PW_R^0$, $\Delta M_b^0$ are the initial conditions; $PW_L^s$, $PW_R^s$, $\Delta M_b^s$ are the stationary conditions. $\Delta t_C$ is the time needed to reach symmetry.

In order to obtain an unbalance in the healthy subjects, we started from different initial values of $PW$ and symmetry was reached in less than 30 s. In the trial performed by P2, the controller increased the $PW_L$ till the maximum value and decreased the $PW_R$ down to 90 µs. Nevertheless, it was not able to reach the symmetry, because of the excessive difference in the motor condition of the two limbs.

4 Discussion and conclusion

In the present study, a novel automatic symmetry controller for FES cycling was developed and first trials both on healthy subjects and hemiplegic patients were carried out in order to test the controller. These trials showed that the controller, starting from a measurement in real time of the unbalance between the two legs, was able to reach and then to maintain a symmetrical pedalling, modifying independently the stimulation parameters of the two lower limbs. In particular, about 1 minute seems to be enough to reach a stable condition. Indeed, even if the condition of the patient does not permit to achieve symmetry (see P2, Table 3), the controller tries to nullify the unbalance and then maintains the best feasible result.

In the future, the design of the automatic controller for symmetry could be improved. by empirically tuning the controller gains for individual patients.

In addition, considering the pushing action of the quadriceps and the pulling action of the hamstrings, it could be possible to distinguish the contribution of each muscular group in terms of $M_b$. Thus, the stimulation could be adjusted independently on each muscle, not only on each leg.

5 Acknowledgements

This work was partly funded through grant by the German Federal Ministry of Education and Research within the project RehaRobES (FKZ 01EZ0766).

6 References