Ergometer system with electrical stimulation for training of lower limb motor coordination in stroke patients

T. Schauer, H. Nahrstaedt, D. Vieira
Control Systems Group, Technische Universität Berlin, Germany

E. Ambrossini, S. Ferrante
NearLab, Bioengineering Department, Politecnico di Milano, Italy

Abstract
This contribution describes the prototype of a cycling ergometer system for the training of lower limb motor coordination in hemiparetic patients. A commercially available cycling ergometer with functional electrical stimulation of paretic muscles and auxiliary motor was equipped with force sensors at both crank arms to assess the torque produced individually by the healthy and the paretic leg during pedalling. Based on these measurements a symmetry index of the movement can be computed. Additionally to the force measurements, volitional activities of the stimulated muscles can be detected by an electromyography (EMG) device integrated with the ergometer system. During isokinetic cycling exercises, in which the electric motor maintains a constant cadence, the symmetry index as well as the degree of volitional activity of the paretic leg can be fed back visually to the patient. This shall enable patients with moderate cognitive abilities to generate a symmetric movement with a maximal volitional contribution of the paretic leg. An EMG-triggered electrical stimulation and a spasticity detection method based on force and EMG measurements are other important features of the system. The training system was developed within the project RehaRobES funded by the German Federal Ministry of Education and Research (BMBF).

1 Introduction
Cycling on an ergometer represents an often used training modality in the rehabilitation of stroke patients. Cycling exercises can be safely performed also from a wheelchair before gait training is possible. Modern ergometer systems possess electrical drives to support or hinder the cycling movement dependent on the abilities of the patient. Ergometer training shall prevent contractures of the leg joints and delay or prevent the onset of spasticity. Active cycling exercises also lead to an increase in muscle strength of both legs and endurance. These improvements lead to an increase of walking speed as reported in several studies [1-4]. However, locomotor coordination does not improve post intervention as shown by Kautz et al. [2].

The application of functional electrical stimulation (FES) via surface electrodes to the lower limbs synchronised to the cycling movement may enhance the rehabilitation progress of the patients. FES activates the paretic muscles. This prevents muscle atrophy and helps to build up muscle mass and strength. The possible gain in force production due to FES of the paretic leg is usually limited since residual sensation at the paretic leg limits the stimulation intensity. A complete compensation of motor deficits thanks to FES is therefore not realistic in stroke patients.

FES induced afferent-efferent stimulation together with cutaneous and proprioceptive inputs could be important in “reminding” subjects how to perform the movement. Indeed, this complete afference of the task could enhance the synaptic controls and modify the excitability of specific motor neurons, thus, facilitating the reorganization of the motor schemes and accelerating the process of functional recovery [5].

Ferrante et al. [6] compared FES cycling and standard rehabilitation in a controlled randomised study including 20 sub-acute stroke patients. Quadriceps, hamstrings, gluteus maximus and tibialis anterior of both legs (healthy and impaired) were stimulated while the patients did not contribute voluntary to the isokinetic cycling movement induced by a motorised ergometer. Exercises, lasting for 35 minutes, were performed daily for 4 weeks. The FES group had a significantly higher increase of the muscular force produced by both the quadriceps during maximum voluntary isometric contraction with respect to the control group. Seventy percent of FES patients learned how to perform a sit to stand movement with three different rising speeds while no control patient developed the ability to perform the task properly. All patients of the FES group reached indoor movement ability (passing 50 meter walking test) while 20 percent of the control patients remained unable to walk for 50 meter.

Janssen et al. [7] carried out a controlled randomized clinical study to compare the effects of FES cycling with sensory stimulation with those of FES cycling with maximal tolerated stimulation intensity. Twelve chronic stroke patients have been recruited within this study. Patients trained twice a week for 6 weeks on an isotonic cycle ergometer (Ergys2) stimulating the quadriceps, hamstrings and gluteus maximum. It is not clearly reported if one or both legs have been stimulated. Aerobic capacity and maximal power output significantly increased for both groups, but muscle strength was not significantly enhanced after training. Functional performance improved (i.e., scores on the Berg Balance Scale and the six minute walk test). There was no significant effect on the Rivermead Mobility Index. Training-induced changes were not significantly different between the two groups. Changes in cycling performance and aerobic capacity were not significantly related to changes in functional performance.
Sezsci et al. [8] investigated the kinetic and kinematic effects of FES assisted cycling in 39 patients with sub-acute stroke on a tricycle test bed with adjustable resistance. Only the quadriceps and hamstrings of the affected leg were stimulated. During ergometric measurements, volitional pedalling was alternated by combined pedalling (volitional supported by stimulation). Power, smoothness and symmetry of cycling were evaluated. Twenty-six percent of the subjects significantly improved the smoothness of their cycling with FES. Only eight and ten percent of the patients significantly increased their power and symmetry, respectively. Further, the data revealed significant correlations between the improvement of smoothness of the cycling movement and the electrically evokable isometric torque. The published studies reveal that there are no standard protocols for FES cycling at the moment, defining the best number of stimulation channels, the side of stimulation (one or two legs) and the training intensity. The studies are also difficult to compare because of different patient groups (sub-acute, chronic), ergometer settings (isokinetic, isotonic) and different involvement of the patient during the exercise (active, passive). Resistance levels are also not well reported.

In the study by Janssen et al. [7] and Szecsi et al. [8] patients were allowed to cycle voluntary assisted by the electrical stimulation. This leads of course to an asymmetry of the muscle activity of the both legs, as the healthy leg dominated the paralysed leg when propelling the ergometer. Indeed, FES cannot compensate entirely for the strength deficits of the impaired leg as the maximal tolerated stimulation intensities are usually low. This may explain why muscle contraction evoked by FES did not yield better results than cycling with sensory stimulation as shown in [7]. While muscle strength and endurance may increase by such therapy forms, the effects on motor relearning and muscle coordination are unclear. Kautz et al. [2] showed that similar ergometer training of stroke patients without FES did not improve muscle coordination. In [6], the symmetry in the task was the aim of the therapy. Therefore both legs were stimulated and no voluntary muscle activity was requested from the patients. The chosen approach may yield better motor relearning and muscle coordination as indicated by the presented results of the sit to stand test.

Existing FES cycling systems (research systems and commercially available systems) do not observe the immediate effect of the intervention on movement symmetry, muscle coordination and spasticity. There is also no check if muscle fatigue is present or not. This contribution describes the development towards a new FES-ergometer system which automatically adapts to the patient based on an observation of the immediate effects caused by the FES cycling. To observe these effects force measurements at both crank arms and EMG recordings at stimulated and non-stimulated muscles are used. To achieve symmetry in torque generation of both legs feedback control of electrical stimulation and biofeedback methods are considered. Biofeedback may also be a promising approach to train patients with strong defects in muscle coordination.

2 Methods

Basis of the development is a commercially available cycling ergometer with functional electrical stimulation (RehaMove, HASOMED GmbH, Magdeburg, Germany) which consists of a motor assisted ergometer (MOTOmed Viva2, RECK-Technik GmbH & Co. KG, Betzenweiler, Germany) and a 8 channel neuromuscular electrical stimulator (RehaStim, HASOMED GmbH, Magdeburg, Germany). Stimulated muscles are the hamstrings and quadriceps of one leg or both legs. Large stimulation electrodes (5x9cm) are used to activate these muscles. The ergometer can be parametrised externally via a serial link and provides periodic readings of cadence, crank angle and motor torque. Possible exercise forms are isokinetic or isotonic cycling. The stimulator can also be controlled from a PC via an optically isolated USB interface. The ergometer was equipped with force sensors (PowerTec, o-tec GmbH, Bensheim, Germany) to measure the radial and tangential forces acting at both crank arms in real-time. A wireless data transmission of the force measurements was realised by using two OEM Bluetooth modules (Bluesense AD, CorScience GmbH & Co. KG, Erlangen, Germany). For EMG-measurement, a multi-channel signal amplifier system with 22 Bit A/D conversion is used (Porti, TMS International BV, Enschede, The Netherlands). The EMG electrodes (Ambu® Blue Sensor NF-S, Ambu A/S, Ballerup, Denmark) are placed between the stimulation electrodes in muscle fibre direction. The design of the EMG system integrates a true DC reference amplifier. The active cable shielding guarantees optimal signal quality, no mains or other interference and complete absence of movement artefacts. The system includes no hardware filtering, so that all digital signal processing steps for the EMG must be performed on a PC. The sampling rate of all channels is at 2048 Hz. The digital real-time link between amplifier and PC is realised via an optically isolated USB interface. Fig. 1 shows the schematic ergometer set-up. All control algorithms for adjustment and timing of the electrical stimulation and the signal processing of forces and EMG are implemented on a tablet PC running Linux with RTAI real-time extension.
The tool chain Rtai-lab in combination with Scilab/Scicos (www.scilab.org) is employed for controller / filter design and for automatic real-time code generation. For operation of the ergometer system, a graphical user interface based on the Qt4 library was developed. Control and filter programs run at stimulation frequency of 20 Hz. Signals with higher sampling rates, like EMG and forces, are buffered and read batch-wise at 20 Hz. In the beginning of every stimulation period (50ms), the EMG and force readings of the last period will be therefore available. Voluntary muscle contractions or spastic reactions can be detected by filtering the EMG as described in [9]. The EMG amplifier used in this work provides a very fast recovery from stimulation artefacts, so that no additional hardware muting is required. Forces and EMG signals are analysed only revolution-wise with the option to take even averages over some revolutions to reduce noise. Based on the obtained EMG- and force-profiles (parameterised by the crank angle) and the expected intervals the following situations may be detected:

1. Asymmetry in the produced muscular torques of impaired and healthy leg
2. Fatigue of the stimulated muscles
3. Presence of an abnormal muscle activation or spasticity
4. Presence of voluntary muscle activities

Based on the detected situations, the ES will be altered or the training form changed.

Training forms:

1. **Passive Cycling**: The legs of the patients are solely moved by the electric motor of the ergometer at a low cadence (e.g. 20 rpm). This training form shall reduce the level of spasticity and shall increase the motoricity of the leg joints. The assessment of spasticity can be realised via EMG recordings of the paretic leg. When no or less spasticity is present, “Isokinetic Symmetry Training” can be activated.

2. **Isokinetic Symmetry Training**: During this training form, patients still do not actively contribute to the cycling movement. Both legs of the patients are electrically stimulated while the ergometer operates at a constant cadence (motor controlled). A symmetry controller adjusts the stimulation intensities for both legs individually to maintain symmetry in the crank torque production of both legs. In the event of spasticity or abnormal muscle activation, a change back to the program “Passive Cycling” will be performed. Patients without cognitive impairments, no spasticity and undisturbed residual volitional control of the impaired leg can change to the training program “Isotonic or Isokinetic Biofeedback Symmetry”.

3. **Isotonic or Isokinetic Biofeedback Symmetry Training**: Patients can voluntary pedal during this training program either in isokinetic or in isotonic (constant resistance) ergometer mode. The paretic leg will be stimulated at maximal tolerated intensity dependent on the detected volitional muscle activity of the stimulated muscles. The patient must voluntary cycle with the impaired leg to be rewarded with electrical stimulation (EMG-triggered). In addition, the symmetry of the cycling movement is visually displayed to the patient for biofeedback. The patient is therefore responsible to generate a symmetric cycling movement. Symmetry is determined via pedal force measurements. In the event of spasticity or abnormal muscle activation, a change back to the program “Passive Cycling” will be performed.
The before outlined training methods may be not optimal for patients with strong defects in motor control, as it only steps back to passive cycling when a disturbed coordination of the muscle activity is observed. Such a strategy will avoid wrong muscle activities during the rehabilitation. However, no direct measures are taken to counteract this problem. When the patient suffers permanently from incorrect muscle coordination the training of muscular activations timing during cycling may be more promising. When riding the ergometer in an isokinetic mode at low cadence, the patient could exercise to activate selected muscle groups, e.g. the right and the left quadriceps, at pre-specified crank angular intervals (Coordination Training). This training can involve different forms of biofeedback.

3 Results

At first, the “Isokinetic Symmetry Training” was realised. During isokinetic cycling, the produced moments due to FES on both legs are recorded and the average for every revolution is computed. Based on a comparison between of these average torques, the stimulation intensities of the both legs are adjusted individually in order to nullify the torque difference [10]. The rationale of the controller is to stimulate as much as possible the weaker leg till the maximum stimulation intensity and, then, if an unbalance is still present, to decrease the intensity of the stronger leg till symmetry is reached. The control strategy was validated in isokinetic trials performed both by healthy subjects and by hemiparetic patients [10]. The results showed that the controller was able to reach and then to maintain a symmetrical pedalling. When it was not possible to reach the symmetry, the controller reached the best feasible result.

4 Conclusions and Discussion

This contribution has described an instrumented ergometer for automatic control and biofeedback in FES cycling for stroke patients. Based on the available bio-mechanical and electro-physiological signals the immediate effects of the FES and the volitional effort can be continuously monitored and used for feedback control or biofeedback. Trials on stroke patients are carried out currently to investigate the feasibility of the proposed training forms. First positive results have been obtained for an isokinetic symmetry training in which both legs are stimulated. During such training the subjects are asked not to contribute voluntarily to the pedalling. In future, the EMG measurement shall be integrated into the stimulation electrodes. The development of such a system is on the way within the RehaRobES project.

References


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Contact: Dr. Thomas Schauer, schauer@control.tu-berlin.de, +49 30 314 24404