

# Feedback Control of an FES Lower Limb Cycling Ergometer

Schauer T<sup>1</sup>, Behling C<sup>3</sup>, Liedecke W<sup>3</sup>, Negård N-O<sup>2</sup>, Raisch J<sup>1,2</sup>

<sup>1</sup> Technische Universität Berlin, Fachgebiet Regelungssysteme, Berlin, Germany

<sup>2</sup> Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany

<sup>3</sup> HASOMED GmbH, Magdeburg, Germany

schauer@control.tu-berlin.de

## Abstract

*This work presents a feedback controlled ergometer for isotonic and isokinetic lower limb cycling exercises by means of Functional Electrical Stimulation (FES). People with SCI or other upper motor neuron lesions may use this ergometer for regular lower limb exercise. The system is based on a commercially available motorised ergometer which has been extended by a newly developed 8 channel stimulator. No hardware modifications were necessary on the ergometer site. System parameters and control concepts used within the cycling system are presented here. For scientific purposes, ergometer and stimulator can be controlled by an external host PC.*

## 1. INTRODUCTION

FES cycling is known to be a promising lower limb exercise for improving cardio-pulmonary fitness and to restrengthen muscles after SCI. Other medical and therapeutical benefits are linked with this training method. However, only regular exercise is really effective. Having the possibility to train at home is a prerequisite for high intensity training. Existing commercially available FES cycling ergometers are relatively large and require a patient transfer from the wheelchair onto the ergometer seat.

Fornusek et al. [1] have presented a new cycling system based on a compact motorised ergometer. The system consisted of an ergometer and a stimulator; both controlled from a laptop. Only an isokinetic training mode was available. This was different from the default isotonic training mode of the commercially available ergometers, like the Ergys II rehabilitation system.

Alternatively, recumbent tricycles have been used as stationary ergometers by mounting on cycle trainers. Converting the mobile system into a trainer and vice versa cannot be carried

out by the paraplegic cyclist alone; assistance is required. A transfer of the paralysed cyclist between tricycle and wheelchair is always necessary. Transfers may require further assistance and carry the risk of falls. Space and assistance are usually no problem in a clinical or research environment but may be limitations in using such an FES cycling system at home.

The system presented in this work is based on the extension of commercially available motorised ergometers by a newly developed multi-channel stimulator.

## 2. METHODS

### 2.1. System Description

The commercially available ergometers THERA-vital and THERA-live by the German company medica Medizintechnik GmbH have been chosen for setting up the FES cycling ergometers. Each THERA trainer is motor driven and controlled by a microcontroller.

In paraplegia, benefits of passive, motor supported cycling exercises are a reduction of spasticity, the prevention of joint contractures and the improvement of range of motion. During the training the patient is seated on a chair or in a wheel-chair in front of the ergometer. The feet are fixed to foot rests and the legs are stabilised by ankle joint orthoses. Depending on the chosen accessories crank arm lengths in the range 50...110mm can be realised.

By applying electrical stimulation to the paralysed muscles during the cycling, the exercise can be rendered from passive to active for a paraplegic subject. Typically, stimulated muscles are the quadriceps, hamstrings, gluteus maximus and gastrocnemius.

The developed lower limb FES cycling ergometer, named RehaMove, consists of the motorised ergometer, the stimulator and optionally a laptop.

Two approaches can be distinguished. For clinical research, the stimulation control is PC-based. The stimulator's functionality reduces in this case to the generation of stimulation pulses that are requested by the PC software. The stimulation intensity can be controlled automatically or is adjusted manually by means of an electronic dial/switch which is connected to the laptop's USB port. The FES cycling algorithms and ergometer/stimulator interface have been implemented in Matlab/Simulink under Linux. A customised soft real-time solution has been employed.

For daily clinical or home use, the stimulation is directly controlled by the stimulator's built-in microcontroller bypassing the PC (cf. Figure 1). Data logging and complexity of control algorithms are reduced in this configuration.

The ergometer has a serial interface (RS232) to enable the periodic transfer of ergometer signals to an external device (PC or stimulator). It is further possible to influence the ergometer behaviour through this serial link, by changing parameters of the internal motor control unit.

The connection between PC and stimulator corresponds to the USB 1.1 standard. Galvanic isolation is provided by the ergometer's serial interface and the USB interface of the stimulator. The current-controlled 8 channel stimulator, named RehaStim<sup>1</sup>, possesses two independent current sources which are multiplexed to 4 outputs each. Biphasic pulses with current amplitudes of up to 126mA and pulse-widths of up to 500us are delivered by the device. The stimulation frequency is in the range 1...100 Hz. The generation of doublets and triplets with short inter-pulse-intervals is possible within the PC-controlled setup in order to design variable frequency trains (see [2]).

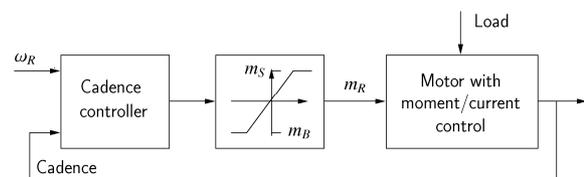
## 2.2. Stimulation Control

The stimulation of the individual muscle groups is switched on and off dependent on crank angle and cadence. The angle information is estimated by an extended Kalman filter from the available cadence measurement and some light barrier events generated when the crank is moving. Furthermore, the ergometer sends via the serial link the measured motor torque which is used to estimate the muscular drive moment at the crank. Calibration of the motor moment is performed by moving a known weight only at one crank arm at different cadences. The stimulation intensity can be automatically

altered to maintain a desired muscular power output by the patient.



**Figure 1:** Stand-alone system RehaMove<sup>2</sup> for FES lower limb cycling ergometry.



**Figure 2:** Internal ergometer control ( $\omega_R$  - reference cadence,  $m_R$  - reference motor moment).

## 2.2 Internal Ergometer Control

The electric motor of the ergometer is speed controlled in the range 10...60 rpm whereas the reference cadence  $\omega_R$ , the maximum support torque  $m_S$  and maximum brake torque  $m_B$  of the motor can be specified via the serial link (cf. Fig. 2). The torque range is -15...15 Nm.

## 2.3 Training Modes

In all training modes, the power output of the cyclist is controlled. Power is defined as the product of cadence and muscular drive moment/mechanical resistance at the crank. One of these variables is controlled by the motor and the other consequently by the stimulation intensity. Therefore, we can distinguish two different exercise regimes as outlined in the next two sections. In both cases, a power  $P_D$  is specified and for a constant desired cadence  $\omega_D$  the required drive torque/resistance  $m_D$  at the crank is determined by  $m_D = P_D / \omega_D$ .

<sup>1</sup> <http://www.rehastim.de>

<sup>2</sup> <http://www.rehamove.de>

### 2.3.1 Isokinetic Training Mode

In the case of an isokinetic cycling exercise, the motor is controlled to maintain a desired cadence  $\omega_D$  while the cyclist tries to work against the motor aiming to accelerate the crank by electrical stimulation of the paralysed muscles. In order to realise isokinetic training with the ergometer's motor control, the support moment limit  $m_S$  has to be set to the maximum and the brake moment limit  $m_B$  to the largest possible negative value. The desired cadence is  $\omega_R = \omega_D$ . To obtain the specified power, the muscularly produced drive torque must be maintained at  $m_D$  by modulating the stimulation intensity of the paralysed muscles. Simple integral control for the moment has been used within the clinical setup. For the PC-controlled setup, a self-tuning adaptive control approach has been chosen yielding a larger closed-loop bandwidth [3].

### 2.3.2 Isotonic Training Mode

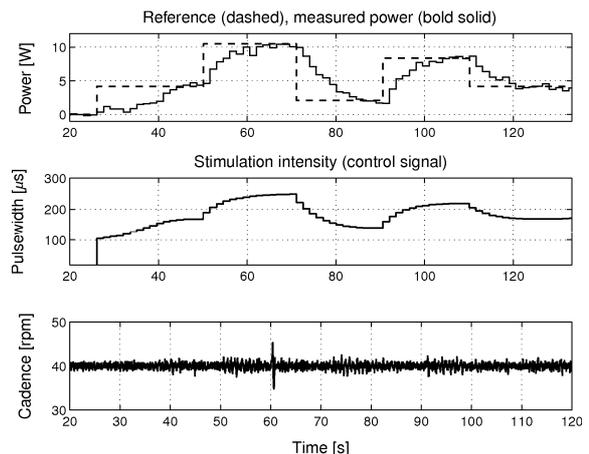
The braking moment  $m_D$  at the crank is realised under isotonic training conditions by the 4-quadrants DC drive. Compared to purely mechanical trainers, the motor can provide not only a resisting moment but can also support the cycling by compensating for mechanical friction. A strategy is to set-up a base cadence  $\omega_B$  first which is below  $\omega_D$ . This base cadence is initially realised by the DC drive. This initiates the cycling movement, and most important, helps to get the angle estimation running. In order to achieve the base cadence  $\omega_B$ , the support moment limit  $m_S$  is set to its maximum and the reference motor cadence  $\omega_R$  is chosen as  $\omega_B$ .

As soon as the electrical stimulation is active, the required motor torque for maintaining  $\omega_B$  is reduced by the amount of active (muscular) moment at the crank. For stronger increasing active moment, the motor starts to work against the cyclist up to a resistive moment specified by  $m_D = m_B$ . For any cadence larger than the base cadence, the resistive moment  $m_D$  is realised at the crank shaft on average over one cycle.

The cycling cadence can be controlled by the stimulation intensity and so maintained at a constant level  $\omega_D$ , while the braking moment  $m_D$  can be varied to set different cycling power levels. Simple integral control for the cadence has been used within the clinical setup. For the PC-controlled setup, the system identification based approach presented in [3] was applied.

## 3. RESULTS

The feedback control strategies of the new FES cycling system were tested with neurologically intact subjects. Figure 4 shows exemplary the result of a power control test during an isokinetic exercise with the PC-controlled setup. The upper graph shows the reference power and the actual power. In the middle graph the pulsewidth is shown while the lower subplot represents the motor controlled cadence of 40 rpm. Quadriceps and hamstrings have been stimulated with current amplitudes of 60 mA.



**Figure 4:** Power control test during an isokinetic cycling exercise. Note that the controlled power is the average over one cycle.

## 4. DISCUSSION AND CONCLUSIONS

The presented FES cycling ergometer is compact and suitable for clinical and home use. CE-marking of the devices has been already carried out. The user and/or therapist have the choice of different training modes which all allow precise power control. PC-control of system was realised for scientific purposes.

### References

- [1] Fornusek C, Davis G, Sinclair P, and Milthorpe B, Development of an Isokinetic Functional Electrical Stimulation Cycle Ergometer, *Neuromodulation*, 2004, 7;56-64, 2004
- [2] Ferrante S, Schauer T, Ferrigno G, Raisch J, The effect of variable frequency trains during FES cycling, In *Proc. of the 11<sup>th</sup> Annual Conf. of the Int. FES Society*, Zao, Japan, 2006.
- [3] Schauer T, Feedback Control of Cycling in Spinal Cord Injury using Functional Electrical Stimulation., *PhD Thesis, University of Glasgow, Scotland*, 2005.

### Acknowledgements

We are grateful to the German Federal Ministry of Education and Research for the financial support of this project (InnoMed Network within the InnoRegio Initiative, FKZ: 0310411).