Abstract
The Lokomat gait orthosis automates treadmill training after SCI or stroke. The patient’s engagement was shown to have major influence onto the outcome of the rehabilitation. In order to influence the engagement of a patient during training, we try to control the patient’s psycho-physiological state via measurable quantities. As an example, we control the heart rate by adapting the Lokomat walking speed. On the one side, this enables us to prevent patient overstress during training. On the other side, this is the first step towards influencing the patient’s psycho-physiological state, which is reflected by physiological quantities such as the heart rate. We implemented a real time processing algorithm that uses a combination of steep-slope-threshold and beat expectation for heart beat detection. A PI fuzzy logic controller was implemented, which controls the Lokomat walking speed in order to stabilize the heart rate at a desired value. Single case results show that the controller was able to stabilize the heart rate of subjects around a desired value. Future developments of such controllers will have take into account the level of active participation shown by the subject during walking.

1. Introduction
Psycho-physiological reactions of patients with neurological disorder have been neglected so far as an input signal for the rehabilitation process or device. The psychological state of a subject, in particular the motivation, was shown to have major influence on the outcome of the rehabilitation (I. H. Robertson and J. M. J. Murre, 1999; R. Loureiro et al., 2001; D. G. Liebemann et al., 2006). Our goal is to increase engagement and motivation of the patients and, thus, improve the rehabilitation outcome of the subject during Lokomat training. This work is based on the assumption that the current psychological state of a subject is reflected in physiological signals (K. Hugdahl, 1995). By controlling these physiological signals, we intend to indirectly influence the psychological state.

In a first step, we want to control heart rate to a desired level by adapting the Lokomat walking speed. The heart rate is determined from the ECG signal by extracting the RR-intervals. The heart rate can be used as an indicator of physical as well as mental load [Mulder et al., 2000]. On the one side, controlling heart rate enables us to prevent subject overstress during training. On the other side, this is the first step towards influencing the subject’s psycho-physiological state.

Various researchers have employed PID, fuzzy or robust control to control heart rate during treadmill training via treadmill speed or treadmill incline (S. Su et al., 2005; T. Cheng et al., 2008a; T. Cheng et al., 2008b). These previous results cannot be directly transferred to the Lokomat, because the physical workload cannot be affected by changing the inclination of the Lokomat treadmill, neither by gaining higher walking speeds, which are – for safety reasons – restricted to 3.2 km/h. Previous results of other researchers employed walking speeds of at least 7km/h. Furthermore, unlike free walking, where the subject always has to produce the movement actively, during Lokomat training a subject can choose between and active or passive participation, with varying contribution of the Lokomat.

Therefore, we first quantified the relationship between active participation and heart rate. Based on these results, we designed a fuzzy controller that enables us to control heart rate of the subject during Lokomat walking.

2. Methods
To evaluate the effects of different walking speeds and active or passive walking behaviour, we recorded ECG from five healthy subjects (two female, three male, in average 26.4 years old) walking at three different speeds (Figure 1). Approval for all studies was obtained from local ethics committees, and the subjects gave written informed consent.

We compared the differences in heart rate for walking on a treadmill (without Lokomat) and for walking in a position controlled Lokomat® Pro system (Hocoma AG, Volketswil, Switzerland). In the Lokomat, subjects can behave passively and “get walked” by the robot. Alternatively, they can walk actively and thereby get slowed down by the exoskeleton. We, therefore, also quantified the heart rate in reaction to different levels of active participation. The level of activity and participation was quantified by weighted force measurements, the so-
called biofeedback values. The forces were measured in series with the spindle gear drives of the Lokomat (L. Lunenburger et al., 2004; L. Lunenburger et al., 2007). To simulate realistic training conditions as with Lokomat patients, all subjects were body weight supported with 30% of their body weight. All three conditions were randomized.

ECG was recorded with a gtec amplifier (www.gtec.at) and Matlab 2007b (www.mathworks.com). We implemented a real time processing algorithm that used a combination of steep-slope-threshold and beat expectation for heart beat detection as depicted in Figure 2A (I. Christov, 2004).

![Figure 2: A - ECG signal and beat detection threshold – when the ECG exceeds the threshold, a beat is detected. For 200ms after a detection, we do not allow a beat to be detected (1 - beat expectation between 200ms and 1200ms after the last beat). After 200ms, we increase the threshold to 0.6 of the maximum value of the last 5 beats. The amplitude is decreased over time (2 - steep slope threshold) until the next beat is detected. B - Controller overview. The Lokomat performs in position control mode while the treadmill speed is controlled as a function of the heart rate]

Based on the results of our first recordings, we designed a PI fuzzy controller to drive the heart rate of subjects to a desired value in a closed control loop setting (Figure 2, B). Subjects were instructed to walk with normal effort and to not exaggerate their walking pattern. The current heart rate of subjects varied strongly over time even during baseline recordings when subjects were standing. To smooth this effect, we used a moving average filter with exponentially decreasing filter coefficients and set the sampling time of the fuzzy controller to five seconds. The controller design was adapted from (S. Su et al., 2005). We used the error signal \( e(k) = \text{Heart rate}_{rec} - \text{Heart rate}_{des} \) to compute the difference \( de(k) = e(k) - e(k-1) \). In combination with the current error \( e(k-1) \), the controller was a PI controller seen from the time \( k-1 \). Trapezoidal membership functions were used for \( de(k) \) and \( e(k-1) \). The defuzzification used a center of mass function for computation of the output treadmill speed \( v_{TM} \) (Figure 3). We investigated the functionality of our fuzzy controller in a single subject.

![Figure 3: PI fuzzy controller]

The heart rate profile to be tracked started with a baseline measurement, followed by desired heart rates each lasting 100 seconds, ending with another 100 seconds baseline measurement (Figure 5 A).
3. Results and discussion

3.1. Effects of effort and treadmill speed on the heart rate

Investigating the effects of different treadmill speeds on the heart rate we found that for walking speeds up to 3km/h, the heart rate increased with increasing treadmill speed for walking without Lokomat. Subject walking in the Lokomat had a significantly increased heart rate at the same speed level during active walking compared to passive walking (p<0.05, one way Anova). Walking actively compared to walking without Lokomat did not show a significant increase of heart rate.

Particularly during passive walking, an increase in walking speed did not result in a significantly increased heart rate. The biofeedback values were computed to ensure that subjects walked actively or passively as instructed. During passive walking, the mean biofeedback values showed significant differences (-7±11 during passive walking, 34±12 during active walking).

![Figure 4: Comparison between heart rates at three different walking speeds at different conditions. Without Lokomat (1), in the Lokomat position controlled passively (2), in the Lokomat position controlled actively (3).](image)

3.2. Results of fuzzy heart rate controller

The baseline heart rate at rest was around 78±4 beats per minute (bpm). The controller showed an acceptable performance for desired heart rates in the vicinity of the baseline heart rate (70 and 80 bpm), keeping the standard deviation below 3 bpm (Figure 5A).

![Figure 5: Results of heart rate tracking using a PI fuzzy controller. A: The desired and recorded mean heart rate - B: the control signal to the Lokomat and treadmill](image)
In baseline measurements, the heart rate during quiet standing fluctuated with approximately ±4 bpm. With our controller, we were able to stabilize this fluctuation around the desired value. Interestingly, the variability of the heart rate seemed to decrease during walking compared to resting condition. For 90 bpm desired heart rate, the controller was not able to perform equally well, which can be attributed to the fact that the treadmill speed was not allowed to exceed the security limit of 3.2km/h (Figure 5 B).

4. Outlook

The next step will be the design of a controller that uses friction forces instead of the treadmill speed as control signal. Thereby, we will be able to control the effort needed to walk in the Lokomat, which we showed to have major effect on the heart rate. We will then determine the effort needed during walking in order to find a model which can predict changes in heart rate. Once we can predict and control heart rate, we will perform similar experiments with Galvanic Skin Response (GSR), breathing frequency and skin temperature. A psychological model will then enable us to quantify the current psychological state and influence it using the Lokomat within a virtual environment comprising audiovisual displays. In the long run we want to be able to predict the effect of Lokomat training on the physiological signals mentioned above to distinguish between effects caused by physical stress and effects caused by changes in the psychological state of the patient. We will close the loop around the human by adapting the training environment according to the current psychological state. This will enable us to use physiological signals to quantify the current psychological state of the subject.

5. Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 215756. A. Koenig and M. Wieser are supported by the National Center of Competence in Research (NCCR), Switzerland.

6. References


Contact: Alexander Koenig, Sensory-Motor Systems Lab, ETH Zurich and Spinal Cord Injury Center, University Hospital Balgrist, Zurich, Switzerland, email: Koenig@mavt.ethz.ch, phone:0041 (0) 44 386 37 39