Introduction
Treadmill training is a recent, but already established rehabilitation exercise to improve the mobility of spinal cord injured patients [2],[3]. Physiotherapists move the legs of the partially body-weight unloaded patients in a periodic way to achieve walking on the treadmill. A robotic orthosis called Lokomat (4 DOF, joint-trajectory position control) was built at ParaCare to automate the treadmill training in order to provide more regular and prolonged training and to relieve the physiotherapists (Fig.1), [1]. However, an active patient effort and a varying gait-pattern might increase the therapeutic effect of the training. An on-line gait-pattern adaptation algorithm was therefore developed for this purpose. It allows the patient to influence and modify the reference hip and knee angle trajectories that are controlled by the position controllers. In this way, the patient is able to train with the desired gait-pattern that due to the in-built constraints remains physiological.

Methods
The algorithm is based on the minimization of physical (force) interaction between the patient and Lokomat. Active forces that the patient exerts onto Lokomat in order to change the gait-pattern are measured by force sensors in linear drives that actuate the hip and knee joints. These active forces are then recalculated to hip and knee interaction torques used in the gait-pattern adaptation algorithm. The algorithm employs a steepest descend optimization method to determine the variation in the parameterized joint-trajectories that will, when applied, result in a variation in the torques necessary to move the Lokomat and the patient, which will cancel the interaction torques. The variation in the gait-pattern $\delta q_r$ is calculated by minimizing the following functional $J$:

$$J(\delta q_r, F_1, F_2) = \| \delta \tau_{PAT,ACT}(F_1, F_2) - \delta \tau(\delta q_r) \|_2^2 =$$

$$= \int_0^T \| \delta \tau_{PAT,ACT}(F_1, F_2) - \delta \tau(\delta q_r) \|_2^2 dt \rightarrow \text{min}$$

$$\delta q_{r,\text{~adapt}} = \arg \min_{\delta q_r} J(\delta q_r, F_1, F_2)$$
The $\delta\tau_{\text{PAT,ACT}}$ is the torque component estimated via the force measurements. The $\delta\tau(\delta q)$ is the torque component calculated by a nonlinear model (standard robotic dynamic equation) that describes the variation in the torques due to a variation in the reference angle trajectories. The algorithm runs in real-time where the reference joint-trajectories are adapted on-line according to the performed minimization.

![Image](image1.jpg)

**Fig.1:** A subject walking in Lokomat (left), and a detailed view of the construction of a Lokomat’s leg (right).

The algorithm has been tested in real experiments on three healthy volunteers that have tried to change the initial gait-pattern to one of the following gait-patterns: (1) larger steps, (2) shorter steps, or that have continued to walk with an active, physiological gait (3), or that have remained completely passive (4). The study was designed as a blind-study with half of the trials performed with enabled and the other half performed with disabled gait-pattern adaptation. The subjects were asked to quantify the adaptation on a 1-5 scale (1= no adaptation, 5=very good adaptation). Several other pilot studies including one patient experiment were performed as well, but are not reported here.

**Results**

The experiments (1) resulted in an increased hip flexion and not significantly changed knee motion. The outcome of the experiments (2) was slightly reduced (sometimes oscillatory changing) hip motion with increased hip extension and a slightly increased knee flexion. Changes in (3) were minor and hard to quantify. The experiments (4) resulted in a decreased range of the hip motion and an increased knee flexion. The subjective opinion about the extent of adaptation was 1.33±0.60 (mean±s.d.) and 1.83±1.93 for the disabled and enabled adaptation respectively. An example of a gait-pattern adaptation is shown in Fig.2.
Fig.2: Adaptation in the reference trajectories (top panels) where the subject tried to change the gait-pattern after 80 s to walk with larger steps. The bottom panels show the minimization of the active patient torques (hip+knee) that the subject exerted onto Lokomat in order to change the gait-pattern (dashed lines: $\delta\tau_{\text{PAT,ACT}}$; solid lines: $\delta\tau(\delta\theta)$).

Discussion
The gait-pattern adaptation algorithm could provide significant adaptation of the joint-trajectories where such adaptation was expected (experiments (1),(2), and (4)), and was stable (no adaptation) in the experiment (3), where no adaptation was expected. Further testing and tuning of the algorithm performance is required. This should be followed by well designed experiments with spinal cord injured patients.

References

Acknowledgment
The authors would like to thank Dipl.Ing.FH Reinhard Schreier for his technical assistance. The study was supported by The Swiss Commission for Technology and Innovation (Proj. Nr. 4005.1).