# Patient-Driven Cooperative Gait Training with the Rehabilitation Robot Lokomat

A. Duschau-Wicke[1,2,3], J. v. Zitzewitz[1], L. Lünenburger[3], and R. Riener[1,2]

[1] Sensory-Motor Systems Lab, Institute of Robotics and Intelligent Systems, ETH Zurich, Zurich, Switzerland
[2] Spinal Cord Injury Center, University Clinic Balgrist, Zurich, Switzerland
[3] Hocoma AG, Volketswil, Switzerland

*Abstract*—**Rehabilitation robots can support the training of patients with neurological gait disorders. Classical control approaches permit patients to remain passive during the robot-assisted training. We hypothesize that promoting active participation of patients will improve training efficacy. In this paper, we evaluate the combination of two existing patient-cooperative control strategies. These strategies are applicable to robotic exoskeletons that assist a patient walking on a treadmill. The first strategy, Automatic treadmill speed adaptation, detects the patient's desired walking speed and accelerates the treadmill accordingly. The second strategy, Path control, provides spatial guidance of the legs via the rehabilitation robot while the patient controls the timing of his/her movements. We demonstrate that both strategies can be successfully combined towards an approach that allows subjects to walk on their own with the support of a robot instead of being passively moved.**

*Keywords*—**rehabilitation, robotics, patient-cooperative, treadmill, training.**

## I. INTRODUCTION

The rehabilitation robot Lokomat (Fig. 1; Hocoma AG, Volketswil, CH) allows automated treadmill training for patients with neurological gait disorders [1]. The robot moves patients along pre-defined movement patterns to stimulate physiological afferent input. This training helps the nervous system to relearn walking. However, patients can remain passive during this kind of training [2].

We hypothesize that a control strategy which provides patient-driven instead of robot-driven movements may substantially increase the efficacy of robot-aided therapy. Therefore, we developed the cooperative *Path Control* strategy [3] that allows patients to influence the timing of their leg movements along a physiological walking pattern. In this strategy, the robot simulates compliant virtual walls, which keep the patients' feet within a "tunnel" around the spatial path of the walking pattern. Graphical feedback provides visual training instructions to patients [4]. The strategy was successfully tested with 10 healthy and 16 neurologically impaired subjects. The subjects participated more actively compared to the classical position-controlled training mode in which their movements were completely controlled by the robot [5].

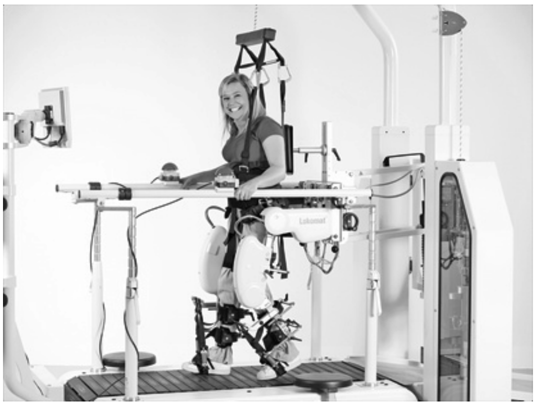

Fig. 1 The Lokomat® robot (photo courtesy of Hocoma AG)

However, free timing of movements was limited to swing phase only as constant settings for the treadmill speed were used during the training with the Path Control strategy. A previously developed control approach for adapting the treadmill speed during Lokomat training [6] provides free timing of movements also during stance phase. This algorithm uses force measurements to determine the subject's intention to accelerate or decelerate his/her walking speed. The force measurement principle behind this approach requires subjects to freely control the timing of the leg movement during stance phase. Until now, such free timing was only possible in a special mode of controlling the Lokomat (*free-run mode*), which does not provide sufficient guidance to train subjects with gait impairments.

We expect that the combination of Path Control and Automatic Treadmill Speed Adaptation (ATSA) will cumulate the benefits of both approaches: the Lokomat robot provides spatial guidance of the legs along a physiological walking trajectory while the subject controls walking speed and the timing of his/her leg movements.

The aim of this paper is to evaluate whether the two patient-cooperative approaches can be successfully combined to establish completely patient-driven, cooperative robotic gait training.

## II. Methods

### A. Path Control

The path control algorithm is based on the impedance controller presented in [7]. However, the time-dependent walking *trajectories* are now converted to walking *paths* with free timing. This is comparable to fixing the patient's feet to rails, thus limiting the accessible domain of foot positions (which can be calculated as a function of hip and knee angle).

Along these *virtual rails*, which form a template for possible motions in space, the patient is free to move on his/her own. During stance phase, however, the patients' feet are propelled by the treadmill with constant speed. Therefore, free timing is effectively limited to swing phase movements.

Freedom of timing is implemented by augmenting the Lokomat impedance controller by a *set point generation* algorithm that derives the reference joint angles $\underline{\varphi}_{\mathrm{ref}}$ from the actual angles $\underline{\varphi}_{\mathrm{act}}$ (Fig. 2). The leg posture in the standard Lokomat gait pattern $\Phi_{\mathrm{ref}}$ with the smallest Euclidean distance to the actual angles $\underline{\varphi}_{\mathrm{act}}$ is chosen as controller reference $\underline{\varphi}_{\mathrm{ref}}$ ($\underline{\varphi}_{\mathrm{ref}} \in \Phi_{\mathrm{ref}}$).

In order to adapt the amount of freedom to the individual patients' capabilities, the region of free timing can be limited to a *moving window* ($\underline{\varphi}_{\mathrm{win}}$). This window moves with a pre-defined speed along the path and the set point generation limits the set of available control references to the allowed postures contained in this window (Fig. 3). Thus, the moving window prevents large deviations from the desired speed, yet it allows a certain amount of temporal variation, depending on the window width.

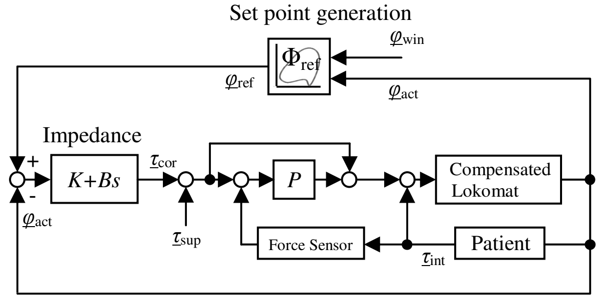

Fig. 2 Block diagram of the path controller. K and B are the spring and damping parameters, respectively, of the virtual impedance. P is the gain of the inner force control loop. $\underline{\tau}_{\mathrm{int}}$ denotes the interaction torques between patient and Lokomat.

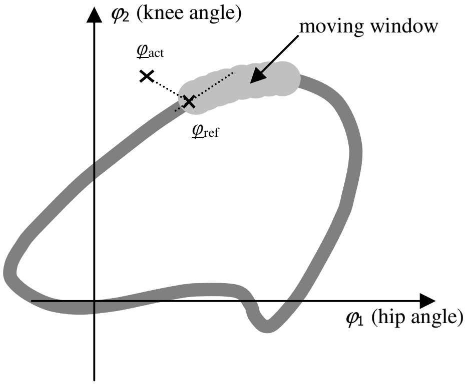

Fig. 3 Set point generation with moving window. The solid curve corresponds to the standard gait pattern $\Phi_{\mathrm{ref}}$ of the Lokomat. The element of the subset of $\Phi_{\mathrm{ref}}$ in the moving window with the smallest Euclidean distance to the actual angles $\underline{\varphi}_{\mathrm{act}}$ is chosen as set point $\underline{\varphi}_{\mathrm{ref}}$.

Supplementary to the *corrective* actions ($\underline{\tau}_{\mathrm{cor}}$) of the Lokomat, a *supportive* force field of adjustable magnitude can be added ($\underline{\tau}_{\mathrm{sup}}$). Depending on the actual position of the patient's legs, forces tangential to the path are generated.

### B. Automatic Treadmill Speed Adaptation (ATSA)

The algorithm and setup for ATSA is described in detail in [6]. The concept can briefly be summarized as follows: the user's position on the treadmill is mechanically constrained in walking direction. The interaction forces between the user and the constraining mechanism are measured with a force sensor. The measured force serves as the input for an admittance type control architecture which controls the treadmill speed (Fig. 4).

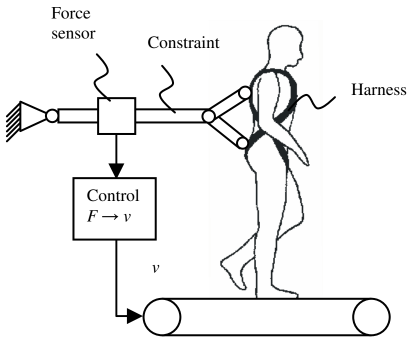

Fig. 4 Sensor and control concept for automatic treadmill speed adaptation

In the Lokomat setup, the constraining mechanism is formed by the parallelogram construction which fixes the orthosis to its supporting frame.

### *C. Synchronization of stance and swing leg*

When the treadmill speed is controlled by the ATSA algorithm, the subject can accelerate or decelerate his/her stance leg dynamically by modulating the push off of the foot. To maintain stable walking, the subject has to accelerate the swing leg in accordance with the stance leg. The synchronization of both legs can be supported by the moving window of the path controller. In the combined path control/ATSA strategy, the moving window is controlled as follows:

1. For the stance leg, the center of the moving window $\varphi_{\text{win,stance}}$ is set to the current leg posture $\varphi_{\text{act}}$. Thus, the stance leg is never restrained by the moving window.
2. For the swing leg, the center of the moving window $\varphi_{\text{win,swing}}$ is set to a posture half a gait cycle ahead of the stance leg $\varphi_{\text{win,stance}}$.
3. During the double support phase, the control of the moving window is faded to the new stance leg.

### *D. Experimental evaluation*

To evaluate the combined control strategies, four healthy subjects performed a speed adaptation task in the Lokomat with the following setup: a 3x2m back-projection screen in front of the Lokomat displayed visual feedback for the task. A virtual representation of the subject (avatar) was shown walking through a virtual scene with the current speed of the treadmill (Fig. 5). If the subject accelerated or decelerated the treadmill, the avatar changed its speed in the virtual world accordingly.

Additionally, a rolling soccer ball was presented. The rolling speed of the ball $v_{\text{ball}}$ was continuously changing between 0.56 m/s and 0.84 m/s with a frequency of 1/240 Hz.

$$v_{\text{ball}}(t) = 0.7\ \text{m/s} + 0.14\ \text{m/s} \cdot \sin((2\pi/240\ \text{s}) \cdot t) \qquad (1)$$

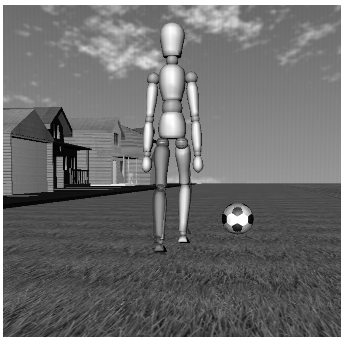

Fig. 5 Visual feedback for speed adaptation task. The avatar displays the movements of the subject. The soccer ball rolls forward with a varying speed. The subject is instructed to match the speed of the soccer ball.

The subjects were instructed to match the speed of the soccer ball, i.e. to keep the avatar at a constant distance to the ball.

The joint angles of the subjects' legs were recorded from potentiometers located at the Lokomat joints. The resulting treadmill speed was recorded from a tachometer located at the motor axis of the treadmill.

For each subject, we calculated the speed error by subtracting the actual treadmill speed from the desired treadmill speed (which corresponds to $v_{\text{ball}}(t)$). The mean and standard deviation of the speed error were calculated to assess the accuracy of speed tracking. To analyze the variations of speed during one gait cycle, we averaged all strides of all four subjects to an average speed profile.

## III. RESULTS & DISCUSSION

All subjects could start and stop walking autonomously and were able to successfully match the speed of the virtual soccer ball, i.e. they were able to voluntarily control their walking speed. The resulting treadmill speed oscillated around the speed of the soccer ball (Fig. 6). The mean speed errors of the subjects were considerably small (Table 1).

The experimentally obtained speed profile (Fig. 7) qualitatively matches the physiological speed profile during over-ground walking as described in the literature [8]. In contrast to the literature data, the obtained speed profiles are slightly asymmetric, showing higher accelerations when the right leg is in stance phase.

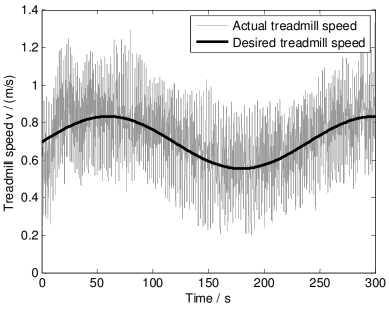

Fig. 6 Treadmill speed of subject 1 over the whole experiment

Table 1 Mean and standard deviation of the speed errors

| Subject | Mean speed error | Std. dev. of speed error |
|---|---|---|
| 1 | 0.008 m/s | 0.171 m/s |
| 2 | 0.018 m/s | 0.267 m/s |
| 3 | 0.039 m/s | 0.230 m/s |
| 4 | 0.005 m/s | 0.133 m/s |

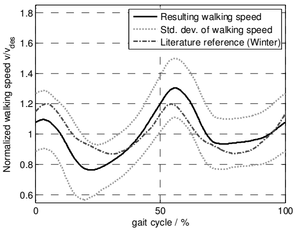

Fig. 7 Treadmill speed over a single stride. The solid line shows the average speed profile of all 4 subjects. The dotted lines mark the region of one standard deviation around the average. The dash-dotted line shows reference data for the center-of-mass during over ground walking [8].

This behavior can be explained by the asymmetrical placement of force sensors in the Lokomat setup and is discussed in detail in [6].

Finally, we were interested in the spatial guidance by the Lokomat during the experiment. The resulting trajectories are closely following the desired spatial path (Fig. 8). Some systematic deviations can be observed. Subjects tended to rely on the corrective torques of the controller for preventing excess knee flexion during stance phase and for supporting knee flexion during swing phase. Furthermore, subjects tended to walk with less hip extension at the end of stance phase, and with more hip flexion at the end of swing phase than desired by the reference path.

Both the ATSA algorithm and the path controller showed no degradation of performance compared to previous evaluations where only ATSA [8] or only the path controller [4,5] were used.

## IV. CONCLUSION

We evaluated the combination of an adaptive treadmill speed adaptation algorithm with the Path Control strategy with four healthy subjects. The subjects were able to initiate and terminate walking autonomously after a few minutes of familiarization. Furthermore, they could successfully follow a continuously changing reference speed with the help of graphical feedback. The recorded joint angles show that the leg movements were effectively guided along the desired walking pattern by the path-controlled Lokomat.

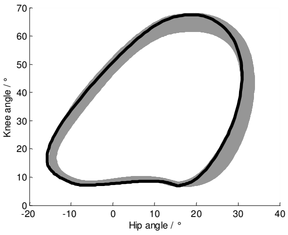

Fig. 8 Desired spatial path (solid line) and mean resulting trajectory +/- standard deviation (grey shaded area) of four healthy subjects.

No detrimental mutual influences of the two patient-cooperative control strategies could be identified. Therefore, we conclude that these two independent control strategies can be successfully combined. The resulting cooperative control of a gait rehabilitation robot and a treadmill allows subjects to walk on their own with the help of a robot instead of being passively moved.

## ACKNOWLEDGMENT

The authors would like to thank Heike Vallery for her support.

The contents of this publication were developed in part with support of the National Center of Competence in Research (NCCR) on Neural Plasticity and Repair of the Swiss National Science Foundation and in part under a grant from the US Department of Education NIDRR grant number H133E070013. However, those contents do not necessarily represent the policy of the US Department of Education, and you should not assume endorsement by the Federal Government of the United States of America.

## REFERENCES

1. Colombo G, Joerg M, Schreier R, and Dietz V (2000). Treadmill training of paraplegic patients using a robotic orthosis. *J Rehabil Res Dev*, 37(6):693-700.
2. Israel J, Campbell D, Kahn J, and Hornby G (2006). Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys. Therapy*, 86(11):1466-1478.
3. von Zitzewitz J, Duschau-Wicke A, et al. (2006). Path control: A new approach in patient-cooperative gait training with the rehabilitation robot Lokomat. In *Joint Meet. of German, Austrian, and Swiss Soc. Biomed. Eng., Zurich*
4. Duschau-Wicke A, von Zitzewitz J, et al. (2007). Path control – a strategy for patient-cooperative training of gait timing. In *Proc. 7th Automed Workshop*, pages 1-2, Munich.
5. Caprez A (2008). Evaluation of a patient-cooperative robotic training in incomplete spinal cord injury patients. Master's thesis, ETH Zurich, Switzerland.
6. von Zitzewitz J, Bernhardt M, and Riener R (2007). A novel method for automatic treadmill speed adaptation. *IEEE Trans. Neural Syst. Rehabil. Eng.*, 15(3):401-409.
7. Riener R, Lünenburger L, Jezernik S, et al. (2005). Patient-cooperative strategies for robot-aided treadmill training: first experimental results. *IEEE Trans. Neural Syst. Rehabil. Eng.*, 13(3):380-394.
8. Winter D (2004). *Biomechanics and Motor Control of Human Movement*. Wiley.

- Author: Alexander Duschau-Wicke
- Institute: SMS Lab, ETH Zurich
- Street: Tannenstr. 1, TAN E5
- City: Zurich
- Country: Switzerland
- Email: duschau@mavt.ethz.ch