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Original Article

Adaptive robotic rehabilitation of locomotion: a clinical study in spinally injured individuals

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Study design: Clinical study on six spinal cord-injured subjects. The performance of two automatic gait-pattern adaptation algorithms for *automated treadmill training* rehabilitation of locomotion (called DJATA1 and DJATA2) was tested and compared in this study.

Objectives: To test the performance of the two algorithms and to evaluate the corresponding patient satisfaction. We also wanted to evaluate the motivation of the patients to train with a fixed gait pattern versus training where they can influence and change the gait pattern (gait-pattern adaptation).

Setting: Spinal Cord Injury Center Paracare, Balgrist, Zürich, Switzerland.

Methods: The experimental data were collected during six blinded and randomized training trials (comprising three different conditions per algorithm) split into two training sessions per patient. During the experiments, we have recorded the time courses of the six parameters describing the adaptation. Additionally, a special patient questionnaire was developed that allowed us to collect data regarding the quality, perception, speed, and required effort of the adaptation, as well as patients' opinion that addressed their motivation. The achieved adaptation was evaluated based on the time course of adaptation parameters and based on the patient questionnaire. A statistical analysis was made in order to quantify the data and to compare the two algorithms.

Results: Significant adaptation of the gait pattern took place. The patients were in most cases able to change the gait pattern to a desired one and have always perceived the adaptation. No statistically significant differences were found between the performances of the two algorithms based on the evaluated data. However, DJATA2 achieved better adaptation scores. All patients preferred treadmill training with gait-pattern adaptation.

Conclusion: In the future, the patients would like to train with gait-pattern adaptation. Besides the subjective opinion indicating the choice of this training modality, gait-pattern adaptation also might lead to additional improvement of the rehabilitation of locomotion as it increases and promotes active training.

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Introduction

This manuscript reports results from a clinical study on rehabilitation of locomotion in spinal cord-injured (SCI) patients. The aim of the study was the evaluation of two algorithms for adaptive robotic rehabilitation with an automated treadmill training system.

First approaches to rehabilitation of locomotion in SCI individuals were developed in the 1980s based on the results of experiments performed with spinalized cats. These were shown to be able to walk on a treadmill in spite of spinal transection if their body weight was supported.[1,2] This research led to the development of a so-called treadmill training rehabilitation exercise. In the manual treadmill training, two physiotherapists move the legs of the patient suspended over a treadmill in order to simulate walking. During the training, the body

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weight of the patient is counteracted by a special unloading system, since the patients are not able to maintain their equilibrium and to walk by themselves. In a later stage of rehabilitation, some patients regain the ability to walk by themselves, but might still require body-weight support to do so.

During the last two decades, treadmill training has become an established rehabilitation exercise for individuals with locomotor dysfunction such as SCI and stroke patients.[3–6] This is due to faster and greater mobility improvement demonstrated with a combined treadmill training and conventional physiotherapy versus conventional physiotherapy only.[5] The mechanism for the improvement of locomotor function in SCI individuals is likely the following one: a periodic excitation of the cutaneous, muscular, and joint receptors provides a periodic afferent input to the neural circuits located in the spinal cord (central pattern generator, CPG). These circuits are responsible for coordinated muscle activation that generates locomotion.[8,9] Treadmill training reactivates and retrains the CPG, and therefore improves the generated muscle activation pattern. The result is a faster and better relearning of locomotion.[3,7]

Since assisting the patient's leg movement in manual treadmill training is a very strenuous task for the physiotherapists (which limits the training duration) and also results in an irregular and not completely physiological gait pattern, several developments were undertaken to automate the training and to increase its duration. One such automated treadmill training system is the Lokomat system,[10] which was developed and is in regular use at our rehabilitation center. Figure 1 shows the manual treadmill training (panel a) and the automated treadmill training with the Lokomat (panel b). Since 1999, more than 10 patients have gone through the regular Lokomat training that consisted of several weekly sessions (each having a duration of 1 h) over a period of 2–4 months. Current Lokomat training,
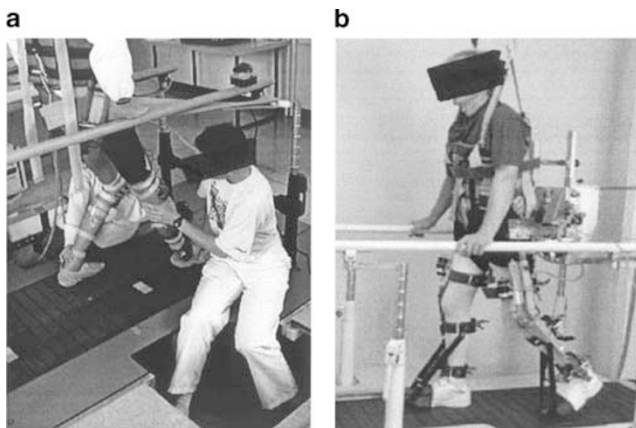
however, only provides treadmill training with a fixed gait pattern without the possibility for the patient to influence the way he/she is walking on the treadmill. To encourage the patients to walk more actively and to increase their motivation, algorithms have been developed that enable automatic gait-pattern adaptation during the Lokomat training. These algorithms are used (in combination with sensing of the remaining voluntary activity of the patient) to determine the change in the gait pattern that the patient would like to achieve. The gait pattern is adapted in an automatic way. The desired adaptation is determined as a solution of a nonlinear optimization (minimization) problem that is solved online. A thorough treatment of the theoretical aspects of the algorithms and some initial results are described in Jezernik et al.[11–13]

The goal of this work was a clinical evaluation of the two gait-pattern adaptation algorithms called DJATA1 and DJATA2 (DJATA stands for direct joint-angle trajectory adaptation). The evaluation took into account technical as well as subjective aspects. The latter were assessed based on a specially developed patient questionnaire.

Methods

Gait-pattern adaptation principle
The conventional Lokomat training is realized with a position controller that tracks reference hip and knee joint-angle trajectories. If the patient tries to change this reference movement and acts against the movement with his remaining voluntary activity, the controller is going to counteract the patient (from the 'viewpoint' of the controller the extra forces generated by the patient represent unwanted disturbances that cause deviations from the reference motion). The idea of the gait-pattern adaptation is, on the contrary, to allow the patient to change the controlled motion. The underlying principle of gait-pattern adaptation algorithms is that the gait pattern is adapted in a way that minimizes (reduces) the interaction between the Lokomat and the patient, so that the Lokomat 'yields' to the voluntary exerted patient forces. The Lokomat motion thus synchronizes with the desired patient movement. DJATA1 minimizes the interaction based on estimated desired angular acceleration changes. DJATA2 minimizes the interaction based on a so-called impedance control and on estimated desired angular changes. The interaction was estimated from the actuator force measurement.

Since the Lokomat training is based on nominal (reference) hip and knee angle trajectories, the adaptation of the gait pattern is achieved by changing these angle trajectories. To ensure that the adapted gait-pattern trajectories always result in a physiological gait pattern, the nominal hip and knee angle trajectories $\varphi_{i,\mathrm{Nom}}$ were parameterized each with three parameters: a_i (amplitude scaling), c_i (time stretch), and d_i (amplitude offset). $i = 1$ for hip and $i = 2$ for knee joint-angle trajectory. The parameters were used to calculate the

Figure 1 Panel a shows two physiotherapists performing a manual treadmill training with an SCI patient, whereas panel b shows an SCI patient during an automated treadmill training with the robotic orthosis Lokomat
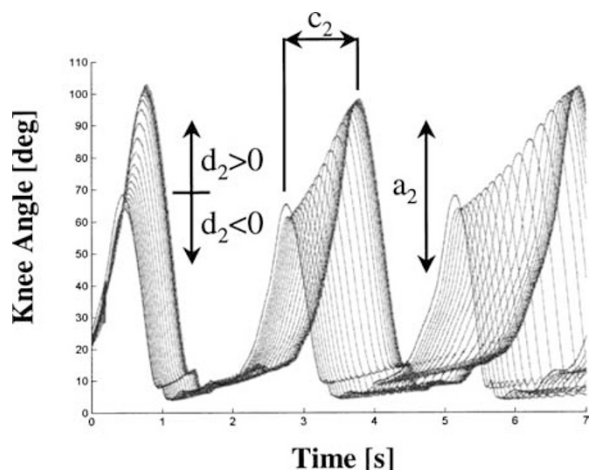
Figure 2 Depicted is a variation of the knee joint-angle trajectory that can be achieved by varying the introduced adaptation parameters a, c, and d. Parameter a (amplitude scaling) can increase or decrease the range of motion, parameter c (time stretch) can change the time period, and parameter d (amplitude offset) can shift the trajectory upwards or downwards

adapted angle trajectories φ_i in the following way:

$$\varphi_i = a_i \varphi_{i,\text{Nom}}\left(\frac{t}{c_i}\right) + d_i$$

The nominal parameter values are $a_i = 1$, $c_i = 1$, and $d_i = 0$.

The chosen parameterization was shown to be able to describe a large class of gait-pattern variations sufficiently well. The effect of varying the parameters a_2, c_2, and d_2 on the knee joint-angle trajectory is shown in Figure 2. The DJATA1 and DJATA2 algorithms adapted the gait pattern by adapting the values of the six parameters. The steepest descent method was used to solve on-line the nonlinear optimization problem and thus to calculate the adapted parameter values. Since the adaptation algorithms perform an on-line optimization, they actually provide a dynamic adaptation (dynamic tracking of the desired gait pattern). For additional technical details consult Jezernik et al.[11–13]

Experimental study design
The clinical study comprised five incomplete paraplegic and one incomplete tetraplegic patient. The study was approved by the local ethics committee and the patients have given a written consent to participate in the study. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Each experiment was carried out at a fixed treadmill speed that has ranged from 1.7 to 1.9 km/h across experiments (approximate stride periods were 2–2.5 s) and with an unloading that has ranged from 50 to 90%. The age, lesion heights, training parameters, and the ASIA motor and sensory scores of the participating patients are listed in Table 1.

Three different conditions were tested in the experiments. These conditions corresponded to trials 1–3 for DJATA1 and to trials 4–6 for DJATA2. The trials were conducted in two separate blinded experimental series per patient in a semirandomized order, since one full experiment would be too long and too tiring. Each experimental series (three trials) lasted about 1 h.

In condition 1 (trials 1 and 4), the patients were asked first to follow the motion of the Lokomat for 5 min (they had to try to synchronize their own gait pattern with the gait pattern of the Lokomat). During the next 5 min, they were asked to try to change the gait pattern in different ways. The changes belonged to a well-defined adaptation set (more/less hip flexion/extension, more/less knee flexion/extension, larger/shorter steps, faster/slower motion).

In condition 2 (trials 2 and 5), the patients had to follow the motion of the Lokomat for 2 min, then they had 8 min time to try to walk with their own, preferred gait pattern.

In condition 3 (trials 3 and 6), the patients had initially to follow an unphysiological gait pattern for 2 min, then they had 8 min time to try to walk with their own, more physiological gait pattern. The unphysiological gait pattern had an extensively scaled nominal hip motion (increased hip flexion and extension, scaled by 1.2) and a reduced knee flexion (scaled by 0.7 and added offset of $+4°$). The idea behind condition 3 was to demonstrate that an unphysiological gait pattern can

Table 1 Summarized data of the SCI patients who took part in the study

Pat. No.	Age (Years)	Height of the lesion	ASIA–motor score	ASIA–l. touch sensory score	ASIA–p. prick sensory score	Treadmill speed (km/h)	Percent of body-weight unloading (%)
1	73	C4	20	12	12	1.9	72
2	38	L2	50	82	82	1.9	27
3	58	T9	77	88	88	1.9	31
4	45	L2	58	94	88	1.9	61
5	46	C3/4	89	NA	NA	1.7	58
6	62	C7	96	67	27	1.9	83

NA, not applicable

be changed to a physiological one (by the use of a gait pattern adaptation algorithm).

The adaptation was switched on after 20 strides, which corresponded to a time of approximately 40 s. In case that for some reason the patient could not perform a trial for the full duration of 10 min, the trial duration was shortened by 1–4 min.

The data needed for later evaluation included trajectory parameters a_i, c_i, and d_i that corresponded to the gait-pattern adaptation. The force measurements were not collected and analyzed as the focus of the clinical study was on the achieved gait-pattern adaptation and not on the technical correctness of the gait-pattern adaptation algorithms. A quantitative assessment of interaction forces that has shown correct adaptation was performed earlier in computer simulations and in some pilot experiments with SCI and healthy subjects (where the extent of reduction of interaction forces was evaluated based on direct force measurement and based on calculation of special factors related to the functional that was minimized with the steepest descent method). These results were reported in Jezernik et al.[11–13]

Patient questionnaire Besides the analysis of the obtained parameter adaptation, we have also evaluated patient's subjective opinion about the achieved adaptation. For this purpose, a special questionnaire was developed. After each trial, the quality of adaptation was assessed (judged by the patient and ranked with 0 = bad, 1 = good, and 2 = very good with resolution of 0.5), and the patients were asked if they could perceive a difference between the initial and the adapted gait pattern. They were also asked how fast the adaptation was, if perceived, and what was their general well-being. Further, they had to quantify how exhausting each trial was for them. The Borg scale was used for the last question (0 = no effort, 5 = medium effort, 10 = maximally tiring, resolution = 1). The questions are summarized in Table 2.

Apart from the questions relating to the actual gait-pattern adaptation, several questions were also asked to determine the patient's motivation for treadmill training with gait-pattern adaptation versus training with fixed gait pattern. These included the following questions: (1) 'how do you judge the overall quality of the training with gait-pattern adaptation', (2) 'do you think that training *with* gait-pattern adaptation leads to better rehabilitation', and (3) 'in the future would you like to train with the fixed or with the adaptive gait pattern'. The patients also had to give reasons for their answer to the third question.

Analysis of the experimental data
The data analysis consisted of several calculations. To obtain a representative (average) adapted gait-pattern trajectory for conditions 2 and 3, an average of the parameters $a–d$ was calculated over the last 30 strides in

Table 2 List of questions from the patient questionnaire with the corresponding possible answers and the chosen ranking

Question	Answer	Ranking
1. Quality of adaptation	Bad	0
	Good	1
	Very good	2
2. Difference between the initial and adapted gait-pattern perceived	No	0
	Yes	1
3. Speed of adaptation	Slow	0
	Medium–fast	1
	Fast	2
	Very fast	3
4. Patient's general well-being	Very bad	0
	Bad	1
	So–so	2
	Good	3
	Very good	4
5. Physical effort (Borg scale)	Borg Scale	1–10

case the parameter values settled after the adaptation (Figure 3a), or over the last 60 strides in case the parameter values did not settle (Figure 3b).

To assess the variation of the parameter values around the nominal values, the following para-meter-variation root-mean-square (RMS) values were calculated two times: (a) after the adaptation was switched on but before the patient tried to change the gait-pattern, and (b) after the adaptation was switched on and after the patient tried to change the gait pattern):

$$PV_{\text{RMS}}(a_i) = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{Z}(a_i - 1)^2\right)},$$

$$PV_{\text{RMS}}(c_i) = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N}(c_i - 1)^2\right)},$$

$$PV_{\text{RMS}}(d_i) = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N}(d_i)^2\right)}$$

The number of strides N ranged from 76 to 253 across the calculations. The duration of the initial walking with switched-on adaptation, but no effort of the patient to change the gait pattern was about 2 min (equals to approximately 60 strides).

Furthermore, we also calculated the RMS differences between the adapted and the initial joint-angle trajectories (JAT-RMS)

$$JAT_{\text{RMS}} = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N}(\varphi_{\text{TR}_1} - \varphi_{\text{TR}_2})^2\right)}$$

The indices TR$_1$ and TR$_2$ stand for angle trajectory 1 and angle trajectory 2, respectively. The JAT-RMS was
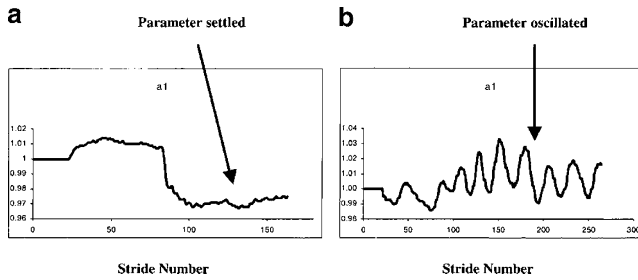
Figure 3 Experimentally recorded time course of the parameter a_1 in case where the parameter settled after the adaptation (panel a), and in case where the parameter value kept changing in a periodic way (panel b)

calculated over three strides with $N = 450$ for three TR_1/TR_2 combinations:

(1) $TR_1 = $ nominal trajectory/$TR_2 = $ adapted nominal trajectory;

(2) $TR_1 = $ nominal trajectory/$TR_2 = $ adapted unphysiological trajectory;

(3) $TR_1 = $ nominal trajectory/$TR_2 = $ unphysiological trajectory.

The last part of the experimental data analysis consisted of 'expert' evaluation (by the authors of this paper) of the recorded parameter adaptation observed in different conditions. In condition 1, the parameter adaptation could be judged quite easily, since it was known what kind of gait-pattern change the patient would like to achieve. In condition 3, we could see if the parameter adaptation led to a more physiological gait pattern. Condition 2 was more difficult to judge, since the preferred gait pattern was unknown *a priori*. Especially in this condition, but also in the other two, we have also judged the stabilization of the parameter values versus drift. All trials were analyzed according to the above criteria and afterwards ranked on the following scale: 0 = bad adaptation, 1 = good adaptation, 2 = very good adaptation (resolution = 0.5).

Statistical analysis

Patient questionnaire Statistical analysis of the ranked replies to questions from the patient questionnaire included calculation of the mean, median, standard deviation, and the nonparametric Wilcoxon test in order to test for significant differences between the experiments performed with the two algorithms DJATA1 and DJATA2.

Experimental data For the PV-RMS and JAT-RMS values, we have also calculated the mean, median, and the standard deviation. F- and *t*-test were performed afterwards in order to compare the parameter/joint-angle trajectory variation *before versus after* the actual adaptation.

The ranks assigned to the parameter adaptation in each trial (expert opinion) were analyzed in the same

way as the data stemming from the patient questionnaire (Wilcoxon's test). Table 2 summarizes different questions that were analyzed by ranking.

Results

Experimental results

The SCI subjects were able to influence the gait pattern with their remaining voluntary activity. The extent of gait-pattern adaptation depended, of course, on the force that they were able to produce. Usually, they could achieve large adaptation for periods of 5–8 min. In most cases, the patients were able to adapt the nominal gait pattern to be alike the desired one (condition 1), and they were satisfied with the outcome of the adaptation.

Most of the patients, however, had problems with following and adapting the unphysiological initial gait pattern (condition 3). Their feet (or one foot) hit the treadmill during the swing phase so that they were tripping over. We had to unload them almost completely to prevent this tripping, which was impossible to avoid entirely. Due to a large amount of unloading, the patients had difficulties in developing large moments in order to change the gait pattern. Therefore, in many cases the gait pattern remained unphysiological or sometimes even adapted to an even more unphysiological one. There were a few cases where the gait pattern became slightly more physiological.

Next, we will present a couple of typical experimental results based on figures showing the observed adaptation of the parameters. The six graphs in Figure 4 show
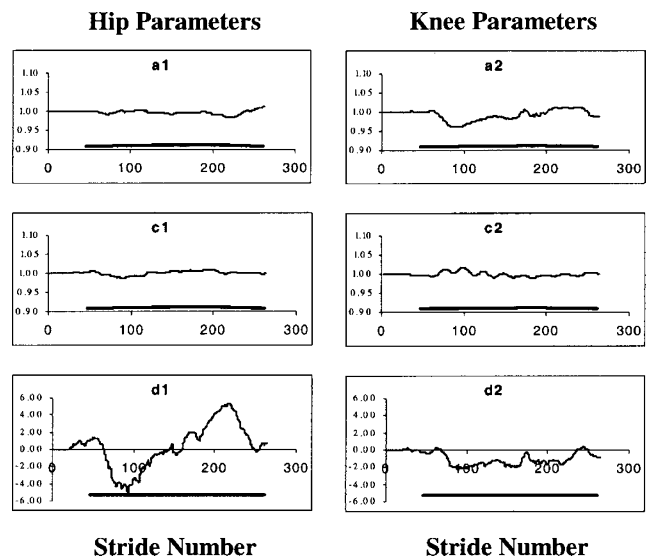

Figure 4 Experimental data consisting of six adaptation parameters for hip and knee joint-angle trajectories (hip parameters with index 1 shown in the left three graphs and knee parameters with index 2 shown in the right three graphs). Data stem from experimental condition 2 and algorithm DJATA2 (the time during which the patient tried to adapt the gait pattern to his own, preferred gait pattern, is indicated by bars)
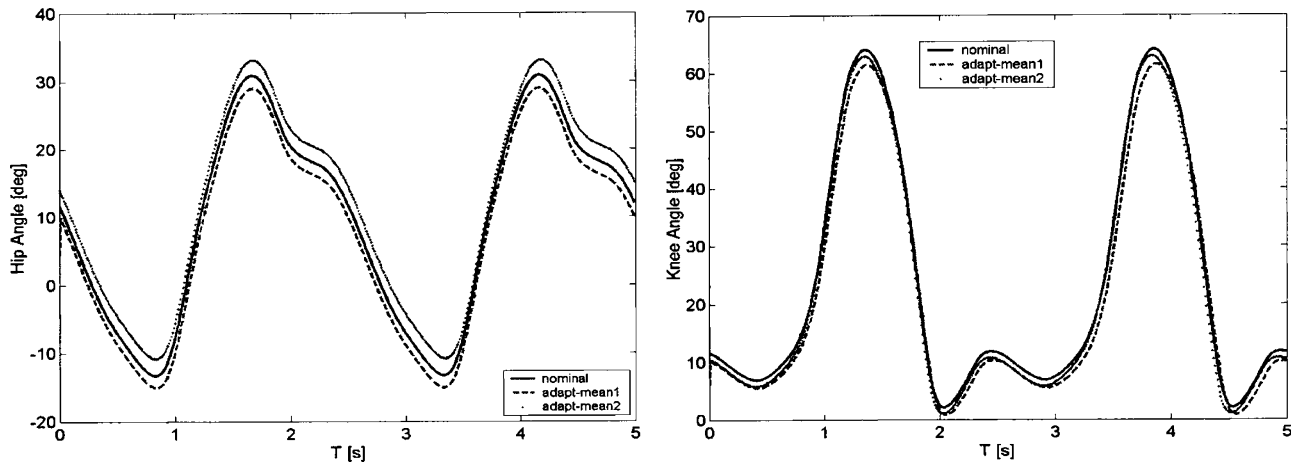
Figure 5 Mean adapted joint-angle trajectories calculated during strides 50–150 (dashed lines), and during strides 150–250 (dotted lines) from the adaptation experiment/parameters shown in Figure 4. Two different sets of mean trajectories were calculated as the two periods show a distinctive parameter adaptation

the time courses of the hip (a_1, c_1, d_1) and knee (a_2, c_2, d_2) adaptation parameters plotted against the stride number for condition 2, trial 5 (DJATA2). The time when the patient tried to adapt the nominal gait pattern to a preferred one is indicated by horizontal bars. A notable change in the parameters a_2, c_2, d_1, and d_2 can be observed. To get a better picture of how the changes in the parameters influenced the gait pattern in terms of joint angles, the two graphs in Figure 5 show the average hip (left) and knee (right) joint angles for two cases: (1) mean trajectory between strides 50 and 150 (plotted with dashed line) and (2) mean trajectory between strides 150 and 250 (plotted with dotted line). The nominal trajectories are plotted with solid line for comparison. Two different mean trajectories are shown as the parameter d_1 and partially also a_2 show a different behavior during these two periods. Negative d_1 during the first period shifted the nominal hip trajectory downwards, whereas positive d_1 during the second period shifted the nominal hip trajectory upwards (compare dashed and dotted lines). We can conclude that the desired gait pattern in this case was not the same during these two periods. The adaptation algorithm has tracked the desired gait pattern in a dynamic way, that is, the gait pattern was continuously adapted according to the dynamic interaction between the patient and the Lokomat, and this interaction was not constant but has changed with time.

Figures 6 and 7 show two examples of parameter adaptation during condition 1. Figure 6 represents trial 1 (DJATA1), where the patient first tried to walk faster (indicated by solid bars), then tried to increase the hip flexion (dashed bars), and finally tried to walk with shorter steps (double bars). During the first period, the parameters did not change much. During the second period, hip and knee flexion increased due to increased a_1, d_1, and a_2. During the third period, the hip and knee flexion decreased due to decreased a_1, d_1, and a_2. d_2 has increased, but the change in a_2 had a greater effect on
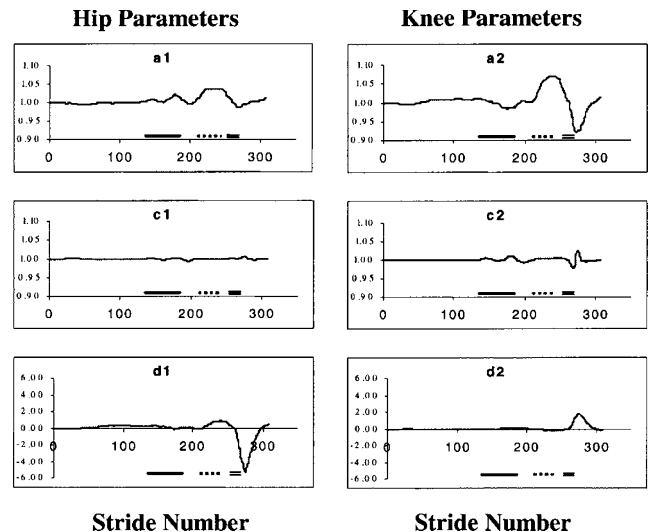

Figure 6 Experimental data consisting of six adaptation parameters for experimental condition 1 and DJATA1 algorithm. See text for more details

the decrease of the knee flexion. Figure 7 represents trial 4 (DJATA2), where the first three periods (solid bars, dashed bars, and double bars) are the same as in Figure 6, and where during the fourth period (double dashed bars) the patient tried to increase hip extension. During the first period, a_1 and d_1 have increased. The changes in parameters during the second and third period were, as expected, opposite and had the desired effect on the gait pattern. During the fourth period, d_1 has additionally decreased and the other parameters remained quite the same. Decreased d_1 means increased hip extension (as desired).

The shown examples demonstrate that the adaptation took place, and that in most cases it corresponded to a change in the gait pattern that the patient tried to achieve.
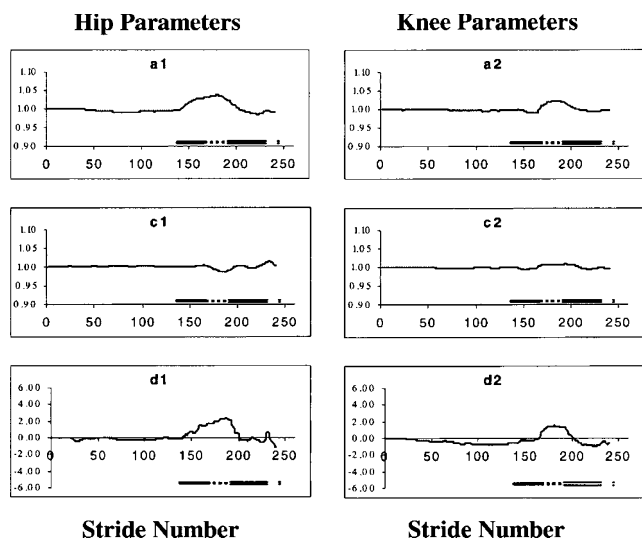
Hip Parameters   **Knee Parameters**

Stride Number   **Stride Number**

Figure 7 Experimental data consisting of six adaptation parameters for experimental condition 1 and DJATA2 algorithm. See text for more details
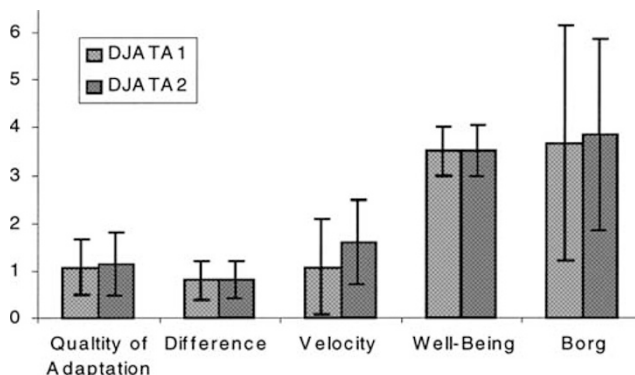

Figure 8 Bar graph showing the means (column bars) and standard deviations (lines) of ranked answers to the patient questionnaire (Table 2). The calculations were made across all experiments and separately for the two algorithms DJATA1 and DJATA2 to enable comparison

Statistical results

The statistical results concerning the patient questionnaire are shown in Table 3 and Figure 8 (left columns are plotted for data from DJATA1 and right columns for data from DJATA2). No statistically significant differences were found between the two algorithms. The average values for the quality of adaptation were 1.08 and 1.15 for DJATA1 and DJATA2, respectively, which indicates good adaptation. Most patients were also able to perceive a difference between the nominal and the adapted gait pattern (mean = 0.8 for both algorithms). They stated that the adaptation occurred medium–fast to fast (mean = 1.08 and 1.58), which meant that the gait pattern adapted to a new one after four to six strides (8–12 s). In all cases, the well-being of the patients was between good (3) and very good (4). The mean effort of trials was 3.66 and 3.82 for DJATA1 and DJATA2 respectively (middle effort).

Table 4 shows the mean values of the parameter variation RMS (PV-RMS) calculated for all the six parameters and for both the algorithms, DJATA1 and DJATA2, before (left column) and after (right column) the patient tried to change the gait pattern. Statistically significant changes in PV-RMS are indicated by asterisks. The average values were almost always greater in the right than in the left column, and were in DJATA2 significantly greater in five out of six cases,

Table 4 Mean values of the PV-RMS before the patient tried to change the gait pattern (first and third columns), and during gait pattern adaptation (second and fourth columns)

	DJATA 1: mean PV-RMS		DJATA 2: mean PV-RMS	
	Before adapt.	After adapt.	Before adapt.	After adapt.
a_1	0.006	0.016*	0.005	0.021**
c_1,	0.001	0.004*	0.003	0.016**
d_1	0.503	0.702	1.050	1.772*
a_2	0.030	0.028	0.003	0.016**
c_2	0.001	0.006**	0.003	0.020**
d_2	0.288	0.348	0.683	0.902

A paired t-test was made to analyze if the parameter variation significantly increased after the patients tried to adapt the gait pattern. The t-test was made for each parameter separately Statistical significance is indicated by **($P < 0.05$) or by *($P < 0.1$)

which demonstrates that significant adaptation took place.

Table 5 shows the means and standard deviations of the differences between the nominal and adapted joint-angle trajectories (in degrees). The mean differences were higher for DJATA2 (2.09 and 2.71° for hip and knee angle trajectories, respectively) than for DJATA1 (0.69 and 1.20°). The differences between the nominal and unphysiological angle trajectories (2.67/1.68 and 6.74/8.59° for hip and knee angle trajectories,

Table 3 Means ± SDs calculated from the ranks from the patient questionnaire (Table 2) across all DJATA1 and DJATA2 trials and across all SCI subjects

	Quality of adaptation	Difference init./adapt. gait pattern	Speed of adapt.	General well-being	Borg scale
DJATA1	1.08 ± 0.59	0.80 ± 0.41	1.08 ± 0.99	3.50 ± 0.51	3.66 ± 2.47
DJATA2	1.15 ± 0.65	0.80 ± 0.41	1.58 ± 0.90	3.52 ± 0.51	3.82 ± 2.02

Table 5 For conditions 2 and 3, also the RMS differences between the nominal and adapted joint-angle trajectories were calculated

	Nom-adapt DJATA1	Nom-adapt DJATA2	Nom-adapt unphys. DJATA1	Nom-adapt unphys. DJATA2	Nom-unphys. DJATA1	Nom-unphys. DJATA2
Hip	0.69 + 0.35	2.09 + 1.51	1.68 + 0.53	3.00 + 0.82	2.67 + 3.63	1.68 + 0.58
Knee	1.20 + 1.02	2.71 + 2.81	6.57 + 2.40	8.41 + 1.42	6.74 + 2.76	8.59 + 1.93

Means ± SDs for hip and knee trajectories and for condition 2 (first two columns), condition 3 (third and fourth column), as well as initial RMS differences between the unphysiological and nominal trajectories (last two columns)
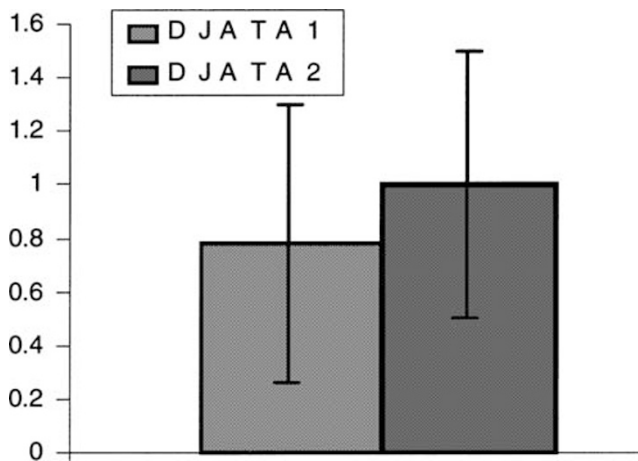

Figure 9 Bar graph showing the means (column bars) and standard deviations (lines) of ranks given for the quality of parameter adaptation by experts (separate calculations for DJATA1 and DJATA2 algorithms)

respectively) did not decrease much or effectively decrease after the adaptation (1.68/3.00 and 6.57/8.41°) for DJATA1/DJATA2 algorithms.

The last statistical analysis dealt with the evaluation of the expert opinion of the quality of adaptation (based on parameter adaptation). The mean results are shown in Figure 9 together with standard deviations (mean ± SD = 0.78 ± 0.52 and 1.00 ± 0.50 for DJATA1 and DJATA2, respectively). The difference in means was not statistically significant. The means were close or equal to the ranking good (good = 1).

Patient motivation
All patients have noted (perceived) the gait-pattern adaptation and have, on average, judged it as good (see above). Furthermore, they all thought that the training modality with gait-pattern adaptation will lead to better rehabilitation outcome, and they would all prefer to train with the new training modality in the future. The given argumentation for the training with gait-pattern adaptation included the following reasons: (a) they can train with their own gait pattern; (b) the training with gait-pattern adaptation is more comfortable; (c) it is possible for them to train more actively (with more

active effort); and (d) they are able to vary the gait pattern and therefore walk in a more differentiated way.

Discussion and conclusions

The aim of the clinical study was to evaluate the performance of the two algorithms for automatic gait-pattern adaptation for automated treadmill training. The emphasis was not only placed on the analysis of the performance, but maybe even more importantly, on the patient's opinion and motivation. The study has shown the feasibility of gait-pattern adaptation, demonstrated good algorithm performance, and revealed that in the future the patients prefer to train with the gait-pattern adaptation (versus conventional training with fixed gait pattern).

It is important to remember that the subjects who want to adapt their gait pattern necessitate sufficient residual motor capacity to do so. If they do not posses this capacity, they will not be able to change the gait pattern. Therefore, the training with gait-pattern adaptation is meant only for incomplete SCI patients with sufficient remaining motor capacity. Since the algorithms have been successfully tested in extensive computer simulations and also with the healthy subjects, it is clear that if an SCI patient fails to generate the desired gait-pattern adaptation, then the cause for this is his insufficient motor capacity and not the algorithm failure. It is true that the disability limits the ability of the patient to generate enough force to change the gait pattern, but the patient still knows well in which way he/she wants to change the gait pattern.

The algorithm DJATA2 performed slightly better than DJATA1, but the differences derived from the performed analysis were not statistically significant. However, the adaptation of the gait pattern was more significant in the case of DJATA2 than DJATA1 (based on PV-RMS analysis), but this might have been a consequence of a higher chosen sensitivity in the case of DJATA2 algorithm. It was not possible to exactly equalize the two sensitivities as they depend on different factors and algorithm properties. In the opinion of the authors and according to additional testing and simulation results, DJATA2 should be preferred and is therefore recommended to be used in the future.

The problems that the patients experienced when trying to change the initial unphysiological gait pattern
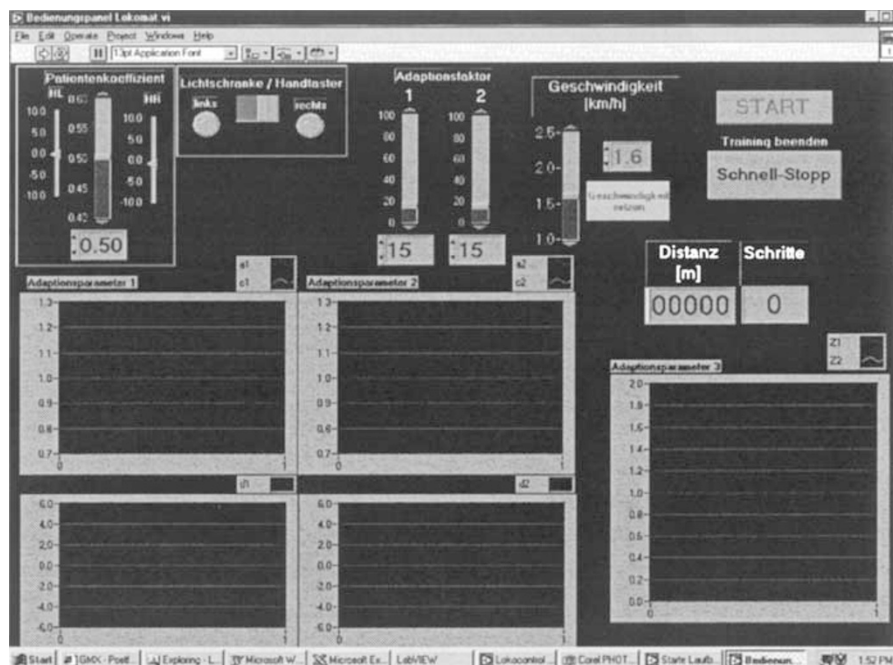
Figure 10 Graphical user interface (GUI) for the adaptive gait-pattern rehabilitation as used by physiotherapists. The interfaces in the top right allow the physiotherapists to start and stop the training, to change the treadmill speed, and to change the extent of gait-pattern adaptation. The adaptation parameters are shown in four bottom-left windows

(condition 3) can partially be explained by the fact that the unphysiological gait pattern prevented the patients to exert sufficient forces onto the Lokomat in order to adapt the gait pattern. However, treadmill training with unphysiological gait pattern anyway does not make much sense, and during an actual training the patients only have to adapt the initial nominal gait pattern.

Currently, the adaptation algorithms assume symmetry between the left and right legs. The present software/hardware estimates the interaction only on one body side/one leg (there exist, however, a software switch that allows us to use either the force measurements from the left or from the right leg). In the future, the adaptation algorithms will possibly be adapted to allow independent adaptation of the left and right leg trajectories (except for parameters c, which are related). However, unsymmetrical gaits are energetically nonoptimal and undesired because of other reasons (balance, comfort, smoothness of the movement, internal torques/ forces). Regarding this issue, we would also like to mention that we have developed another adaptive training concept for treadmill training of stroke patients,[14] which takes into account the existing asymmetry between the kinematics of the healthy and impaired legs. We believe that the asymmetry is more important in the case of stroke than in the case of SCI patients.

On the basis of the presented results, it can further be concluded that the treadmill training with gait-pattern adaptation increases the motivation of the patient and gives him/her the feeling that they are controlling the machine versus that the machine is controlling them. Gait-pattern adaptation also increases and promotes active training, which might lead to better rehabilitation outcome. The latter hypothesis will need to be tested in further clinical studies that will also include EMG measurements and follow-up of the rehabilitation outcome for different experimental groups (conventional versus adaptive treadmill training).

With a simple but powerful graphical user interface (Figure 10) developed for the physiotherapist (that also allows the gait-pattern adaptation to be switched off, so that a training with a fixed gait pattern can be done with the same software and that as well allows adjustment of the adaptation sensitivity), the gait-pattern adaptation will most likely substitute the current treadmill training modality in the future.

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