Computerized visual feedback: an adjunct to robotic-assisted gait training

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Abstract

BACKGROUND AND PURPOSE: Robotic devices for walking rehabilitation allow new possibilities for providing performance-related information to patients during gait training. Based on motor learning principles, augmented feedback during robotic-assisted gait training might improve the rehabilitation process used to regain walking function. This report presents a method to provide visual feedback implemented in a driven gait orthosis (DGO). The purpose of the study was to compare the immediate effect on motor output in subjects during robotic-assisted gait training when they used computerized visual feedback and when they followed verbal instructions of a physical therapist. SUBJECTS: Twelve people with neurological gait disorders due to incomplete spinal cord injury participated. METHODS: Subjects were instructed to walk within the DGO in 2 different conditions. They were asked to increase their motor output by following the instructions of a therapist and by observing visual feedback. In addition, the subjects’ opinions about using visual feedback were investigated by a questionnaire. RESULTS: Computerized visual feedback and verbal instructions by the therapist were observed to result in a similar change in motor output in subjects when walking within the DGO. Subjects reported that they were more motivated and concentrated on their movements when using computerized visual feedback compared with when no form of feedback was provided. DISCUSSION AND CONCLUSION: Computerized visual feedback is a valuable adjunct to robotic-assisted gait training. It represents a relevant tool to increase patients’ motor output, involvement, and motivation during gait training, similar to verbal instructions by a therapist.
Background and Purpose. Robotic devices for walking rehabilitation allow new possibilities for providing performance-related information to patients during gait training. Based on motor learning principles, augmented feedback during robotic-assisted gait training might improve the rehabilitation process used to regain walking function. This report presents a method to provide visual feedback implemented in a driven gait orthosis (DGO). The purpose of the study was to compare the immediate effect on motor output in subjects during robotic-assisted gait training when they used computerized visual feedback and when they followed verbal instructions of a physical therapist.

Subjects. Twelve people with neurological gait disorders due to incomplete spinal cord injury participated.

Methods. Subjects were instructed to walk within the DGO in 2 different conditions. They were asked to increase their motor output by following the instructions of a therapist and by observing visual feedback. In addition, the subjects’ opinions about using visual feedback were investigated by a questionnaire.

Results. Computerized visual feedback and verbal instructions by the therapist were observed to result in a similar change in motor output in subjects when walking within the DGO. Subjects reported that they were more motivated and concentrated on their movements when using computerized visual feedback compared with when no form of feedback was provided.

Discussion and Conclusion. Computerized visual feedback is a valuable adjunct to robotic-assisted gait training. It represents a relevant tool to increase patients’ motor output, involvement, and motivation during gait training, similar to verbal instructions by a therapist.
Restoration of walking is an important part of the rehabilitation process for patients with neurological disorders such as spinal cord injury, stroke, and traumatic brain injury. Locomotor training with partial body-weight support is a commonly used intervention to improve walking ability.1–4 Because manually assisted treadmill training is strenuous work for the therapist and because reproducible gait patterns are difficult to induce, various mechanized devices have been developed to optimize gait training and to reduce the physical strain on the therapist.5–8 Although positive effects of such devices on rehabilitation outcome have been demonstrated,9–12 one of the major concerns of therapists about robotic-assisted gait training is the lack of information about the activity of patients when walking with such devices. Additionally, most devices for automated gait training provide passive guidance during walking and, therefore, may reduce the voluntary participation of individuals during training.13

The Lokomat* driven gait orthosis (DGO) is one of the devices that have been developed to conduct robotic-assisted gait training with partial body-weight support and a treadmill.7,9,10,12,14 To overcome the limitations of robotic-assisted gait training, the Lokomat DGO was instrumented with sensors to measure human-machine interaction forces in order to estimate the activity of a patient. With this equipment, the DGO offers new possibilities to provide performance-related feedback to the patient and therapist during robotic-assisted gait training.15–17 The first version of a feedback method for the DGO has been presented and tested for its practicability with a limited number of subjects without gait impairments.15 The purpose of the current study was to compare the immediate effect on motor output in subjects during robotic-assisted gait training when observing visual feedback and when following verbal instructions of a therapist. In addition, the opinions of the subjects about the feedback method and the potential benefits of using computerized visual feedback during gait training were investigated.

Method

DGO

The Lokomat DGO is a bilateral robotic gait orthosis that is used in conjunction with a body weight-support system to control a patient’s leg movements in the sagittal plane (Fig. 1). The hip and knee joints of the DGO are actuated by linear drives, which are integrated into an exoskeletal structure. The legs of the patient are moved with predefined hip and knee joint trajectories.7,16

Visual Feedback Method for the DGO

The feedback of the DGO is based on the interaction torques between the patient and the orthosis. For this purpose, the hip and knee linear drives are equipped with force sensors (Fig. 1, insert). These sensors measure the force that is required to keep the patient on the predefined gait trajectory. For this strategy, the patient’s legs are guided with high impedance (i.e., the movement of the legs is 100% supported by the DGO). With this high stiffness, changes in the patient’s behavior are best detectable because small deviations lead to large counteracting forces. The interaction forces are transformed online to interaction torques based on the geometry of the force sensors and the exoskeleton. If a patient could perfectly match the movement of the device, the interaction torques would be zero. The interaction torques change depending on voluntary muscle activation of the

* Hocoma AG, Industriestrasse 4, CH-8604, Volketswil, Switzerland.

Figure 1.
The Lokomat driven gait orthosis. The Lokomat system consists of a treadmill, a body weight–support system, and the driven gait orthosis. The visual feedback is presented on a patient monitor and on a monitor for the therapist. Insert: The exoskeletal structure with force sensors in the hip and knee linear drives (arrows). Photo courtesy of Hocoma AG, Volketswil, Switzerland.
patient or involuntary contractions such as excessive reflex activity (Fig. 2A).

By definition, a positive torque is measured when the movement of the patient is corrected by the DGO in the direction of joint extension, and a negative torque is measured when the movement of the patient is corrected in the direction of joint flexion. The interaction torques are multiplied by corresponding weighting functions for each joint and step cycle (Figs. 2B–D). The purpose of the weighting functions is to provide positive feedback values for desired movements and negative feedback values for undesired movements. In addition, different sections of the gait cycle are weighted differently. Sections with

Figure 2. Calculation of the hip feedback value. (A) For demonstration purposes, a subject without neurological gait disorders was walking with full activity (black lines) and behaved passively (blue lines). Thirty strides are displayed for both conditions. Initial contact is at 0% of the gait cycle, and toe-off is at 55% of the gait cycle (vertical line). To calculate a feedback value, the hip torque of one step cycle (B) is multiplied with its corresponding weighting function (C). The resulting feedback curve is averaged for the stance and swing phases separately (D).
higher joint angular velocities have more weight, given that the patient has to work harder where the joint angular velocity is high.

Mathematically, the weighting function is the first derivative of the joint angular position for the hip joint during stance phase and swing phase and for the knee joint during swing phase. For the hip, a cosine function was introduced during the mid-swing phase to reduce the weight of that particular section, where interaction torques are partly due to passive components rather than muscle activity (Fig. 2C). The weighting function of the knee during the stance phase is set constant to reward knee extension. The product of joint torque and weighting function is averaged for the swing phase and stance phase of each joint (Fig. 2D). The windows for averaging are (in percentage of the step cycle): 0% to 50% for the hip stance phase, 55% to 82% for the hip swing phase, 0% to 50% for the knee stance phase, and 51% to 90% for the knee swing phase. These averages are compensated for the passive components of the DGO. Following this procedure, 8 different feedback values result for one step cycle: right hip during stance and swing phases, left hip during stance and swing phases, right knee during stance and swing phases, and left knee during stance and swing phases (Fig. 3).

Due to the weighting and averaging of the joint torques, the feedback values are arbitrary units. However, the feedback values are closely related to the measured joint torques. The feedback values are displayed as line graphs on the patient monitor and on the monitor for the physical therapist. Additionally, for the patient, there is the option to display the feedback as a smiley face, which changes according to the feedback values, or as a thermometer, which indicates the feedback values. The feedback can be displayed as an average of all 8 individual values or by selecting a subset of feedback values (eg, knee extension of the left leg during the stance phase).

Subjects
Twelve subjects (5 female, 7 male) with neurological gait disorders due to sensorimotor incomplete spinal cord injury (iSCI) participated in the study. They had an average weight of 68 kg (SD=8), an average height of 169 cm (SD=10), and an average age of 51 years (SD=17). The subjects were classified according to the American Spinal Injury Association Impairment Scale (AIS). Six subjects were classified as AIS C, and 6 subjects were classified as AIS D. The median of time postinjury was 15
months, ranging from 7 weeks to 25 years. All subjects were being treated as inpatients or outpatients in our rehabilitation clinic. As a part of their rehabilitation program, they performed gait training with the DGO for 30 to 40 minutes twice a week. The subjects had a mean of 9.6 weeks (SD = 6.8) of experience training with the DGO. We only recruited subjects with at least minimal voluntary control of their lower-extremity muscles to ensure that they had the ability to respond and to adapt their walking in order to influence the feedback values. The treating physical therapists judged the ability of the subjects to voluntarily control their lower extremities (ie, at least minimal movement in hip and knee joints was observed upon instruction). Subjects were recruited over a period of 19 months. All of the subjects who fulfilled the requirements took part in the study. None of these subjects was excluded from the analysis. All subjects gave written informed consent before inclusion in the study.

**Measurements**

Measurements were conducted during the subjects’ regular training sessions with the DGO in our rehabilitation clinic. The treadmill speed was set for each subject individually according to the treadmill speed of the last training session. The average speed was 0.55 m/s (SD = 0.08 m/s) with the lowest possible body-weight support (where knee buckling was still prevented for passively behaving subjects). The impedance for the DGO control program was set to maximum (ie, the “guidance force” was set at 100%).

Five measurements were conducted. Measurements 1, 3, and 5 were reference measurements (REF1, REF2, and REF3) where subjects were in-

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Figure 4.

Averaged single-joint feedback values of 12 subjects with incomplete spinal cord injury. Single-joint feedback values were averaged for each measurement individually for all 12 subjects. Five conditions are shown: 3 reference measurements (REF), one measurement where the subjects were visually observing the feedback values (VIS), and one measurement where the subjects were following the instructions of a therapist (THER). One line represents one subject.
structed to behave passively and not to contribute to the imposed movement of the DGO. Between the reference measurements, the subjects were instructed to enhance their contribution to the movement in 2 conditions. In one condition, the visual feedback unit was turned off for the subjects and the treating therapists. The therapists instructed and motivated the subjects to execute the stepping movement (THER). The instruction referred mainly to knee and hip extension during the stance phase and to hip flexion at the initiation of the swing phase. During the second condition, the subjects had to change their walking performance by increasing their feedback values, which were displayed on their monitor (VIS). The feedback was displayed with line graphs for all joints during the stance and swing phases. The subjects were instructed mainly to enhance their motor output in all joints where they observed low feedback values. The order of therapists’ instruction (THER) and the visual feedback (VIS) was randomly determined. During the measurements, joint angles were recorded using potentiometers and force signals obtained with force sensors at the hip and knee drives of the DGO. Heel-strike trigger signals were determined by the combination of joint angles. In each condition, 30 seconds (approximately 14 strides) of data were recorded at a sampling rate of 100 Hz. After the measurements, the subjects completed their training session with a total duration of 30 to 40 minutes and experienced 2 further options of the visual feedback display, namely the smiley face and the thermometer.

Data Processing

Data processing was conducted using Matlab 7.0.1 software.† All recorded forces were transformed to torques based on the geometry of the linear drives. The feedback values were calculated offline according to the computation of the Lokomat Pro software version 4.24 described above and elsewhere.17 Eight feedback values were calculated for each recorded stride (bilateral hip and knee joints during the stance and swing phases) in every condition (REF1, REF2, REF3, THER, and VIS). The calculated averages are illustrated in Figure 4, where one line represents one subject. The number of subjects with an increase of feedback values during the THER and VIS conditions (compared with the antecedent reference condition) was counted for each joint and for the stance and swing phases.

To describe the overall walking performance of each subject, the mean of all 8 feedback values was calculated for each step, providing a single feedback value for every stride. Thereafter, the mean of all feedback values during one measurement was calculated. This provided one feedback value to describe the performance during each of the 5 measurements (REF1, VIS, REF2, THER, and REF3). This procedure was repeated for each of the 12 subjects (Fig. 5).

Data Analysis

For each subject, the feedback values for each measurement (approximately 14 step cycles) were averaged bilaterally for the hip and knee joints during the stance and swing phases in every condition (REF1, REF2, REF3, THER, and VIS). The calculated averages are illustrated in Figure 4, where one line represents one subject. The number of subjects with an increase of feedback values during the THER and VIS conditions (compared with the antecedent reference condition) was counted for each joint and for the stance and swing phases.

† The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.
Table.
Subjects’ Opinions About Visual Feedback

<table>
<thead>
<tr>
<th>Statement</th>
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<tbody>
<tr>
<td>Training with visual feedback was motivating (compared with training without any form of feedback)</td>
<td>6</td>
<td>6</td>
<td></td>
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<tr>
<td>I could better concentrate on my walking when using visual feedback (compared with training without feedback)</td>
<td>6</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The biofeedback reflected my activity</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>I want to use the biofeedback again during the training</td>
<td>9</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I wish for more scenarios for the visual display of the biofeedback</td>
<td>3</td>
<td>3</td>
<td>6</td>
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* The feedback method was evaluated in 12 subjects with incomplete spinal cord injury using a written questionnaire. + + = strong agreement with the statement presented on the left side, + = agreement with the statement presented on the left side, - = agreement with the statement on the right side, -- = strong agreement with the statement on the right side.

Subjects’ Opinions About the Visual Feedback

After the measurements and after training with further visual feedback options (smiley face and thermometer) in the DGO, the subjects communicated their opinions about the visual feedback method via completion of a written survey covering such aspects as motivation, validity, and visual display options (Table).

Role of the Funding Source

This project was conducted at Balgrist University Hospital of the University of Zurich, which employed the researchers who designed and conducted the study and prepared the manuscript. Funding was received from the Swiss Bureau of Education and Technology, Switzerland, and Hocoma AG, Volketswil, Switzerland, which produces the Lokomat, via Commission for Technology and Innovation projects, as well as from the Swiss National Science Foundation, Switzerland, via the National Center of Competence in Research on Neural Plasticity and Repair (NCCR Neuro P7).

Results

Figure 3 shows the motor output (measured as feedback values) of one subject for every step during the measurements, bilaterally for the hip and knee joints during the stance and swing phases. The values markedly increased when the subject followed the instructions of a therapist or when he observed the visual feedback compared with the reference measurements. The effect also was observed but was less prominent in the hip during the stance phase. Feedback values increased in the VIS and THER conditions for the knee during the swing phase but not during stance phase. For all joints, the magnitude of effect was similar for the THER and VIS conditions.

Figure 4 provides a detailed overview of the effects of using visual feedback and following verbal instructions of a physical therapist for all 12 subjects. For the left hip during the stance phase, increases in feedback values (mean of approximately 14 feedback values of individual steps) were observed in 11 subjects during the VIS condition and in 10 subjects during the THER condition. For the right hip, 11 subjects increased their feedback values in both conditions. For the hip during the swing phase, 10 subjects increased their feedback values on the left leg in the VIS and THER conditions, 8 subjects increased their feedback values on the right leg in the VIS condition, and 9 subjects increased their feedback values on the right leg in the THER condition. For the left knee during the stance phase, 7 subjects increased their feedback values in the VIS condition and 5 subjects increased their feedback values in the THER condition. For the right knee during the stance phase, 6 subjects increased their feedback values in the VIS condition and 5 subjects increased their feedback values in the THER condition. During the swing phase, 6 subjects were observed to increase their feedback val-
ues for the left and right knees in both the VIS and THER conditions.

In Figure 5, the hip and knee feedback values during the stance and swing phases are averaged for each subject to describe the subjects’ overall walking performance. Averages are displayed for 5 conditions. Statistically, the reference conditions and the THER and VIS conditions were significantly different (Friedman test, \( P < .001 \)). There were no differences among the 3 reference conditions (Friedman test, \( P = .78 \)) and between the VIS and THER conditions (Wilcoxon signed rank test, \( P = .58 \)). Higher feedback values were observed in the VIS condition (compared with the previous condition; Wilcoxon signed rank test, \( P < .01 \)) and in the THER condition (compared with the previous condition; Wilcoxon signed rank test, \( P < .01 \)).

All subjects reported that they were more motivated and that they could better concentrate on their walking when using the visual feedback compared with when no feedback was provided during the training. They also reported that they wanted to train again using the visual feedback. Eleven subjects communicated that the visual feedback reflected their activity accurately. One subject reported no coherence between voluntary effort and feedback values. Three subjects reported that they wished for more scenarios to display the feedback. Detailed results are shown in the Table.

Discussion

The aims of this work were to present a computerized visual feedback method for gait rehabilitation with a robotic device and to compare the effect on motor output of using visual feedback and following instructions of a physical therapist during robotic-assisted gait training in subjects with neurological gait disorders due to iSCI. In addition, the subjects’ opinions about the robotic-assisted gait training with visual feedback were investigated.

The main result was that subjects with iSCI achieved a similar increase in motor output during robotic-assisted gait training when they increased their voluntary contribution to the movement by observing the visual feedback or by following the instructions of a physical therapist. The most distinctive changes in motor output were observed in the hip joint during the swing and stance phases, whereas only minimal changes were observed for the knee. All subjects reported that visual feedback improved their motivation and concentration during the training compared with when no form of feedback was provided. Eleven subjects communicated that the visual feedback reflected their activity well, whereas 1 subject saw no coherence between the feedback values and his performance. In general, the subjects were satisfied with the number of scenarios for displaying the feedback; 3 subjects wished that there were more visual scenarios to display the feedback.

To our knowledge, the presented feedback approach is the first that has been developed for robotic-assisted gait training. Feedback systems exist for nonrobotic gait rehabilitation. Several strategies were based on electromyography (EMG). Evidence for the benefit of EMG feedback has been described but is controversial. Electromyographic feedback requires long preparation times and, therefore, is hardly applicable for daily gait training. In addition, EMG measures only the signal of single muscles, information about the resulting net joint torque is missing. In contrast, the feedback in the DGO is based on robot-patient interaction torques directly related to the actual limb movement. It has been shown that EMG may not always be the best feedback source for illustrating motor control during dynamic movements. As opposed to EMG feedback, the presented torque-based approach does not require any additional preparation time for patients and therapists.

Clinical Significance

With the introduction of robotic-assisted devices, the physical strain for the therapist to conduct locomotor training using partial body-weight support with a patient with neurological gait disorders was greatly reduced. However, the direct manual contact between the therapist and the patient is lost with robotic devices, and the patient’s performance is difficult to estimate. With the high body-weight support and the high impedance of the fixed leg trajectory imposed by the DGO, the patient has the possibility to follow the gait movement in an almost passive manner without actively contributing to the conductance of iterative step cycles. This situation should be avoided because passive guidance was shown to be less effective than active training for motor learning. The presented feedback detects different walking behaviors of the patient and, therefore, allows an observation of the patient’s performance during gait training. The present study showed that using visual feedback (as well as instructions by a therapist) increased the motor output mainly in the hip during the stance and swing phases. This is of special importance for the swing phase because it has been shown that the hip flexors might not be activated accurately with passive guidance during training with the DGO.

The motor output of patients can be increased either by instruction and verbal motivation by a physical therapist or by visual feedback. The rationale for using visual feedback is certainly not to replace the physical
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therapist, but rather to add another dimension to the training. The patient is able to directly observe his or her motor behavior on a display in real time and, therefore, is actively involved in the evaluation process as opposed to receiving instructions from another person. The therapist is relieved from constantly instructing and motivating the patient during the training session. Computerized visual feedback offers the opportunity to increase the patient’s responsibility during the training and to conduct patient-centered training. With various visual display options as well as targeted verbal instructions from the therapist, training sessions with the DGO can be diversified and, therefore, might maintain the motivation and motor output of the patient during this highly repetitive exercise.

The presented feedback method has the potential to optimize gait rehabilitation by following the current opinion on motor learning. Skill acquisition with instructions on an external focus has been shown to be superior to skill acquisition with instructions on an internal focus. In addition, feedback that directs the learner’s attention to the effects of his or her movement have been shown to be more beneficial than feedback directing the learner’s attention to the movement itself. These principles often are not used in rehabilitation or are difficult to achieve when complex skills such as walking are trained. The presented visual feedback method offers a new way to achieve these required principles for gait training by displaying the patient’s performance as a remote effect. Assuming that the general and robust phenomenon of the beneficial effect of feedback with an external focus observed in people who are healthy and in people with stroke also applies to people with neurological gait disorders, the visual feedback of the DGO would allow a more optimal training regimen for gait rehabilitation.

A further finding of motor learning research is that the perception of self-control during training enhances learning and that there appear to be benefits from self-controlled feedback in physical therapy. The visual feedback allows the patient to be actively involved in the learning process, which probably leads to deeper processing of relevant information. In addition, the therapist can let the patient decide what type of feedback should be displayed and when it should be displayed. This approach could even be extended in future versions of the computerized feedback in order to let the patient choose the display option directly with a mouse click or on a touch screen.

With visual feedback, it is possible for the patient and the therapist to observe one specific aspect of the gait cycle (eg, flexion of the right hip during the swing phase), a summary of aspects of the gait cycle (eg, extension of the left leg during the stance phase), or an average of all feedback values to describe the overall motor output. This flexibility allows a more variable training regimen, which has been shown to be beneficial. However, summation of the information on different joints into a single feedback value might be a more effective way of providing feedback by avoiding information overloading.

Motivation and attention are key factors in the success of therapies to induce neuroplasticity. The subjects with iSCI in the current study reported that they were more motivated when using visual feedback compared with the condition where no feedback was provided. The subjects were not asked whether they preferred visual feedback to verbal feedback, and we, therefore, cannot conclude whether one of the feedback methods was more motivating for the subjects. However, as stated previously, both methods had the same effect on immediate motor output.

Changes in motor output were measured with forces that were executed by the subjects against the exoskeletal device. Theoretical assumptions were used to process and translate these force data into feedback values, and the results, therefore, might be limited. However, the feedback values reflect the mechan-
ical work that is necessary to guide the patient, and we consider the method the most appropriate way to estimate the motor output of patients during walking within the DGO.

Figures 4 and 5 show that the majority of feedback values were in the negative range, even when the subjects were conducting the stepping movement correctly, there seems to be an offset resulting in feedback values that are too far in the negative range. This offset can be compensated for by using another display (ie, the smiley face) where minimal and maximal values can be adjusted by the therapist to fit to the walking ability of each patient individually. However, the feedback calculations should be improved in order to provide positive feedback values for a good walking performance and negative values for poor walking ability.

Figures 3 and 4 show that the feedback method was sensitive enough to discriminate different walking behaviors in the hip during the stance and swing phases, where an increase in the subjects’ walking performance generally resulted in higher feedback values. However, changes in feedback values of the knee joint during the stance phase were minimal. The following reason might account for that observation: the knee is extended during that section of the gait cycle. With an extended knee joint, the lever contributing to the joint torque is small. Therefore, changes in the force might be canceled out by these small levers.

The feedback calculation is based on information of 4 force sensors that are integrated in the linear drives of the DGO. The calculation of a relevant feedback signal using this small number of parameters is challenging, and the accuracy and sensitivity of this system are limited. On the other hand, feedback based on more information would require more sensors and hardware costs would increase. Therefore, it was the aim to create a simple, yet valuable, feedback system.

Three subjects reported that they wished there were more possibilities in displaying the feedback output. They wished for more visual scenarios where they could observe their walking performance. Preliminary solutions to combine the DGO with a virtual environment exist.31,32 These systems incorporate physiologically meaningful movements such as obstacle avoidance during the training with the DGO. However, further studies are necessary to investigate how much technology is necessary to optimize motor learning for patients during mechanized gait training.

Future Directions

Theoretical evidence of the benefit of using visual feedback during robotic-assisted gait training was found. However, controlled clinical trials are needed to investigate which visual or other forms of augmented feedback in robotic-assisted gait training induce better rehabilitation outcomes compared with robotic-assisted gait training without feedback or manually assisted gait training. In addition, future research is necessary to investigate what type of feedback is most effective (eg, intermittent feedback versus constant feedback, summary feedback versus feedback after each step cycle, detailed feedback values for each joint versus averaged feedback values of multiple joints) and the frequency of presenting feedback. Furthermore, the transfer of behavior observed during robotic-assisted gait training to overground walking and the benefit of visual feedback in other patient populations (eg, patients with stroke, patients with traumatic brain injury) remain to be investigated. In addition to these studies on motor learning, the future will certainly lead to advances in the technical implementation of feedback during robotic-assisted gait training.

Conclusion

We have presented a computerized visual feedback method to estimate gait performance and to increase the motivation and active participation of patients during stepping in a DGO for locomotion training using partial body-weight support. The visual feedback was shown to have a similar effect on immediate motor output of subjects with iSCI during robotic-assisted gait training as verbal instructions by a physical therapist.

Mr Banz, Dr Colombo, and Dr Lünenburger provided concept/idea/research design. Mr Banz, Dr Bolliger, Dr Dietz, and Dr Lünenburger provided writing. Mr Banz and Dr Bolliger provided data collection and analysis. Dr Dietz and Dr Lünenburger provided project management. Dr Dietz provided subjects. Dr Colombo and Dr Dietz provided facilities/equipment. Dr Colombo provided institutional liaisons. All authors provided consultation (including review of manuscript before submission). The authors thank Dr Huub van Hedel for his critical comments and suggestions for manuscript preparation.

This study was conducted at the Balgrist University Hospital, Zurich. The study protocol was approved by the local ethics committee and conformed to the Declaration of Helsinki.

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References