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A mechanized gait trainer for restoration of gait

Stefan Hesse, MD and Dietmar Uhlenbrock, PhD
Klinik Berlin, Department of Neurological Rehabilitation, Free University Berlin, Germany

Abstract—The newly developed gait trainer allows wheelchair-bound subjects the repetitive practice of a gait-like movement without overstressing therapists. The device simulates the phases of gait, supports the subjects according to their abilities, and controls the center of mass (CoM) in the vertical and horizontal directions. The patterns of sagittal lower limb joint kinematics and of muscle activation for a normal subject were similar when using the mechanized trainer and when walking on a treadmill. A non-ambulatory hemiparetic subject required little help from one therapist on the gait trainer, while two therapists were required to support treadmill walking. Gait movements on the trainer were highly symmetrical, impact free, and less spastic. The vertical displacement of the CoM was bi-phasic instead of mono-phasic during each gait cycle on the new device. Two cases of non-ambulatory patients, who regained their walking ability after 4 weeks of daily training on the gait trainer, are reported.

Key words: *center of mass (CoM), gait rehabilitation, gait trainer.*

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Address all correspondence and requests for reprints to: Stefan Hesse, MD, Klinik Berlin, Kladower Damm 223, 14089 Berlin, Germany; email: hesse@reha-hesse.de.

INTRODUCTION

Restoration of gait following stroke, traumatic brain injury, and spinal cord injury is a major task in neurorehabilitation. Modern concepts of motor learning favor task-specific repetitive training, i.e., to re-learn walking, one has to walk repetitively in a correct manner (1). Correspondingly, treadmill training with partial body weight support has shown *considerable promise* at restoring gait in chronic non-ambulant subjects after stroke (2,3) and spinal cord injury (4–6).

The major disadvantage of treadmill training is the great physical effort required by two therapists to assist the patient's gait. This disadvantage has, in the past, impeded the widespread use of treadmill training. One therapist sitting alongside the patient has to place the paretic limb manually while the second therapist standing behind the patient assists lateral weight shifting and trunk erection. As the therapists fatigue, the patient's gait can become asymmetrical, therefore losing the benefit of sustained practice.

The authors therefore designed and constructed a mechanized gait trainer to enable the repetitive practice of a most "physiological" gait pattern without overstraining therapists (7,8), which is analogous to recent developments in the rehabilitation of upper extremities (9,10).

Features of the gait trainer are the simulation of stance and swing with a ratio of 60 percent to 40 percent between stance and swing phases, support of the harness-secured patients' movement according to their abilities, and control of the vertical and horizontal movements of the center of mass (CoM).

The following article has three parts: a description of the technical development of the mechanized gait trainer, the movement analysis of healthy and hemiparetic subjects practicing on the gait trainer as compared to treadmill walking, and first clinical results in two non-ambulatory hemiparetic patients.

METHODS

Design and Construction of the Gait Trainer

The advanced gait trainer (**Figure 1**) incorporated the following objectives:

- Provision of a gait-like movement simulating stance and swing phases with an actual lifting of the foot during swing, and a ratio of 60 percent to 40 percent between the two phases.
- Partial or complete support of gait movements by the machine, according to patients' abilities.
- Control of the center of mass (CoM-control) in vertical and horizontal directions.

Provision of a gait-like movement simulating stance and swing

The gait trainer was based on a doubled crank and rocker gear system. It consists of two footplates positioned on two bars (couplers), two rockers, and two cranks that provided the propulsion (**Figure 2**). The low backward movement of the footplates simulates the stance phase while the forward movement simulates the swing phase. The system generates a different movement of the tip and of the rear of the footplate during the swing. The tip of the plate follows an arc-like movement corresponding to the length of the rocker. The rear end is lifted during swing so that the footplate itself is inclined during swing.

Furthermore, the crank propulsion is modified by a planetary gear system to provide a ratio of 60 percent to 40 percent between stance and swing phases. It consists of fixed sun gears and circulating planet gears of the same diameter. The foot bars are eccentrically connected to the planet gears so that the rear end of the foot bars follows an ellipsoid-like movement. The upper half of the revolution (corresponding to the swing) lasts 40 percent, while the lower half of the revolution (corresponding to the stance) lasts 60 percent of one revolution time. Different gear sizes and eccentricities can be mounted to vary the stride length and the phase duration.

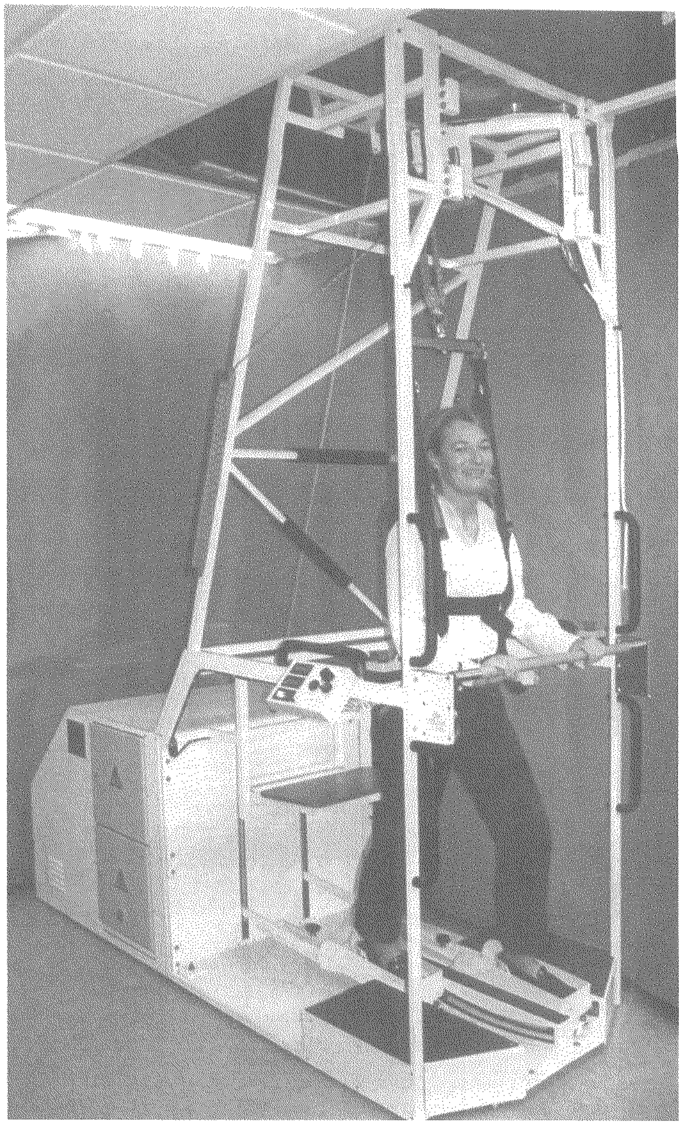

Figure 1.
Hemiparetic subject practicing on the advanced gait trainer.

Partial or Complete Support of Gait Movements

An induction drive and a speed control provide the propulsion. The control unit senses the actual velocity of the gear system and compares it to the preselected velocity. The motor provides full support when the patient pro-

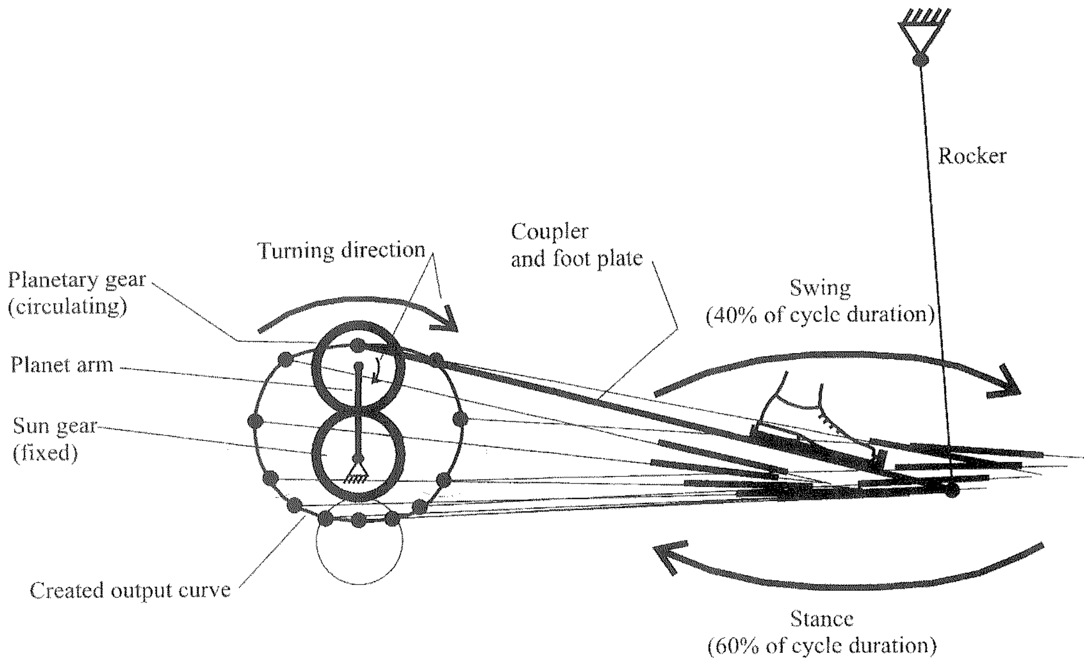

Figure 2.
Modified crank and rocker system including a planetary gear system to simulate stance and swing phases with a ratio of 60 percent to 40 percent.

vides no assistance; it adjusts the output torque (Nm) accordingly when the patient either assists or resists the movement. A chain connects the induction drive and the gear system. The torque generated by the machine is sensed, transmitted, converted from analog to digital, and displayed on-line to provide a biofeedback signal for the patient and therapist.

The output speed of the gear system is steplessly adjustable in a range of 0 to 70 strides/min. The resulting cadence ranged from 0 to 140 steps/min as one revolution of the gear system equaled two steps. With a stride length of 0.95 m, the *equivalent* velocity ranged from 0 to 1.12 m/s.

The CoM-Control in the Vertical and Horizontal Directions

The CoM oscillates sinusoidally in the vertical and horizontal directions. The amplitude of the double-frequent vertical movement is approximately 2 cm and of the monofrequent horizontal movement approximately 4 cm (11). The rotation of the planetary gear system, equaling one gait cycle, controls the movement of the CoM in vertical and horizontal directions. Two cranks, one for the vertical and the other for the horizontal movement CoM-control, are attached to the planetary gear system. The length of the crank controlling the vertical (horizontal) movement is 1 cm (2 cm). A transmission gear I=1/2 was installed between the planetary gear and the crank controlling the vertical CoM displacement to provide a double frequency of the vertical CoM movement within one gait cycle. A rope attached to the crank controlling the vertical CoM displacement served as the central suspension of the patient. A second rope connected to the crank controlling the horizontal CoM displacement was attached to the left lateral aspect of the patient harness at the level of the pelvic crest.

RESULTS

Movement Analysis of a Healthy Subject and a Hemiparetic Subject on the Gait Trainer and During Treadmill Walking

Healthy Subject

A healthy subject (female, 28 years old, no gait impairment) walked on a motor-driven treadmill at self-selected speed and practiced on the gait trainer with the basic and limb-dependent cycle parameters set accordingly. Right sagittal joint kinematics and the kinesiological electromyogram (right tibialis anterior, gastrocnemius, vastus lateralis, rectus femoris, biceps femoris, adductor magnus, gluteus medius, and erector spinae muscles) were recorded.

On the treadmill, the sagittal joint excursions followed the well-known patterns (12). On the gait trainer, the displacement curves were very similar during the major parts of stance and swing. The transition periods (pre-swing and loading), however, were different. Ankle plantarflexor rocker and initial knee bending during loading did not occur and the ankle was less dorsiflexed during the terminal swing in preparation of the "initial contact." Furthermore, the displacement curves of the knee and hip joint appeared more smooth, while the joint amplitudes were comparable.

The pattern of muscle activation during treadmill walking has been documented accurately (**Figure 3**; reference 13). During stance, the gastrocnemius, biceps, vastus, rectus, and gluteus medius muscles were active to secure body weight loading and forward displacement. During swing the tibialis anterior muscle assisted dorsiflexion of the foot and prevented a foot splash. On the gait trainer, the muscle activation pattern of the lower leg and thigh muscles were very similar, particularly in timing of onset and cessation of muscle activity within the gait cycle.

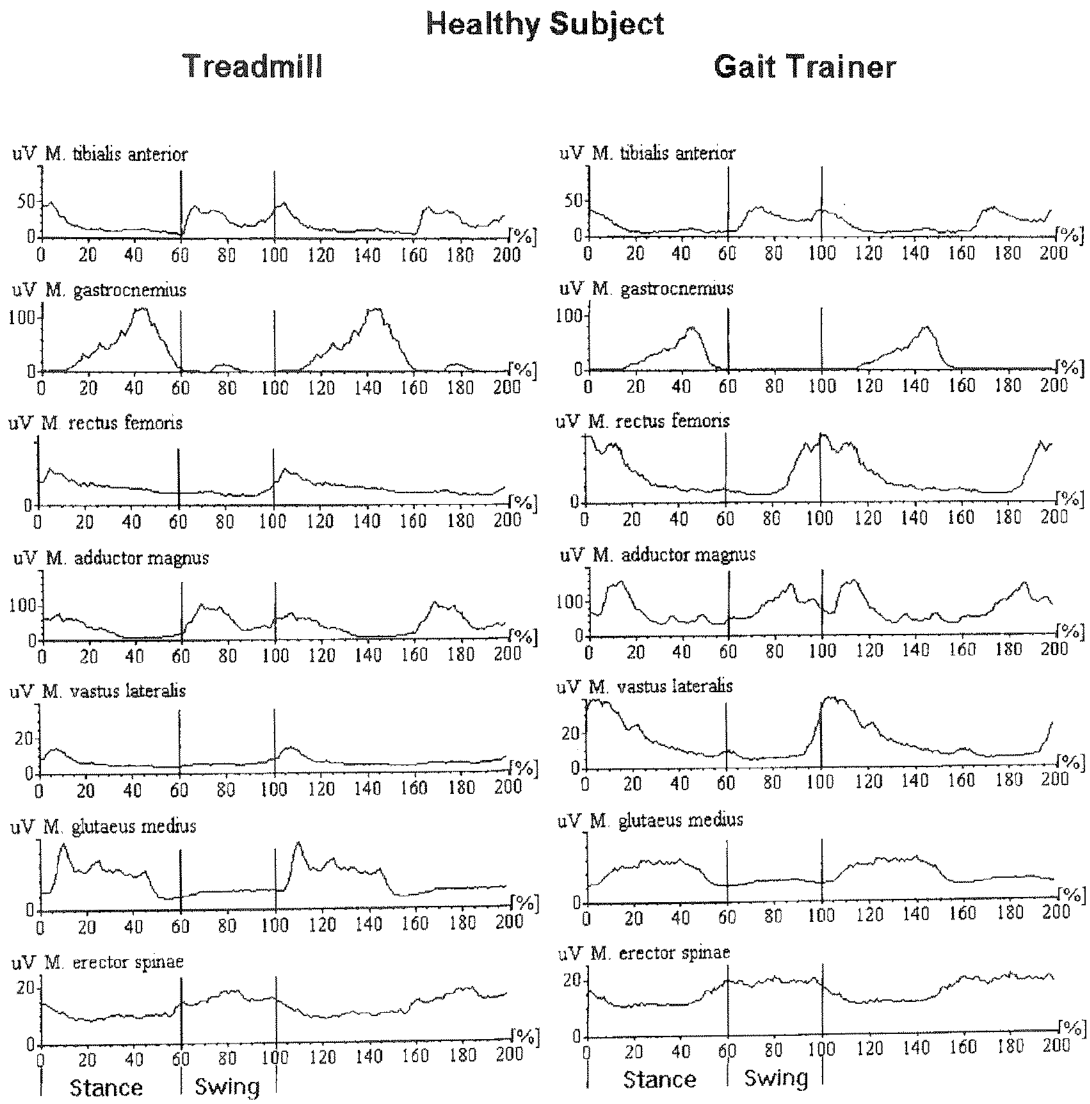

Figure 3.
Averaged and normalized (with respect to the gait cycle) kinesiological electromyogram of the right tibialis anterior, gastrocnemius, rectus femoris, adductor magnus, vastus lateralis, gluteus medius, and erector spinae muscles of a healthy subject on the treadmill (left), and on the advanced gait trainer (right).

Hemiparetic Subject

The hemiparetic subject (male, 55 years old) suffered from a severe right hemiparesis. He could not walk independently and still needed firm physical assistance. On the treadmill, he required 15 percent body weight support, and two therapists facilitated a more normal gait pattern. On the gait trainer, weight relief and basic cycle parameters were kept identical, but only one therapist was needed to assist the paretic knee. The movement analysis included the assessment of sagittal joint kinematics, the kinesiological electromyogram, and the assessment of the movement of the CoM in the vertical direction.

While the subject walked on the treadmill assisted by two therapists, the joint displacement curves resembled the normal pattern. On the gait trainer the curves were similar during the major part of stance and swing, but they differed during the transition periods. Again, a plantarflexor rocker did not occur during the loading phase, and the ankle was not dorsiflexed during the terminal swing.

On the treadmill, the gastrocnemius muscle showed spasticity-related clonic activity and its amplitude was less than that of the antagonistic tibialis anterior on the treadmill (**Figure 4**). On the gait trainer, the plantarflexor did not show any spasticity-related activity (it was well modulated instead), and the tibialis anterior was markedly less active. The activation pattern of the thigh muscles (biceps femoris, vastus lateralis, and adductor magnus) was comparable during both conditions.

The vertical displacement of the CoM on the treadmill was mono-phasic instead of bi-phasic during the gait cycle, with an amplitude ranging from 5 to 8 cm. On the gait trainer, the vertical displacement curve of the CoM corresponded to that of a healthy subject, i.e., it was double frequent, it was lowest during the double support phases, and reached its maximum posi-

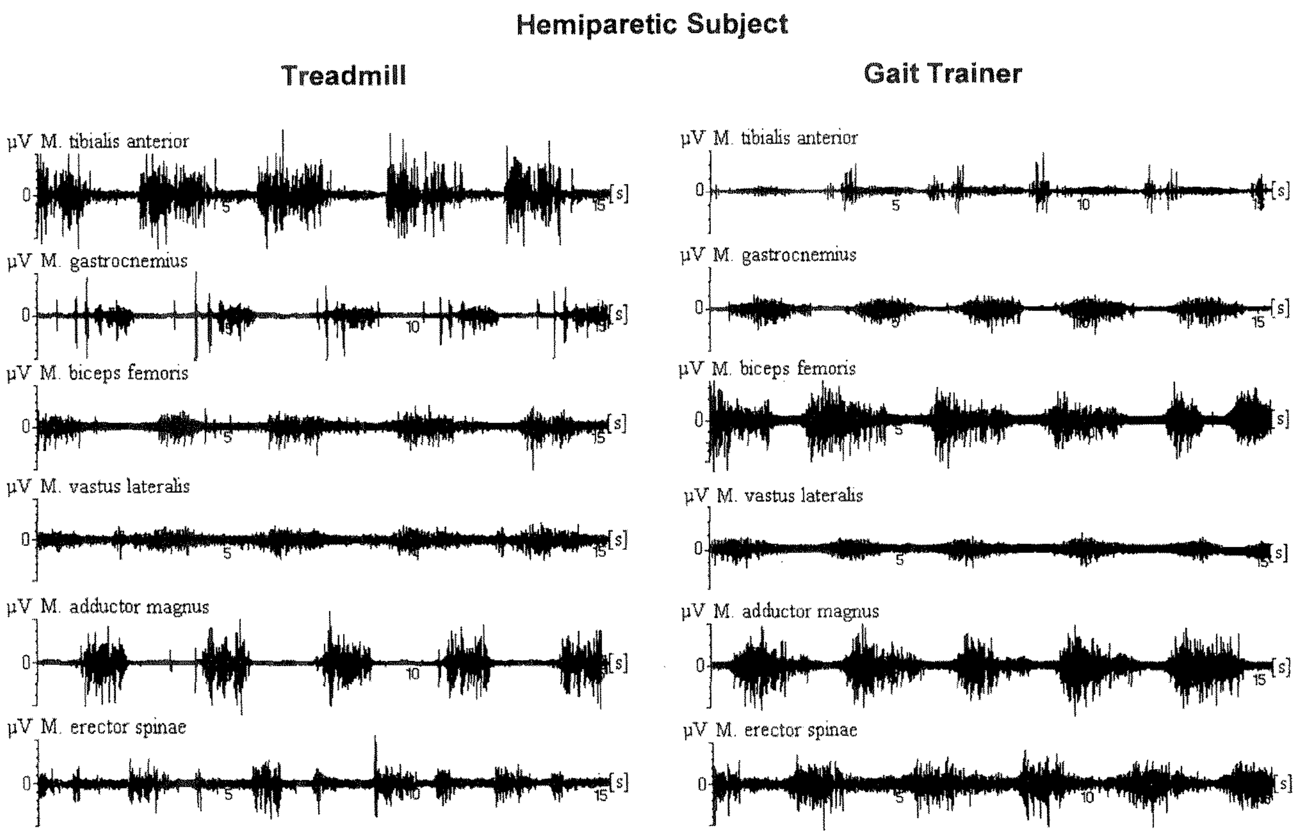

Figure 4.
Raw kinesiological electromyogram of the right tibialis anterior, gastrocnemius, biceps femoris, vastus lateralis, adductor magnus, and erector spinae muscles of a right hemiparetic subject on the treadmill (left), and on the advanced gait trainer (right).

tions during the stance and swing of the paretic limb. The amplitudes were approximately 2 cm (**Figure 5**).

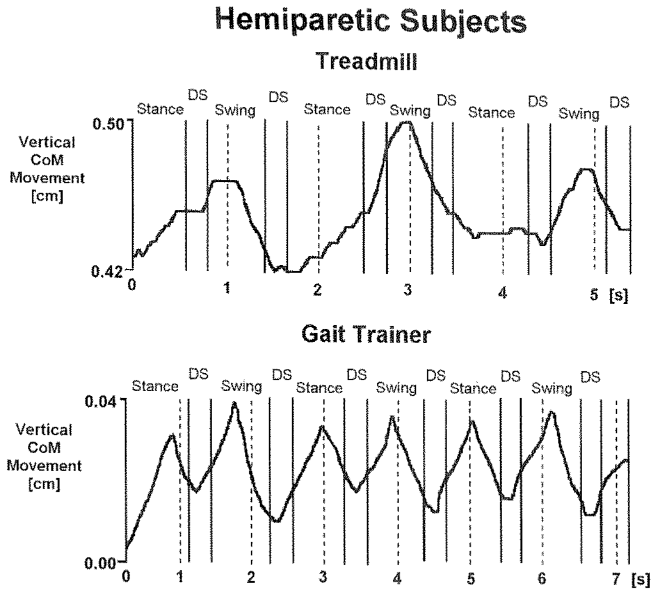

Figure 5.
Vertical displacement of the anterior superior iliac spine indicating the approximate movement of the center of mass of a right hemiparetic subject on the treadmill (above), and on the advanced gait trainer (below) which controls the displacement of the center of mass.

First Clinical Results—A Case Report

Patient #1

Patient #1 (female, 55 years old) was affected by a first time ischemic stroke in the territory of the left middle cerebral artery with a consecutive right-sided severe hemiparesis and marked sensory impairments 2.5 months before admission. Ankle spasticity was mild. She could sit unsupported, and was able to transfer from wheelchair to chair toward the unaffected side and to stand up with the help of her hands. She could not stand arm-free, and while walking required continuous help of one therapist to assist with weight bearing and balance. During the first two weeks of a conventional rehabilitation program, she learned to stand up without using her hands and to stand arm-free with only little support by a therapist. Her walking ability had not improved.

For 4 weeks she received additional therapy on the gait trainer, 5 times a week; each of the 20 sessions lasted 20 minutes. One therapist was responsible for this therapy, supervising the treatment and helping intermittently to stabilize the paretic knee. The initial *equivalent* walking velocity on the gait trainer was 0.2 m/s and was steadily increased to 0.4 m/s toward the end of training. The initial body weight support of 20 percent was quickly reduced; from the second week on she did not need any further relief.

Her gait ability, ground level walking velocity, and other motor functions were assessed every week with the help of the Functional Ambulation Category (FAC, 0–5, details the physical support needed but does not take into account any technical aid) and the gross motor function section of the Rivermead Motor Assessment Score (RMAS, 0–13; reference 14). Her gait ability improved constantly. At the end of the first week, she only required intermittent instead of firm continuous support by one therapist, and after the second and third weeks she required only verbal support or stand-by of one therapist. At the end of treatment she was able to walk independently on level ground with use of a walking stick. The walking velocity had improved from 0.29 m/s to 0.59 m/s. The gross functions of the RMAS increased from 4 to 10, i.e., she could walk at least 40 m outside, was able to pick up objects from the floor, and could climb stairs independently. No side effects had occurred.

The patient enjoyed the gait training on the new device and recommended it without any reservations. The therapist suggested an initial contact with the heel instead of with the entire sole as a future improvement. Furthermore, she observed that the patient mainly took advantage of the machine support during the swing phase of the paretic limb. Correspondingly, the swing effort was less as compared to assisted ground-level walking. *Three months after the end of the study the patient could still walk independently, having an FAC level of 4.*

Patient #2

Patient #2 (male, 62 years old) was affected by a first-time ischemic stroke in the territory of the right middle cerebral artery with a consecutive left-sided severe hemiparesis and distinct sensory impairments 2.3 months before admission. He could sit unsupported and stand up with the help of his non-affected hand, but required help with transfer and standing. During walking he needed firm support by one therapist to help with balance and weight bearing (FAC level 1). Ankle and knee spasticity were moderate to severe with a modified Ashworth grade of 3; a rigid one-bar ankle-foot orthosis (AFO) was prescribed.

His walking and motor abilities did not improve during the first 2 weeks of the conventional rehabilitation program. He then received additional therapy on the gait trainer as described above. During that period his gait ability increased markedly; after 4 weeks of the additional treatment he was able to walk independently on even surfaces

(FAC level 4), taking advantage of an AFO and a walking stick. The walking velocity improved from 0.14 m/s to 0.63 m/s. The gross function section of the RMAS increased from 3 to 10, i.e., he could walk at least 40 m outside, was able to pick up objects from the floor, and could climb stairs independently. *The patient did not appear at follow-up.*

DISCUSSION

The intention of this study was to construct an advanced mechanized gait trainer that would enable patients to practice gait-like movements repetitively without overstressing therapists. The three specific original objectives have been addressed in the design.

The duration of swing phase, when the foot is lifted, dorsiflexed, and brought forward, can be varied between 30 percent to 50 percent of the gait cycle. The cadence and step length can also be continuously adjusted, while ensuring that gait movements remain symmetrical. The propulsion of the gait trainer helps with the movement of the feet during both stance and swing, while the motor-driven treadmill only helps with the stance phase. Thus, the unfavorable manual work of assisting the swing of the paretic limb is no longer necessary. Further, the machine assists the weight shifting and maintains trunk erection because of the control of the CoM in horizontal and vertical directions. On the treadmill, another therapist is required for this task. *On the gait trainer, however, one therapist should pay attention to knee motion in order to prevent knee hyperextension. This can happen during the initial sessions of the therapy program; later on the patients learn to control the knee motion by themselves.*

The movements and pattern of muscle activation of a healthy subject were similar on the trainer and treadmill, suggesting that the healthy subject could practice a gait-like movement on the new device. Minor differences occurred during the terminal swing and loading phases. During terminal swing, the subject's ankle was less dorsiflexed on the gait trainer, because, due to geometrical constraints of the chosen mechanical solution, the rear of the footplate was lowered only minimally. Consequently, the activity of the tibialis anterior muscle was reduced on the gait trainer compared to the treadmill. During the subsequent loading phase, the impact-free transition on the gait trainer rendered the shock-absorbing heel rocker and an initial knee flexion unnecessary.

Assessment of the wheelchair-bound hemiparetic subject walking on the treadmill and on the gait trainer demonstrated the rehabilitation potential of the new training device. Two therapists laboriously assisted gait on the treadmill whereas only one therapist gently helped with knee stabilization on the gait trainer. Asymmetry of stance and swing is a major characteristic of hemiparetic gait, and physiotherapists aim to reestablish a balanced gait (15). The gait-like pattern of the hemiparetic subject on the new gait device was perfectly symmetrical. The alternating pattern of loading and unloading was also reflected in more normal movement of the CoM on the gait trainer.

The activity pattern of the paretic vastus lateralis, biceps femoris, and adductor magnus muscles corresponded to each other during both conditions. With regard to the shank muscles, the subject showed less pathologically premature activity of the plantarflexors, characteristic of spasticity (16), while on the gait trainer. This may have been due to the impact-free transition from swing to stance. At the same time, the antagonistic tibialis anterior muscle was markedly less active on the gait trainer, probably because the patient took advantage of the machine support during the swing phase.

The case reports demonstrated that the two non-ambulatory hemiparetic subjects regained their walking ability during the additional therapy on the gait trainer. *However, the reader should keep in mind that the therapy on the gait trainer was additional; therefore, a controlled study is needed to evaluate its effectiveness.*

The gait trainer enabled the practice of up to 1,000 repetitions of a gait-like movement during one session. The patients and the therapist experienced the movement on the machine as gait-like and highly symmetric. Further, the therapist noted an almost physiological movement of the trunk, probably due to the control of the movement of the CoM. Most importantly, the therapist worked with less effort compared to fully assisted ground-level walking or treadmill training with partial body weight support, which often requires two or even three therapists.

In conclusion, the gait trainer enables severely affected subjects to experience the repetitive practice of a gait-like movement without overstraining therapists. Future outcome studies will be necessary to demonstrate the clinical benefit of this promising device in the gait rehabilitation of wheelchair-bound subjects.

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