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RESTORATION OF GAIT BY COMBINED TREADMILL TRAINING AND MULTICHANNEL ELECTRICAL STIMULATION IN NON-AMBULATORY HEMIPARETIC PATIENTS

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ABSTRACTS. Functional electrical stimulation and treadmill training with partial body weight support through suspension by a parachute harness were combined for gait restoration in 11 chronic non-ambulatory hemiparetic patients. Individually adjusted multichannel stimulation of the trunk and of upper and lower limb muscles, as well as a motor driven treadmill, induced functional gait within 3 to 6 weeks. The improvement of gait ability was assessed by the Functional Ambulation Category test. Other motor functions were rated by the Rivermead Motor Score. The leg muscle strength, stride length, cadence, gait velocity and gait pattern were recorded. In seven of the patients, we did a single case research A-B-A study that showed that this combined approach had advantages, in regard to gait restoration and walking velocity ($p < 0.05$) as compared with our common physiotherapeutic programme.

Key words: hemiparesis, gait, electrical stimulation, treadmill.

In a population of patients with hemiparesis due to various etiologies, several remain persistently non-ambulatory. One third of stroke patients do not regain gait ability within the first three months post-onset and have poor prospects for further improvement (19). An intensive therapeutic approach consisting of treadmill training with partial body weight support and multichannel electrical stimulation was therefore introduced in non-ambulatory hemiparetic patients in order to initiate gait and to re-establish its correct pattern within three to six weeks.

It has recently been shown that a motor driven treadmill with partial body-weight support and enforced stepping movements could effectively restore gait within 1.5 to several months in spinal cord injury patients with various degrees of spastic paresis (21). The method turned out to be effective in some ambulatory hemiparetic patients without (18) and with partial body weight-support (10), as well as in 9 non-ambulatory hemiparetic patients (12). In vertebrates, treadmill training is based on the use of a spinal gait pattern and in primates additionally on intact reticulospinal motor pathways descending in the ventral section of the spinal cord (6, 11, 13). These conditions are met in hemiparetic patients and to a lesser extent in patients with clinically incomplete spinal cord injury.

It had also been observed that five- to six-channel electrical stimulation of the main lower extremities muscle groups, synchronized with the phases of stride, efficiently restores the gait pattern and body-weight support in hemiparetic patients after stroke and other injuries. When applied in kinesiologically correct sequences the procedure helped, within a couple of weeks, to restore patients' gait faster and more effectively than did conventional physiotherapeutic techniques (3, 15). Multichannel functional electrical stimulation (FES) and treadmill training with partial body-weight support were therefore applied together for the restoration of gait in severely affected non-ambulatory hemiparetic patients. A combination of interactive stepping and externally induced muscle activation was expected to render possible additive effects of both methods. Further external limb stimulation should decrease the physical effort needed by the therapists to assist walking on the treadmill. Additionally, by stabilization of the trunk, the gait pattern could be restored without associated mass synergies (5), also reducing the support of the physiotherapists. In the first preliminary part of the procedure, the combined locomotor training was applied additionally and in the second part a single-case design study was conducted to evaluate its efficiency in comparison with regular physiotherapy.

MATERIAL AND METHODS

Eleven non-ambulatory male hemiparetic patients aged 30 to 71 years participated in the treatment programme. Four had right-sided and seven left-sided hemiparesis; the median

Table I. *Patient demography*

Patient	Age	Onset (Week)	Hemiparesis	Etiology	Sensory impaired	Neglect syndrome	Additionally
1	44	41	Left	Tumor	Yes	Yes	Hemianopsy, painful knee
2	30	300	Left/T11–12	Trauma	Yes		
3	62	15	Right	Ischemia			Ataxia, diab polyneuropathy
4	71	11	Right	Ischemia			
5	49	20	Right	Ischemia			Global aphasia
6	58	20	Left	Hemorrhage	Yes	Yes	
7	39	41	Left	Hemorrhage	Yes	Yes	Partial lobectomy
8	35	35	Left	Hemorrhage		Yes	Hemianopsy, pusher syndrome
9	53	13	Left	Ischemia	Yes	Yes	
10	63	26	Left	Hemorrhage		Yes	Knee contracture
11	59	30	Right	Hemorrhage	Yes		Hemianopsy, aphasia

post-injury interval was 25 weeks (range 11 weeks to 6 years). Nine patients suffered from a stroke, one had undergone brain tumour surgery, another had a post-trauma syndrome after a brain injury. The etiology in stroke patients was a supratentorial lesion with ischemia in the middle cerebral artery region (4 subjects) and hemorrhage in 5 subjects. Six patients had distinct sensory hemi-impairments. A detailed description of the sample on admission to the study is presented in Table I.

Five patients additionally suffered from a neglect syndrome with non-perception and non-use of the affected lower limb (4). Three were hemianopic, two were aphasic, one of them globally; one also had a Wallenberg syndrome with persisting ataxia and diabetic polyneuropathy, while the patient with brain injury had an additional incomplete T11–12 spinal cord lesion. One patient had a knee contracture with a 10° extension deficit and another suffered from a painful and swollen knee due to a strong ankle equinovarus, knee extensor thrust at midstance, and overweight. They were all severely affected and were not able to walk in spite of a previous conventional comprehensive rehabilitation programme.

A similar treadmill system as described previously was used in the study (1). The patients walked suspended by a modified tandem parachute harness over a motor driven treadmill. The body weight support was initially set at approximately 30% by a spring scale and a system of pulleys, and was gradually reduced to 5% during the first two weeks of the treatment with a median of 10 days. Clinical criteria for the amount of body weight support were the patients' ability to carry the remaining load on the paretic leg during its single support phase. The spring scale with a rather long range of motion also dampened sudden loading during the stance phases of the affected limb. The treadmill speed was chosen according to measurements of the free level gait and adjusted daily according to abilities and preferences of the patients.

Multichannel electrical stimulation of the affected lower limb, trunk and upper limb muscles was applied by a surface felt pad or self adhesive polymer electrodes. Two to three programmable dual channel stimulators (16) were connected together, forming a four-to-six channel stimulation unit. It provided a selection of the stimulation within eight stance and eight swing phase increments for every channel. The stimulator's microprocessor continuously adapted the duration of selected stimulation sequences to the patient's gait cadence and synchronized them within the swing and stance phases, respectively. Triple foot switches under the heels, lateral and medial metatarsals measured the phases of stride. Biphasic constant current pulses with the duration of 0.1 to 0.5 ms and frequency of 20 to 30 Hz were adjusted up to 50 mA for strong but painless muscular contractions. Number of stimulation channels, electrode sites and sequences of the stimulation within the gait cycle were fitted to individual needs of the patients. A rather rigid stimulation paradigm, as used previously (3, 14), was avoided in favour of a simple, clinically viable application. Less intervention for the same effect was the main criterion there. Three to six stimulation channels were applied for the correction of gait deficiencies, as assessed by clinical gait analysis (17).

The peroneal nerve was stimulated for the dorsal flexion and moderate eversion during the swing and initial stance phase in ten subjects; a monopolar electrode set with a 10×2.5 cm anode and 2.5 cm round cathode was attached to a single Velcro band. In the remaining patient, who could not tolerate the stimulation of the peroneal nerve, the 8×5 cm bipolar electrodes were placed over the tibialis anterior, extensor hallucis and extensor digitorum longus muscles, covering also a part of the peroneus longus and brevis muscles. The quadriceps muscle was stimulated for the knee extension in the terminal swing and the first part of the stance phase in nine subjects. Wet, 8×5 cm bipolar felt pad electrodes were placed over the muscle bellies with the distal cathode placed more medially and the proximal anode more laterally. The hamstring muscles were stimulated for the knee flexion in the pre- and initial swing phase by the 8×5 cm bipolar electrodes in four patients. The gluteus maximus muscle was stimulated for hip extension throughout the stance phase by the 8×5 cm bipolar electrodes in eight subjects, in one of them bilaterally. The gluteus medius and minimus muscles were similarly stimulated for the hip abduction in eight patients. A combined shoulder/arm stimulation was applied during the swing of the ipsilateral leg in ten patients and the abdominal muscles were stimulated during the stance phase of the affected leg in four patients.

The combined shoulder/arm stimulation was performed by bipolar 13×5 cm self adhesive polymer electrodes, one over the supraspinatus and part of the trapezius muscles and another slanting downwards from the spinal and acromial part of the deltoid muscle over the lateral head of the triceps brachii muscle. The stimulation was introduced for simultaneous abduction and elevation of the shoulder, and its retroversion and extension of the elbow. It should provide a release of the associated spastic pattern of the arm flexion during gait (5) when present, correction of the depressed shoulder and a reactive reciprocal arm swing forward during the following swing of the contralateral leg. In addition, a sustained trunk erection was expected by a compensatory reflex activation of the lumbar erector spinae muscles (7, 8) which should stabilize the trunk and align the pelvis, both considered as integral parts of physiological gait (5).

In four patients a stimulation of the abdominal muscles was introduced to assist protraction of the pelvis during the stance phase. Bipolar 13 × 5 cm self adhesive electrodes were placed over both rectus abdominis muscles below the navel and the upper one extending from the rectus abdominis to the external abdominal oblique muscle on the affected side above the navel.

The treatment included daily treadmill/stimulation sessions, from 10 minutes at the beginning to a little over half an hour at the end of treatment, depending on the physical and mental condition of the patients. They found walking on the treadmill tiresome after that period, probably for both physical (continuous walking) and psychological reasons (monotony). They were also not encouraged to walk faster or "long distances", but the correct gait pattern was stressed throughout the sessions. Besides verbal support the patients were helped manually at the beginning of the treatment by a skilled physiotherapist. The help included stabilization of the trunk, its alignment, initiation of the swing or placement of the foot when necessary. The stimulation parameters were also readjusted with changes of gait pattern during the course of treatment.

The first four patients received the treadmill/stimulation treatment besides their conventional physiotherapy; the number of sessions were 13, 25, 30 and 33. They were tested clinically and their gait was measured at the beginning, in the middle and at the end of treatment. In the next seven patients, a single case research A-B-A study was applied with 15 treadmill/stimulation treatments (A phase), 15 days of a comprehensive neurodevelopmental (2) physiotherapy programme (B phase) and again 15 days of the treadmill/stimulation. All seven patients suffered from a supratentorial stroke and the time interval post stroke was at least 3 months to reduce influences of spontaneous recovery. They were tested clinically once and their gait was measured twice every five days in the weekly sessions.

The clinical tests included assessment of functional ambulation category, hierarchical Rivermead motor assessment score (leg and trunk section, gross functions) designed for hemiparetic patients, motricity index of the affected lower limb and modified Ashworth spasticity scale tested for the ankle dorsiflexion in the prostrate position (20). All clinical tests were applied by two independent physiotherapists who were not unaware when judging the treatment phases. Both were experienced Bobath therapists; one of them did not belong to the scientific staff but was an ordinary member of the physiotherapeutic department.

When assessing gait speed, cadence, and stride length, the patients walked 10 m with their self-adopted gait velocity. One physiotherapist was involved in the task and she was carefully instructed not to push the patients forward but merely prevent them from falling. In the two patients, whose functional ambulation category was 0 at the beginning and gait measurement not possible, a gait velocity of 0 m/s was assumed for statistical analysis.

Statistics

For the seven patients studied within the A-B-A study, increments of the ordinal-scaled values between consecutive measurements were computed and tested for homogeneity using the non-parametric Friedman-test. For the continuous variables a multivariate analysis of variance (MANOVA) was performed. If the two therapies were either ineffective or equally effective, then the corresponding trend in time should be a linear one or a 2nd degree polynomial, i.e. a parabola. If the two therapies were different, the profile over time should have at least one point of deflection. An alpha-level of 5% was chosen, and the SYSTAT standard software package was applied.

RESULTS

Clinical tests showed improvement of walking ability in all the patients. Results of the assessment of functional ambulation category, Rivermead motor assessment score for both, the leg and trunk section and gross functions, motricity index of the affected leg and the Ashworth scores are presented in Table II.

The first four patients improved their gait ability

Table II. *Clinical tests*

B: end of 1st treadmill/stimulation, A: end of physiotherapy

	Functional ambulation category				Rivermead score Affected leg + trunk				Motricity index Affected leg			
Subject	Start	B	A	End	Start	B	A	End	Start	B	A	End
1	0			3	2			4	34			43
2	2			5	3			5	34			45
3	2			3	5			6	43			43
4	1			2	6			7	34			62
5	1	2	2	4	5	6	8	8	33	54	54	54
6	0	1	1	3	2	3	4	5	24	34	24	24
7	1	3	3	4	3	3	3	4	51	51	51	51
8	1	2	2	3	3	3	5	5	54	66	70	70
9	2	3	4	5	4	4	5	6	29	48	48	48
10	1	2	2	3	4	4	5	5	24	33	33	43
11	2	3	3	4	5	5	5	5	19	19	24	24

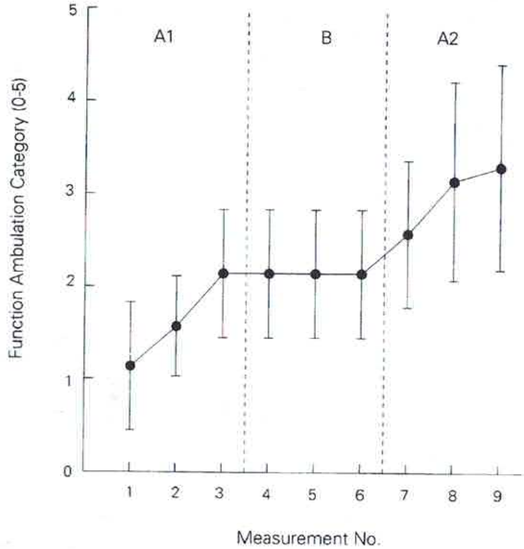

Fig. 1. Functional Ambulation Category (mean, range) in the seven patients during the treadmill/stimulation, subsequent physiotherapy and second treadmill/stimulation phases.

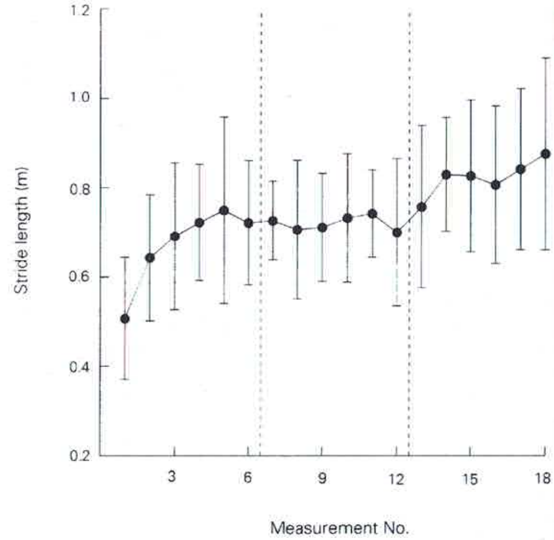

Fig. 2. Stride length, cadence and gait velocity (Means ± SD) in the seven patients during the treadmill/stimulation, subsequent physiotherapy and second treadmill/stimulation phases.

considerably during the additionally applied training: one patient was completely independent, two patients needed verbal support and one patient, who suffered from an additional ataxia, was still dependent on intermittent support after the training. The Rivermead score for both the leg and trunk section and gross functions improved 1.5 points, on an average. The motricity index of the affected lower limb increased 12 points on an average. The muscle tone tested with the help of the modified Ashworth score for one level increased in two of the patients and remained unchanged in the other two patients. The mean improvements in gait velocity, stride length and cadence were: 196%, 66% and 76%, respectively, during the additionally applied training.

In the seven patients assessed in the A-B-A study the functional ambulation category improved on average 1.2 points during the first treadmill/stimulation phase (from mean 1.1 to 2.3), remained fairly stable during the following physiotherapy (mean 2.4) and increased again considerably during the second treadmill/stimulation phase to a final mean of 3.7 points. At the beginning of the study one patient could not walk (category 0), four patients required firm continuous support from one person who helped carrying weight and with balance (category 1), and the remaining two patients needed continuous support or intermittent support from one person to help with balance and co-ordination (category 2). After the study, one patient could walk anywhere (category 5), three patients walked independently and needed help on stairs (category 4), and three needed verbal supervision (category 3). The combined therapy proved to be more effective than the regular physiotherapy with regard to restoration of gait ability ($p < 0.05$, Fig. 1).

The Rivermead score for leg and trunk improved in the same patients throughout the treatment from mean 3.7 to a final 5.4 points with no particular therapy superior to any other. The Rivermead score for gross functions improved steadily from mean 4.6 to a final 6.7 points, neither therapy being superior. The motricity index levelled up after the first treadmill/stimulation phase from the mean initial 34 to the two intermediate 43 and final 45 points. No superiority could be figured out. The Ashworth scores displayed a within-subject variability of up to two grades from one measuring point to the next in the A-B-A study. No consistent trend could be detected.

Courses of the mean stride length, cadence and velocity during free level gait for the seven patients from the A-B-A study are given in Fig. 2. Improvements during the first treadmill/stimulation phase reached 42% in the stride length, 26% in cadence and 85% in velocity. They decreased by 10% in the stride length and levelled up with a further 4% and

1% gain in cadence and gait velocity during the subsequent physiotherapy phase. Eventually, there was another substantial increase of 41%, 20% and 77% respectively to the final improvement of 73% in the stride length, 50% in cadence and 163% in gait velocity at completion of the second treadmill/stimulation phase. The combined therapy was superior to physiotherapy with regard to gait velocity ($p < 0.05$). The improvement of both cadence and stride length did not reach a significant level.

DISCUSSION

The treadmill training with partial body weight support combined with a multichannel electrical stimulation was expected to produce a marked effect. By stabilisation of the trunk and partial reduction of the gravitational force, deficient equilibrium reflexes were substituted. Enforced stepping movements, together with externally activated major lower limb and trunk muscles, enabled the execution of a complex gait pattern instead of only single elements. Physiotherapists, relieved of strenuous manual support, could concentrate better on patients' gait quality. The gait pattern was additionally induced and restored by the multichannel electrical stimulation of the lower middle and upper body segments. Application of the multichannel electrical stimulation itself was modified according to patients' needs during the study.

The introduced shoulder/arm stimulation compensated for a lack of abduction, elevation, and retroversion of the shoulder, as well as for an extension of the elbow. It released an associated spastic pattern of arm flexion during gait when present (5), corrected the depressed shoulder and provided a reactive reciprocal arm swing during the following swing of the contralateral leg at the same time. It was found previously that single electrical stimuli, applied to the brachial plexus at the Erb's point, caused compensatory reflex activation of the ipsilateral and more strongly of the contralateral lumbar erector spinae muscles within 100 ms while standing (7). The effect was increased in patients with spastic hemiparesis compared with normal subjects (8). By the shoulder/arm stimulation, as described in this paper, a sustained contraction of the paraspinal muscles with erection of the trunk was also achieved by a train of 20 to 30 Hz pulses. Besides the stimulation of dorsal flexion, applied in all eleven patients, the shoulder/arm stimulation was found useful in ten of them.

The severely affected patients who were studied had been previously treated by a comprehensive neurodevelopmental rehabilitation programme (2) without regaining walking ability. After the treadmill/stimulation programme one patient could walk with at least an intermittent support, five of them needed a stand-by verbal support, while five were independent. Patient No. 4 (see Table I), who gained only one functional ambulation category level, suffered from ataxia due to an additional Wallenberg syndrome.

With the substantial improvement of walking ability, the Rivermead score for the leg and trunk, not related to gait and only partly to posture, did not improve to such an extent and the motricity index, performed in the prostrate position, even less. This indicates a significance of task-oriented training for the restoration of gait, which was additionally supported by substantial improvement of the walking ability only during the treadmill/stimulation phases in the last seven patients, with unspecific improvement of the Rivermead score and levelling of the motricity index after the first treadmill/stimulation phase. Treadmill training was therefore superior to physiotherapy with regard to restoration of gait function. A contribution of spontaneous recovery, particularly in the six patients whose post-stroke interval was less than six months, could not be ruled out (9). However, spontaneous recovery alone cannot account for the temporal trend actually observed, which differed significantly from a first or second order polynomial (Figs. 1, 2).

Ashworth spasticity scores showed a high variability in single patients during the study with no definite trend in the course of treatments. Obviously there were many tone modulating internal and external factors not under the control of the investigators.

Stride length, cadence and velocity improved uniformly during the study. With the improvements around 50% in the first two variables, the mean gait velocity, as the final intent of mobility, increased even more than twice. The seven patients included in the A-B-A study showed a marked increase in stride length, cadence and velocity during the first treadmill/stimulation phase. The variables levelled up or even decreased during the physiotherapy phase and displayed an additional increase during the second treadmill/stimulation phase. For gait velocity, the combined treadmill/stimulation treatment proved to be superior to physiotherapy.

The combined treadmill/stimulation therapy was capable of restoring gait substantially better after the levelling-up in the physiotherapy phase. It could therefore play an important role in the restoration of gait in non-ambulatory hemiparetic patients. It could also accomplish independent ambulation in those patients who had not been able to achieve it with conventional physiotherapeutic techniques. The new approach could be applied efficiently as an intensive initial treatment for the restoration of gait, which might later be followed by other rehabilitation methods in or not connected with a clinical environment. The combination of treadmill training with external limb stimulation has the operational advantage that a minimum of physical effort is needed by the therapists, which allows them to concentrate wholly on the correction of an impaired gait pattern. The type of interaction of both treatment methods cannot be evaluated on the basis of the present study (future studies with a direct comparison of treadmill and FES, applied separately as well as combined, are needed); however, each regime separately has proved to be effective within their own frames of indication.

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REFERENCES

1. Barbeau, H., Wainberg, W. & Finch, L.: Description and application of a system for locomotor rehabilitation. Med Biol Eng Comput *25:* 341–344, 1987.
2. Bobath, B.: Adult hemiplegia; evaluation and treatment. Heinemann, London, 1978.
3. Bogataj, U., Gros, N., Maležič, M., Kelih, B., Kljajić, M. & Aćimović, R.: Restoration of gait during two to three weeks of therapy with multichannel electrical stimulation. Phys Ther *69:* 319–327, 1989.
4. Brain, W.: Visual disorientation with special reference to lesions of the right cerebral hemisphere. Brain *64:* 244–272, 1941.
5. Davies, P. M.: Right in the middle; selective trunk activity in the treatment of adult hemiplegia. Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, 1990.
6. Eidelberg, E., Walden, J. G. & Nguyen, L. H.: Locomotor control in macaque monkeys. Brain *104*: 647–663, 1981.
7. Ertekin, N. & Ertekin, C.: Erector spinae muscle responses while standing. J Neurol Neurosurg Psychiatry *44:* 73, 1981.
8. Ertekin, N. & Ertekin, C.: Reflex erector spinal responses in disorders of the central nervous system. Acta Neurol Scand *66:* 690, 1982.
9. Good, D. C.: Treatment strategies for enhancing motor recovery in stroke rehabilitation. J Neuro Rehabil *8:* 177–186, 1994.
10. Gregor, R. J., Dobkin, B. & Fowler, E. G.: Interaction between motion analysis lab and physical therapy. Proceedings of the European Symposium on Clinical Gait Analysis, Zurich, Switzerland: 99–103, 1992.
11. Grillner, S.: Neurobiological basis of rhythmic motor acts in vertebrates. Science *228*: 143–149, 1985.
12. Hesse, S., Bertelt, C., Schaffrin, A., Maležič, M. & Mauritz, K. H.: Restoration of gait in non-ambulatory hemiparetic patients by treadmill training with partial body weight support. Arch Phys Med Rehabil *75:* 1087–1093, 1994.
13. Lovely, R. G., Gregor, R. J., Roy, R. R. & Edgerton, V. R.: Effects of training on the recovery of full weight-bearing stepping in the adult spinal cat. Exp Neurol *92:* 421–435, 1986.
14. Maležič, M., Kljajić, M., Aćimović-Janežič, R., Gros, N., Krajnik, J. & Stanič, U.: Therapeutic effects of multisite electric stimulation of gait in motor-disabled patients. Arch Phys Med Rehabil *68:* 553–560, 1987.
15. Maležič, M., Bogataj, U., Gros, N., Kelih, B., Kljajić, M. & Aćimović, R.: Evaluation of gait with multichannel electrical stimulation. Orthopedics *10:* 769–772, 1987.
16. Maležič, M., Bogataj, U., Gros, N., Dečman, I., Vrtačnik, P., Kljajić, M. & Aćimović-Janežič, R.: Application of a programmable dual-channel adaptive electrical system for the control and analysis of gait. J Rehabil Res Dev *29:* 41–53, 1992.
17. Perry, J.: Gait analysis; normal and pathological function. Slack Inc., Thorofare, New Jersey, 1992.
18. Waagfjörd, J., Levangle, P. K. & Certo, C. M. E.: Effects of treadmill training on gait in a hemiparetic patient. Phys Ther *70:* 549–560, 1990.
19. Wade, D. T., Wood, V. A., Heller, A., Maggs, J. & Hewer, R. L.: Walking after stroke. Scand J Rehabil Med *19:* 25–30, 1987.
20. Wade, D. T.: Measurement in neurological rehabilitation. Oxford University Press, Oxford, New York, Tokyo, 1992.
21. Wernig, A. & Müller, S.: Laufband locomotion with body weight support improved walking in persons with severe spinal cord injuries. Paraplegia *30:* 229–238, 1992.

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