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# Use of Functional Electrical Stimulation in the Lower Extremities of Incomplete Spinal Cord Injured Patients

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**Abstract:** After a program of therapeutic electrical stimulation, 3 groups of incomplete spinal cord injured (SCI) patients were identified, those in whom an improvement of both voluntary and stimulated muscle force was observed, those with an increase in stimulation response only, and patients in whom no effect of electrical stimulation training could be recorded. As it is difficult to predict the outcome of the electrical stimulation rehabilitation process, a diagnostic procedure was developed to predict soon after accidents which incomplete SCI patients are candidates for permanent use of a functional electrical stimulation (FES) orthotic aid. The candidates for chronic use of FES are patients with weak ankle dorsiflexors and sufficiently strong knee extensors. These patients are equipped with a single channel peroneal stimulator augmenting dorsiflexion and knee and hip flexion in a total lower limb flexion response. By applying FES to the ankle plantar flexors, the swing phase of walking can be significantly shortened and faster walking obtained. **Key Words:** Functional electrical stimulation—Spinal cord injury—Gait.

In the last few decades, advances in traffic control and motor vehicle engineering together with more efficient first aid and improved transport to emergency centers have resulted in a reduction in the number of complete spinal cord injured (SCI) patients. As a consequence, more incomplete injury cases are arriving in spinal units. There are more incomplete tetraplegic than paraplegic cases. About one-half of the incomplete SCI patients recover and need no orthotic aid. In these patients, functional electrical stimulation (FES) can be used as a therapeutic treatment in the early posttrauma phase. The other incomplete SCI patients are candidates for functional chronic use of FES rehabilitative aids.

Incomplete lesions of the spinal cord are characterized by 3 different kinds of muscles, normal, centrally denervated (spastic), and peripherally denervated (flaccid). All 3 kinds of muscles can be found, not only in the lower extremity of an incomplete SCI patient, but also in a single muscle group. This makes the FES rehabilitative approach rather difficult. It is difficult to predict the outcome of the FES rehabilitation process when patients are admitted to the spinal unit soon after an accident. Similarly, it is not possible to determine what rehabilitation aid the patient will need after recovering from a spinal cord injury.

It was found that the early recovery of quadriceps muscle strength after spinal injury is a useful predictor of future ambulation (4). Motor incomplete SCI patients whose quadriceps strength recovered to a grade greater than 3/5 by 2 months post injury had an excellent prognosis for subsequent ambulation by half a year post injury. No relationship was found between age and ambulatory status. Also, no relationship between the level of injury and recovery of ambulation was observed. This is in accordance with the data presented in a study (11) in which no significant differences in motor recovery were related to the type of injury and type of spinal fracture. In another study (6), all subjects with an early quadriceps muscle grade greater than 0/5 later ambulated. The same examiners also noticed that somatosensory evoked potentials did not offer any additional

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prognostic value over that provided by clinical examination. However, the prognostic value of preserved sensation was proven in the study. The preservation of pinprick sensation between the level of the injury and the sacral dermatomes was the best prognostic indicator for useful motor recovery in the patients regaining the ability to walk (7). The relationship between neurocontrol patterns evoked by lower limb movement in the supine position and the assistive device used for ambulation in chronic incomplete SCI patients was also evaluated (10). Marked decreases in motor unit output and/or loss of motor organization were found in the nonambulatory group of patients. The coactivation of proximal muscles, poor timing of muscle activity, and radiation of activity into contralateral muscles were also noted in subjects who required a walker or crutches.

The purpose of the present investigation was primarily to develop a diagnostic procedure which will predict soon after the accident which incomplete SCI patients are candidates for permanent use of a FES orthotic aid. It was also our goal to discuss the importance of knee extensors, peroneal nerve, and ankle plantar flexor stimulation after incomplete SCI.

## KNEE EXTENSOR STIMULATION

The therapeutic electrical stimulation program consisted of cyclic stimulation of partially paralyzed knee extensor muscles in which stimulation trains of 4 s and equal length 4 s pauses alternately followed one another. The electrical stimulation was applied through large (6 × 4 cm) sheet metal electrodes covered with water soaked gauze. The electrical pulses used were rectangular and monophasic. A stimulation frequency of 20 Hz, a pulse duration of 0.3 ms, and a stimulation amplitude of sufficient intensity to bring the legs into full extension were used. During the training, the patients were positioned supine with both lower extremities semiflexed to approximately 30 degrees by a pillow under the knees. The FES session lasted for a half-hour a day (1).

The effects of a muscle strengthening program were tested and assessed through isometric knee joint torque measurement. The isometric knee joint torque was assessed once every week in each incomplete SCI patient. The training program lasted for about 2 months. Both voluntary and electrically provoked knee joint torques were assessed in a group of 7 incomplete SCI patients and are presented in Fig. 1.

In the first subject, the incomplete T-11 spinal cord lesion resulted from a motorbike accident. The

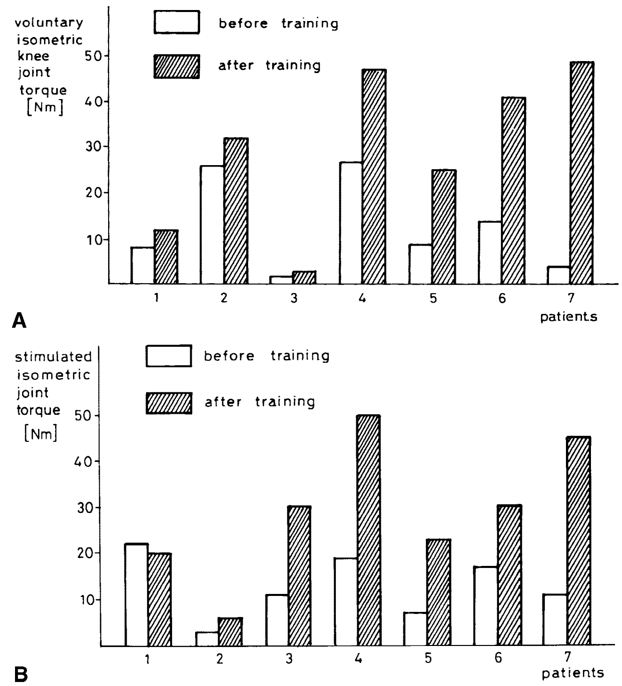


**FIG. 1.** The graph contrasts the maximal voluntary **(above)** and stimulated **(below)** knee joint torques assessed before and after an FES muscle training program.

stimulation was delivered to him 8 months after the injury. No improvement was observed in voluntary or stimulated response. The second subject had a C-6,7 incomplete SCI lesion after a car accident. He came to the spinal unit for electrical stimulation training purposes 2 years after the accident. It was evident that no effect was achieved by daily stimulation of his knee extensors. Because of a rather strong pain sensation, the voluntary responses were stronger than FES induced ones. The patient remained confined to a wheelchair. The third patient suffered a C-3,4 incomplete spinal cord lesion from a car accident. The electrical stimulation training program started 8 months after the injury. Both stimulated and voluntary joint torque had quite low values at the beginning of the program. The voluntary isometric torque remained at this initial value for the rest of the program. In contrast, the stimulated isometric knee joint torque was noticeably increased. After the rehabilitation program, the patient was able to walk with the help of a walker and bilateral m. quadriceps and n. peroneus stimulation for short distances only.

In the next 4 patients, considerable improvement in voluntary knee joint torque was observed. The fourth patient had an incomplete C-5,6 lesion after a stab wound. The improvements in maximal stimulated and voluntary torques were similar. The final result of the strengthening program was 50 Nm of voluntary knee joint torque. This was sufficient for unassisted standing. The patient was able to walk for short distances with the help of 2 crutches and 2 peroneal stimulators. She occasionally used a wheelchair. Patient 5 suffered a C-5,6 incomplete spinal cord lesion from a motor vehicle accident 8 months before being admitted to the rehabilitation center from the neurological clinic. Both stimulated and voluntary joint torques had quite low values at the beginning of the program and increased to about 30 Nm toward the end of the training process. The voluntary torque achieved was not enough to provide solid support. The patient used a wheelchair to a considerable extent. Similar results were obtained in Patient 6 suffering from a tumor at the C-2 spinal cord level. She came to the rehabilitation center 6 years after surgical intervention. Despite an increase in both voluntary and stimulated muscle forces, she was unable to stand unassisted. The seventh patient had an incomplete C-7 spinal cord lesion after a fall. When the electrical stimulation training started, it was 2 months after the injury. An increase of about 50 Nm was observed when comparing the initial and final results obtained during both electrically stimulated and voluntary muscle contractions. The voluntary knee joint torque, which increased from almost zero to about 50 Nm, was sufficient for unassisted walking with the help of 2 crutches. The patient was not using a wheelchair after leaving the rehabilitation center.

In the first 2 subjects presented in Fig. 1, no improvement was observed either in voluntary or stimulated response. Only the stimulated response was improved in the third subject. In the rest of the incomplete SCI patients, similar improvements were assessed in stimulated and voluntary responses.

## PERONEAL NERVE STIMULATION

On every incomplete SCI patient, several simple clinical tests were performed by physiotherapists upon arrival at the rehabilitation unit. First, the manual muscle test was completed. The muscle groups governing the hip movement (extensors, flexors, and abductors), knee movement (extensors and flexors), and ankle joint movement (dorsal and plantar flexors) were evaluated. In the manual muscle test, the responses to voluntary control were estimated by 9 grades (0, 1 −2, 2, −3, 3, −4, 4, and 5). It was observed that both the hip and ankle antagonists were rather severely affected in most of the subjects. The strongest muscle group was the knee extensors. The presence of superficial and deep sensation was also tested in each patient's paralyzed lower extremities. The presence of sensations was indicated by a yes/no answer. The spasticity in the major muscle groups of the lower extremities was estimated by 4 grades. Significant nonsymmetry of the neuromuscular properties of the right and left paralyzed legs was often observed in the group of incomplete SCI patients. The data pertaining to the severely handicapped extremity were taken into consideration for further computer analysis. The general patient data gathered included the year of birth, sex, date of accident, level of spinal cord lesion, and cause of accident or disease. Thirty-one incomplete SCI patients with central (thoracic or cervical) SCI were included in the present study. Only the patients who were unable to walk on the day of examination were taken into account.

Apart from regular therapeutic treatment, cyclic electrical stimulation for restrengthening unused atrophied muscles was delivered to the patients during several months of their stay in the rehabilitation center. In some patients FES for standing and walking was also applied (1). At release from the rehabilitation center, the patients were divided into the following 4 different classes regarding their locomotor capabilities: wheelchair users (19 patients), users of FES and crutches (4 patients), users of mechanical brace and crutches (2 patients), and no orthotic aid users (6 patients).

One channel electrical stimulators were given to the patients for chronic use after release from the rehabilitation center. One channel FES was delivered to the peroneal nerve, resulting in a flexion response of the lower extremity (9). In this way simultaneous hip and knee flexion and ankle dorsiflexion were obtained unilaterally and bilaterally, enabling the swing phase of walking. In this case, it must be noted that electrical stimulators were also given to 10 wheelchair users for gait exercise.

Machine learning tools have been applied in a variety of real world domains. These tools enable the induction of knowledge in different forms, for example, the form of rules or decision trees. In supervised machine learning, a set of examples with known classification is given. An example is described by an outcome (class) and the values of a fixed collection of parameters (attributes). Each attribute can either have a finite set of values (discrete attribute) or have real numbers as values (continuous attribute).

In this study, the program Classification and Regression (CART) (3) as implemented in the S-Plus package was used to construct decision trees. This tree induction algorithm belongs to the ID3 family of systems for top-down induction of decision trees.

The program recursively builds binary decision trees. The nodes of the tree correspond to attributes, arcs correspond to values or sets/intervals of values of attributes, and leaves (terminal nodes) correspond to predicted classes. In each recursive step of decision tree construction, an attribute is selected, and a subtree is built. The recursion stops when all examples belong to the same class, meaning that a generated leaf is labeled with the class of examples.

To classify a new case, a path from the root of the tree is selected on the basis of values of attributes of the new example to be classified. In this way, for a given example, the path leads to a leaf that assigns a class that labels the leaf. The selected path may be viewed as a generalization of the specific example for which the prediction is being determined. If a leaf is labeled with more than one class, each with the probability of class prediction, then the class with the highest probability is selected for the classification of a new case.

The decision tree prognosticating the ambulation abilities of incomplete SCI persons, as obtained through the machine learning approach, is shown in Fig. 2. At the root of the tree, the strength of the ankle dorsiflexors is tested. This is in good accordance with the FES rehabilitative method because peroneal stimulation predominantly results in improved ankle dorsiflexion. In patients with inadequate voluntary ankle dorsiflexion (less than 2), the strength of the knee extensors must be evaluated. This finding is in agreement with the observation of other authors (4,6). Patients with sufficiently strong knee extensors (over 2) are candidates for the use of a peroneal electrical stimulator and crutches. These patients can be considered community walkers. They can use an electrical stimulator for several hours per day during their daily activities. Patients with weak knee extensors are bound to the wheelchair. It is interesting to note that in patients with adequate ankle dorsiflexion (above –2), the voluntary strength of the knee extensor contraction does not have to be tested. These patients are divided on the basis of their age. Older patients are wheelchair users while younger patients can walk without any orthotic aid.

In our study of the prediction of walking abilities in incomplete SCI persons, the data on sensation and spasticity were not found to be relevant, and that is not quite in accordance with some authors (7,10). In further computer analysis of the data gathered, the group of wheelchair users was divided into patients using FES and the wheelchair and those making use of the wheelchair only. No sensible decision tree was obtained in this case. This outcome can be considered as an indication that FES is not really necessary in incomplete SCI patients who are bound to the wheelchair. These patients can only be treated as exercise walkers using FES for about half an hour per day for therapeutic purposes.

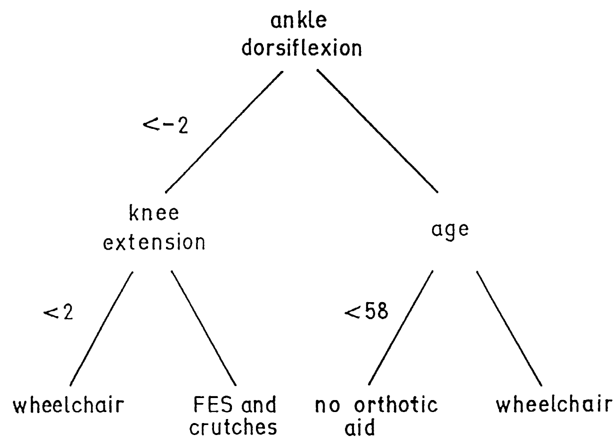


**FIG. 2.** The decision tree shown is for predicting the ambulation capabilities of incomplete SCI subjects.

## ANKLE PLANTAR FLEXOR STIMULATION

The effectiveness of FES delivered during gait to the ankle plantar flexors to obtain an improved swing phase of walking was evaluated experimentally. It was hypothesized that FES of the ankle plantar flexors might provide lifting of the heel, upward propulsion to the swinging leg, and flexion of the knee. Electrical stimulation was delivered to the ankle plantar flexors unilaterally during crutch assisted walking of a group of 5 incomplete SCI patients. One of the patients had a thoracic lesion while the rest had cervical lesions of the spinal cord. All patients were selected from a group of SCI subjects who had 1 leg almost completely paralyzed and the other leg under satisfactory voluntary control.

Three stimulation sequences were investigated. Within the first stimulation sequence, only the peroneal nerve was stimulated. The sequence was controlled by a hand triggered push button built into the handle of a crutch. In this stimulation strategy, the flexion response was elicited with a 50 Hz frequency stimulus. In the second stimulation sequence, FES of the ankle plantar flexors was applied. To obtain strong and fast propulsion, a stimulation frequency of 50 Hz was used to stimulate the calf muscles. The third stimulation sequence was started by stimulation delivered to the ankle plantar flexors lasting for 0.3 s and was completed by the stimulation delivered to the peroneal nerve. In all examples of stimulation sequences, the same amplitudes and pulse durations of stimuli were used (2).

The movements of the swinging leg were assessed by an OPTOTRAK optical measuring system (OPTOTRAK/3010, Nothern Digital Inc., Waterloo, Ontario, Canada). Four markers were placed on the estimated anatomical positions of the hip, knee, ankle, and metatarsal joints in the sagittal plane. In this report, we are presenting the knee goniograms as assessed during 3 consecutive steps of a tetraparetic subject when walking with the use of the 3 stimulation sequences (Fig. 3). The maximal swings were increased when stimulation was applied to the ankle plantar flexors. However, the most significant difference between the 2 gait patterns is evident from the swing time duration, which decreased by almost 50% when FES of the calf muscles was used. A shorter swing phase may result in faster walking by incomplete SCI subjects. A decrease in the walking cycle time of about 15% can also be observed in the middle trace. In this case, it must be stressed that the foot remained in plantar flexion throughout the swing phase. When adding the stimulation of the peroneal nerve after a short burst of stimuli delivered to the ankle plantar flexors (bottom trace), the duration of the swing phase was somewhat increased. However, the appearance of the swinging leg was more cosmetic because of adequate dorsiflexion of the foot.

In this study, we observed that in incomplete SCI subjects, stimulation with electrodes positioned on the posterior side of the calf over the triceps surae

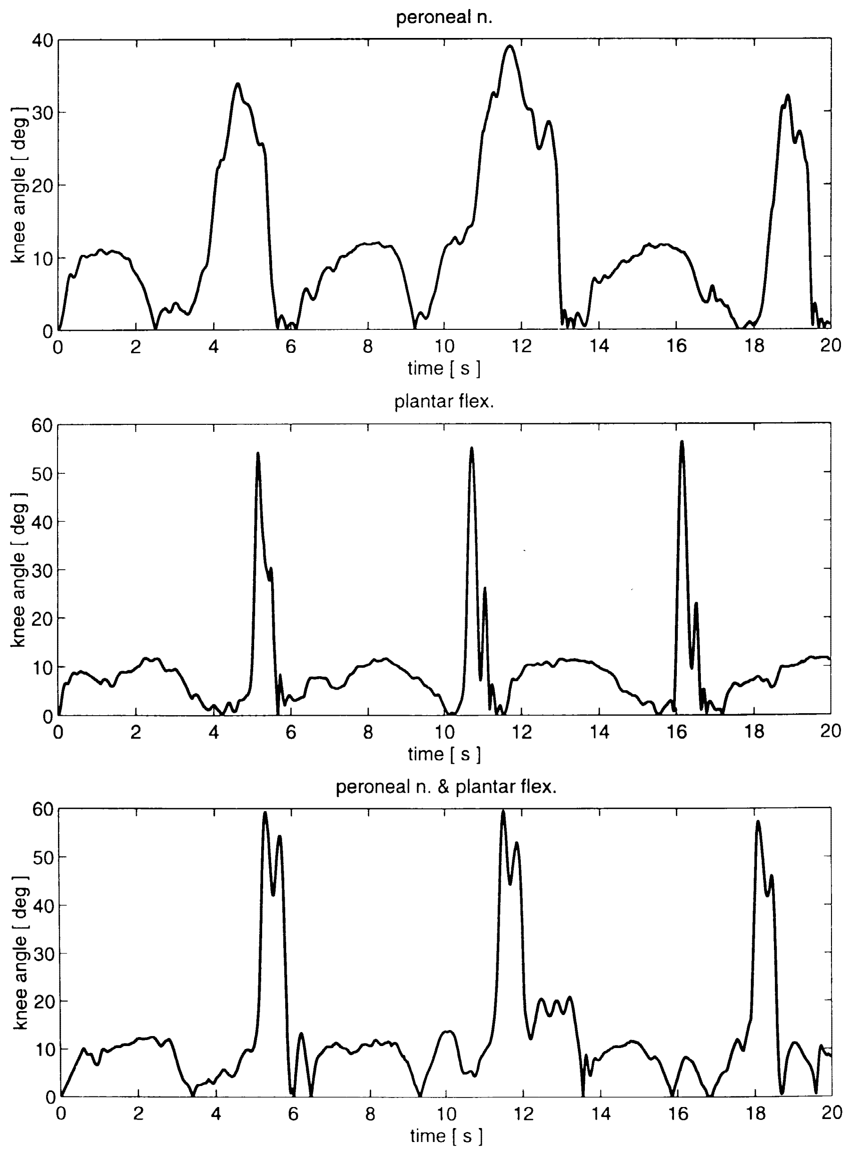


**FIG. 3.** The knee goniograms shown were made during walking with peroneal nerve stimulation **(upper trace)**, with stimulation delivered to the ankle plantar flexors **(middle trace)**, and with stimulation of the ankle plantar flexors and peroneal nerve **(bottom trace)**.

muscle can also provoke the flexion response of the whole limb. Electromyographic recordings showed that surface electrical stimulation over the belly of the ankle plantar flexors results in afferent stimulation and efferent stimulation of the same muscle. By electromyogram (EMG) examination, bursts of flexion reflex activity have been observed in the thigh muscles. Thus, the surface electrical stimulation of the calf muscles results in complex movements consisting of a combination of the efferently provoked ankle plantar flexion and knee flexion, and also the afferently evoked flexion withdrawal response (2).

We demonstrated that FES of the ankle plantar flexors results in a significantly shorter swing phase, which may provide a higher gait speed in incomplete SCI patients. It appears that electrical stimulation of the ankle plantar flexors delivered during the toe-off phase has a similar effect to hip extension produced by the treadmill movement. Hip extension at the end of the stance phase often induces involuntary hip flexion, initiating the swing phase of walking (12). Adding the stimulation of ankle plantar flexors is also essential when producing a high step for a paralyzed extremity. This may be required when walking over rough, uneven terrain, when overcoming obstacles such as pavement curbs, and when climbing stairs.

## CONCLUSIONS

The following conclusions can be redrawn from this review presentation. First, FES training of the knee extensors was found effective in the majority of incomplete SCI subjects in the early period of the rehabilitation process. Second, the voluntary response in knee extensors improved in most of the patients who had been unable to walk in the beginning of the training program. Only rare incomplete SCI patients are candidates for application of permanent FES to their quadriceps muscles. Third, a diagnostic procedure was developed predicting soon after the accident which incomplete SCI patients are candidates for permanent use of an FES orthotic aid. Fourth, peroneal nerve stimulation was found useful in at least 10% of incomplete SCI patients to augment dorsiflexion, knee, and hip flexion in a total lower limb reflex pattern. Stimulation of the ankle plantar flexors results in a significantly shorter swing phase, which may provide a higher gait speed. The stimulation of ankle plantar flexors is essential when producing a high step for a paralyzed extremity. This may be required when walking over rough, uneven terrain, when overcoming obstacles such as pavement curbs, and when climbing stairs.

We can talk about 2 possible applications of FES to incomplete SCI patients. The first is for short-term therapeutic treatment in the clinical environment. The second application is for permanent orthotic use of an FES rehabilitative system.

In the beginning of therapeutic FES treatment, cyclical electrical stimulation can be used with the goal of restrengthening atrophied muscles, increasing the range of motion, and reducing spasticity (5). Electrical stimulation can also be used to predict the extent to which an incomplete SCI patient could improve, as well as to foresee the period within which the patient will increase his strength to a useful level. The comparison of voluntary and electrically elicited responses soon after an injury yields additional information for prognosis. In this case, it should be stressed that FES represents one of the rare rehabilitative approaches for incompletely paralyzed subjects soon after the accident, not only returning them to a vertical position but also restoring their walking patterns (8).

When the recovery at this early therapeutic FES phase is not sufficient, the incomplete SCI patient is a candidate for the life-long application of an FES orthotic system. As a result of greater preserved exteroception and proprioception, most of these patients are excellent candidates for implanted FES systems, which can turn them into community walkers, effectively using the stimulator throughout the day.

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## REFERENCES

1. Bajd T, Kralj A, Turk R, Benko H, Šega J. Use of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injuries. *J Biomed Eng* 1989;11:96–102.
2. Bajd T, Štefančič M, Matjačić Z, Kralj A, Šavrin R, Benko H, Karčnik T, Obreza P. Improvement in step clearance via calf muscle stimulation. *Med Biol Eng Comput* 1997;35:113–6.
3. Breiman L, Friedman JH, Olshen RA, Stone CJ. *Classification and regression trees*. Belmont, CA: Wadsworth Int. Group, 1984.
4. Crozier KS, Cheng LL, Graziani V, Zorn G, Herbison G, Ditunno JF. Spinal cord injury: Prognosis for ambulation based on quadriceps recovery. *Paraplegia* 1992;30:762–7.
5. Granat MH, Ferguson ACB, Andrews BJ, Delargy M. The role of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injury–observed benefits during gait studies. *Paraplegia* 1993;31:207–15.
6. Jacobs SR, Yeaney NK, Herbison GJ, Ditunno JF. Future

ambulation prognosis as predicted by somatosensory evoked potentials in motor complete and incomplete quadriplegia. *Arch Phys Med Rehab* 1995;76:635–41.
7. Katoh S, El Masry WS. Motor recovery of patients presenting with motor paralysis and sensory sparing following cervical spinal cord injuries. *Paraplegia* 1995;33:506–9.
8. Stein RB, Belanger M, Wheeler G, Wieler M, Popović DB, Prochazka A, Davis LA. Electrical systems for improving locomotion after incomplete spinal cord injury: An assessment. *Arch Phys Med Rehab* 1993;74:954–9.
9. Štefančič M, Kralj A, Turk R, Bajd T, Benko H, Šega J. Neurophysiological background of the use of functional electrical stimulation in paraplegia. *Electromyogr Clin Neurophysiol* 1986;26:423–35.
10. Tang SFT, Tuel SM, Mc Kay BW, Dimitrijević MR. Correlation of motor control in the supine position and assistive device used for ambulation in chronic incomplete spinal cord-injured persons. *Am J Phys Med Rehab* 1994;73:268–74.
11. Waters RL, Ien S, Adkins RH, Yakura JS. Injury pattern effect on motor recovery after traumatic spinal cord injury. *Arch Phys Med Rehab* 1995;76:440–3.
12. Wernig A, Müller S. Laufband locomotion with body weight support improved walking in persons with severe spinal cord injuries. *Paraplegia* 1992;30:229–38.