Improvement in step clearance via calf muscle stimulation

T. Bajd[1] M. Štefančič[2] Z. Matjačić[1] A. Kralj[1] R. Šavrin[2]
H. Benko[2] T. Karčnik[1] P. Obreza[2]

[1]Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia
[2]Republic of Slovenia Institute for Rehabilitation, Ljubljana, Slovenia

Abstract—*The aim is to study the influence of electrically stimulated calf muscles on the effectiveness of the swinging leg movement. The study is carried out with a group of patients with incomplete spinal cord injuries both under stationary conditions and during crutch-assisted walking. Before stimulation is applied to the ankle plantar flexors, the knee extensors are inactivated. In each cycle, after ankle plantar flexor stimulation, peroneal stimulation is started, triggering the flexion reflex. From a biomechanical point of view, functional electrical stimulation (FES) of the ankle plantar flexors results in increased ground clearance of the lower extremity. Additionally, the FES-assisted lifting of the heel results in the elimination of extensor tone and thus shortens the swing time.*

Keywords—*Functional electrical stimulation, Gait, Spinal cord injury*

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1 Introduction

THE ANKLE plantar flexors provide significant energy during the push-off phase of human walking and are easily accessible by both surface and implanted functional electrical stimulation (FES). However, because of the lack of the biomechanical knowledge required to synthesize gait in paralysed people the flexors are used only to a limited extent in FES-assisted walking schemes (KOBETIC and MARSOLAIS, 1994). In our preliminary experiments (BAJD *et al.* 1994), we studied the influence of stimulated ankle plantar flexors on the displacement of the centre of body (COB) in the direction of walking. In FES-assisted walking in incomplete spinal cord injury (SCI) patients (BAJD *et al.*, 1995), a noticeable improvement was observed in the instantaneous horizontal velocity of the COB when FES was applied to the ankle plantar flexors. It was found to be more continuous and fluid and more like normal walking patterns.

In the studies performed on uninjured subjects, no important increase was found in the COB energy, resulting from ankle plantar flexor activity (WINTER and ROBERTSON, 1978; HOF *et al.*, 1993). Only a small part of the energy generated by the calf muscles is propagated through the knee joint, and even less energy continues across the hip joint to the trunk. Obviously, as the work of the ankle plantar flexors is not stored in the COB, it must be used in providing kinetic energy, most probably the energy used for the initiation of the swing phase.

In this work we studied the influence of electrically stimulated calf muscles on the effectiveness of the leg swing movement. It was hypothesised that FES of the ankle plantar flexors may provide the following three important gait functions:

(*a*) lifting the heel in preparation of the leg for the swing phase
(*b*) providing the upwards propulsion to the swinging leg
(*c*) enabling knee flexion and thus raising the swinging leg to clear the floor.

These three features of the gait may result in a higher trajectory of the foot during the swing phase of walking.

The hypothesis was partially based on the following clinical practice and observations. Fairly large surface stimulation electrodes are usually placed over both the m. soleus and m. gastrocnemius. M. gastrocnemius is a bi-articular muscle that extends from the heel to the thigh. When the knee joint is in a slightly flexed position, the m. gastrocnemius not only maintains the ankle in plantar flexion but can also provoke further knee flexion.

The hypothesis was tested on a group of patients suffering from incomplete spinal cord lesion, with one leg almost completely paralysed and the other leg under voluntary control and sufficiently strong to provide safe standing.

2 Methods

2.1 *Protocol*

The FES-assisted push-off phase was realised by controlling three channels of stimulation delivered to the ankle plantar flexors, knee extensors and peroneal nerve. The stimulation sequence started with FES of the knee extensors, which were active during the entire mid-stance phase. When the knee extensor stimulation burst was completed, electrical stimulation was delivered to the ankle plantar flexors. An adequate

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swing phase was accomplished by triggering the flexion response of the whole lower extremity through the stimulation of the peroneal nerve. Proper timing of the three stimulation sequences was based on the measurements of incomplete SCI patients.

An important gait parameter is the delay between the start of the stimulation of the peroneal nerve and the occurrence of maximal knee and hip flexion due to the flexion withdrawal response. This latency was found to be in the range of 0.5–0.75 s (KRALJ and BAJD, 1989; GRANAT *et al.*, 1993). Similarly, a delay of 0.3 s was observed between the beginning of the stimulation applied to the ankle plantar flexors and the maximal vertical reaction force (BAJD *et al.*, 1994). Based on these data, the duration of the peroneal nerve stimulation causing the flexion response stimulation was selected to be 0.5 s, and 0.3 s was determined to be the most adequate duration for the stimulation of the ankle plantar flexors.

Three combinations of stimulation sequences, characterised by different stimulation frequencies, were investigated. They are displayed in Fig. 1. The first two-channel stimulation sequence belongs to our present simple FES gait pattern, where only the knee extensors and the peroneal nerve are stimulated (KRALJ and BAJD, 1989). The sequence was controlled by a hand-triggered push-button. In this stimulation strategy, the stimulation frequency of both channels was 20 Hz. In the second two-channel stimulation sequence, the peroneal stimulation frequency was increased to 50 Hz to reduce the latency of the withdrawal response (GRANAT *et al.*, 1993), while the stimulation frequency of the knee extensors remained unchanged. In the third three-channel stimulation sequence, FES of the ankle plantar flexors was added. To obtain strong and fast propulsion, a stimulation frequency of 50 Hz was used to stimulate the calf muscles. The stimulation frequency of the knee extensors was 20 Hz, and the peroneal nerve was stimulated at 50 Hz. The positioning of the surface electrodes over the knee extensors, ankle plantar flexors and peroneal nerve is described in our previous work (BAJD *et al.*, 1995). The amplitudes for all three stimulation channels were selected before the test, when the subject was in a sitting position. In all three examples of stimulation sequences, the same amplitudes were used for each subject. The intensity of the flexion response triggering was calibrated at 50 Hz. The same amplitude of peroneal stimulation was used when the frequency was reduced to 20 Hz in the first stimulation sequence.

2.2 *Subjects*

General data on five incomplete SCI patients who took part in the investigation are presented in Table 1. All patients were selected from a group of SCI subjects who had one leg almost completely paralysed and the other leg under satisfactory

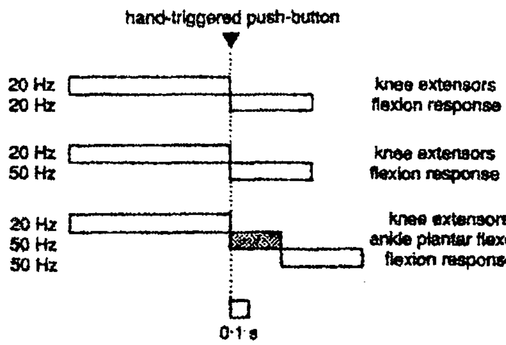

Fig. 1 *Electrical stimulation sequences delivered to knee extensors, ankle plantar flexors and peroneal nerve*

Table 1 General data on five incomplete SCI patients

subject	sex	Age, years	SCI level	time post-injury
1	F	34	T11, 12	5 months
2	M	24	C7	8 months
3	M	18	C7	1 year 11 months
4	M	18	C6	2 years 1 month
5	M	45	C6–T1	4 months

voluntary control. The described stimulation sequences were applied only unilaterally (on the affected leg). In the first four SCI patients (Table 1), repeated measurements were performed under stationary conditions. During the measurements, the incomplete SCI subjects stood supported by parallel bars. The body weight was shifted to the less affected leg. Thereafter, a hand- triggered push-button, controlling the electrical stimulation delivered to the severely paralysed leg, was voluntarily activated by the patient. The test was repeated three times in each SCI subject. In the fifth patient, the second and third sets of stimulation sequences (Fig. 1) were applied during crutch-assisted walking. In this case, the stimulation delivered to the peroneal nerve was discontinued after releasing the hand-triggered push-button built into the handles of the crutches.

2.3 *Instrumentation*

The three stimulation sequences described were generated by an MC68HC705 microcontroller-based four-channel electrical stimulator. The stimulator is primarily intended for locomotor rehabilitation of incomplete SCI patients. The stimulator software is divided into two parts. The first part is represented by a software package for the FES gait pattern synthesis. The package is written in an object-oriented programming language and runs under the Windows* operating system. The synthesised gait pattern can be edited on a personal computer and, when completed, downloaded via a serial link into the microcontroller memory. The second part of the stimulator software is an assembler program that generates stimulation pulses and interprets the loaded stimulation sequences. The amplitude of the stimuli is in the range 0–150 V and is manually adjustable by potentiometers, separately for each stimulation channel. The microcontroller allows different stimulation frequencies for each channel. Four possible stimulation frequencies are 20, 25, 33.3 and 50 Hz. The pulse width is permanently set to 300 μs.

The movements of the swinging leg were assessed by a contactless measuring system†. It consists of two pre-calibrated position camera systems that permit measurement of 3-D marker co-ordinates at 50 Hz sampling rate and accuracy of 0.35 mm. Four markers were placed on the estimated anatomical positions of the hip, knee, ankle and metatarsal joints in the sagittal plane. The data were collected and checked on a 486 computer and further processed on a UNIX-based§ workstation, equipped with commercial software** and custom-written subroutines.

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* trademark

† OPTOTRAK 3010, Northern Digital Inc., Waterloo, Ontario N2L 3V2, Canada

§ HP 9000/700

** Matlab

3 Results

The aim of this study was to evaluate experimentally the effectiveness of FES delivered during gait to the ankle plantar flexors to obtain an improved swing phase. It was hypothesised that the ankle plantar flexors provide a raising of the heel and also contribute to the propulsion and knee flexion of the swinging lower extremity. The maximal vertical swing of the metatarsal joint was found to be a particular interesting parameter when estimating the swinging leg movement. This parameter directly correlates to the propulsion of the swinging limb in the upwards direction and is of interest when planning tasks such as overcoming pavement kerbs or climbing stairs.

The measurements of the maximal vertical swing were first performed under stationary conditions in incomplete SCI subjects 1–4 (Table 1). The measurement results of the maximal vertical swing of the metatarsal joint in the sagittal plane are displayed in Fig. 2. The first two columns belong to stimulation sequences 1 and 2 where only the flexion response was elicited, first with a 20 Hz and secondly with a 50 Hz stimulation frequency. In the third column, the FES of ankle plantar flexors was added. The measurements with each stimulation sequence were performed three times in each subject, with a 30 s interval between each test. As the electrode position remained unchanged, only small differences were observed among the data.

As an example of the repeatability of the measured results, a sequence of three consecutively measured maximal swings of the metatarsal joints are shown, as measured during the application of stimulation sequence 3 to subject 4. The following are the three readings of the vertical maximum in the metatarsal joint trajectory: 10.5 cm, 11.1 cm and 10.6 cm. Therefore, only one example of the measurement results of the single stimulation sequence is shown in Fig. 2.

It is noticeable that stimulation of the ankle plantar flexors resulted in increased responses in incomplete SCI patients 1–4 (Table 1). The influence of stimulated calf muscles is especially evident in subjects 1, 3 and 4, where the flexion response alone was considerably less effective. In the second patient, increasing the stimulation frequency of the flexion response (stimulation sequence 2) resulted in a noticeable improvement in the upwards swing. The stimulation amplitudes were adjusted according to the requirements of level walking. By increasing the stimulation amplitude of the ankle plantar flexors, the stimulated extremity can be lifted sufficiently to be placed on a pavement kerb or a stair.

Figure 3 represents the maximal swing of the whole lower extremity, as produced by the three stimulation strategies. The data, belonging to subject 1 (Table 1), were assessed during stationary conditions. The vertical co-ordinates of the metatarsal joint (black dot) correspond to the three maximal vertical swings assessed in subject 1 and displayed in Fig. 2.

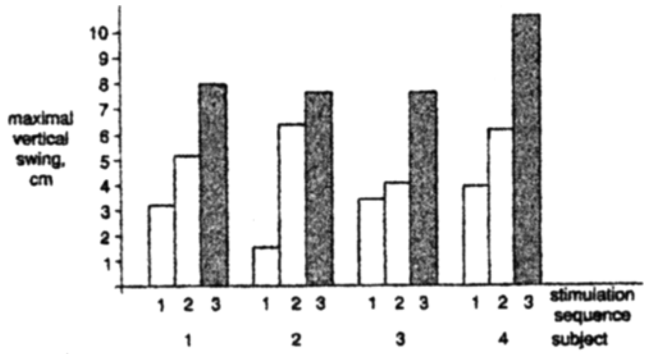

Fig. 2 *Maximal vertical swing of metatarsal joint resulting from application of three stimulation sequences*

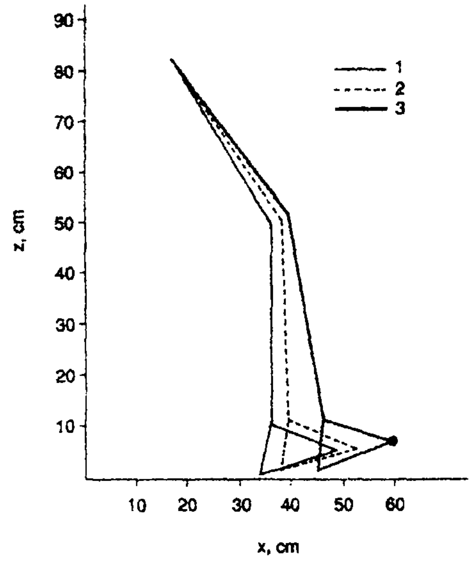

Fig. 3 *Maximal swing of extremity as accomplished by three stimulated sequences; black dot represents the metatarsal joint marker; 1-3 = stimulation sequences*

Improved maximal horizontal swing of the metatarsal joint was also observed when electrical stimulation was applied to the ankle plantar flexors.

The vertical swings of the metatarsal joint, as assessed in three consecutive steps during walking in subject 5 (Table 1), are presented in Fig. 4. Figure 4*a* shows the resulting trajectories for the second stimulation sequence in a severely paralysed limb. By adding FES to the ankle plantar flexors (stimulation sequence 3), the results from Fig. 4*b* were obtained. Similar to the results obtained under stationary conditions (Fig. 2), the maximal vertical swings are increased when stimulation is applied to the ankle plantar flexors. However, the most significant difference between the two gait patterns is evident from the swing time durations, which decrease by almost 50% when FES of calf muscle is added. 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 from Fig. 4. When this last patient was dismissed from the rehabilitation centre several months after the measurements, he was equipped with a single-channel commercially available peroneal stimulator.

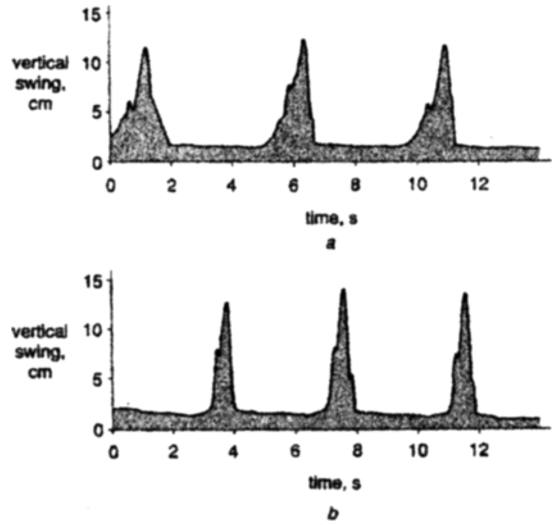

Fig. 4 *Trajectory of vertical swing of metatarsal joint during walking (a) without and (b) with stimulation delivered to ankle plantar flexors*

Subsequently, he reported that he was missing the active push-off produced by electrical stimulation of the ankle plantar flexors.

4 Discussion

The significance of electrically stimulated ankle plantar flexors to incomplete SCI patients was evaluated during FES-assisted waling. Three conclusions were deduced from the experimentally assessed kinematic data.

(*a*) The first conclusion was drawn from comparing the data from this investigation with our previous results (BAJD *et al.*, 1994). It appears that FES-assisted gait is more efficient if the energy produced by the stimulated ankle plantar flexors is directed to the swinging leg rather than to the upper body. To prevent energy transfer to the upper body, FES of the knee extensors must be completed before stimulation of the ankle plantar flexors.
(*b*) Stimulation of ankle plantar flexors under the new regimen results in a significantly shorter swing phase, which may provide a higher gait speed. This is particularly important for incomplete SCI patients who are excellent candidates for community walkers when assisted by multi- channel FES.
(*c*) Adding the stimulation of ankle plantar flexors is essential when producing a high step for a paralysed extremity. This may be required when walking over rough, uneven terrain, when overcoming obstacles such as pavements and when climbing stairs.

In our previous study on myoelectric events during FES, the combined effects of efferent and afferent stimulations were observed during stimulation of the peroneal nerve in the swing phase of clinically complete paraplegic patients (ŠTEFANČIČ *et al.*, 1986). A dorsal flexion and eversion of the foot, followed by a slight flexion of the knee and the hip joint, was achieved in the stimulated leg. This indicated two myoelectric phenomena: a direct response (*M*-waves) in the muscles innervated by the peroneal nerve with a short latency of some milliseconds (efferent stimulation) and late reflex responses with a longer latency, or bursts of flexion reflex activity in hamstrings and even extensors of the knee (afferent stimulation). Both efferent and afferent responses were found suitable to be utilised for obtaining advantageous movement of the leg in the swing phase.

In this study, we have observed that, in incomplete SCI subjects, stimulation with the electrodes positioned on the posterior side of the calf over the triceps surae 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 EMG examination of the fifth subject (Table 1), burst 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.

The effects of the electrically stimulated ankle plantar flexors were more pronounced during walking than when the limb was stimulated under stationary conditions, mimicking the swing phase of gait. FES applied during the toe-off phase of walking not only resulted in an increased maximal vertical swing of the metatarsal joint, but also significantly shortened the swing time and cycle duration of walking. These improvements cannot be attributed solely to the biomechanical behaviour of the ankle joint under the influence of the stimulated calf muscles. In the feline spine (CONWAY *et al.*, 1987), for example, the increased load of the limb extensors during the stance phase enhances and prolongs extensor activity while simultaneously delaying the transition to the swing phase. The difficulty in being able to break the extensor activity appears to be one of the major causes for the low speed of FES-assisted walking in spinal cord injured subjects. In the present FES gait patterns, patients unload the affected leg, which is in transition from stance to swing, by transferring the body weight predominantly to the walking aid. This activity is performed by the arms and preserved trunk muscles, and is reflected in a slow and energy-inefficient walking process. It has been demonstrated that electrical stimulation of ankle plantar flexors, with the knee joint inactivated, results in lifting of the heel. As a consequence, unloading of the ankle plantar flexors occurs, which seems to be necessary to decrease the extensor tone and allow the peroneal stimulation to generate the swing phase.

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Author's biography

Tadej Bajd graduated from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 1972, where he also obtained his MSc and DSc in 1976 and 1979, respectively. He was a Research Assistant at the J. Stefan Institute in Ljubljana and visiting Research Fellow at the University of Southern California, Los Angeles, and Strathclyde University, Glasgow, UK. He is currently Professor of Robotics at the Faculty of Electrical Engineering, University of Ljubljana. He is author and co-author of 50 journal papers in the fields of biomedical engineering and robotics. He has received the Slovene national award for his scientific achievements in the field of functional electrical stimulation for paralysed subjects. He is President of Slovene Society for Medical and Biological Engineering, a member of IFMBE, senior member of IEEE, and a member of the Council of the ESEM.