Communication

Voluntary commands for FES-assisted walking in incomplete SCI subjects

T. Bajd[1] M. Munih[1] A. Kralj[1] R. Šavrin[2] H. Benko[2]

[1] Faculty of Electrical Engineering and Computing, University of Ljubljana, Tržaška 25, 61000 Ljubljana, Slovenia
[2] Republic Slovenia Institute for Rehabilitation, Ljubljana, Slovenia

Keywords—*Functional electrical stimulation (FES), Gait, Spinal cord injury (SCI)*

Med. & Biol. Eng. & Comput., 1995, **33**, 334–337

1 Introduction

THE PERIODIC process of human gait appears more appropriate for the application of automatic control principles than manipulative movements of the upper extremities. However, in the synthesis of functional electrical stimulation (FES)-assisted walking in complete and incomplete spinal cord injured (SCI) humans, voluntary commands play an important role. Paraplegic or paretic walking must be, to a large extent, under the patient's voluntary control because of the following two reasons:

(i) synchronisation of natural movements of the upper non-paralysed part of the body with FES provoked movement of the paralysed lower limbs.
(ii) difficulty in walking over rough, uneven terrain or in an environment with obstacles.

The voluntary command sensor mounting site should be selected and designed to require as little conscious effort as possible. Speed and reliability of command processing are extremely important in lower limb FES systems (CHIZECK *et al.*, 1988). The simplest voluntary command sensor is the heel switch introduced to aid walking in hemiplegic patients (LIBERSON *et al.*, 1961). The switch is located in the sole of the shoe on the affected leg. When the patient is voluntarily raising the heel of the affected leg, the heel switch triggers the stimulator, causing the dorsiflexion of the foot during the swing phase of walking. In the restoration of simple reciprocal walking in paraplegic patients, a crutch hand switch has been introduced (KRALJ and BAJD, 1989). This is a pushbutton built into the handle of the crutch. By pressing and releasing the pushbutton, patients with complete leg paralysis are voluntarily dividing the gait cycle into the swing and stance phase.

Patient commands can also be issued by the use of a joystick-type hand switch (MARSOLAIS *et al.*, 1991). Here, not only is each successive step triggered by pushing one of the pushbuttons, but preprogrammed individualised stimulation sequences for standing, stair-climbing, descent, backstep and sidestep can also be selected.

In incomplete SCI patients' walking assisted by FES, the command sensor mounting sites can be divided into two categories:

(*a*) sensors attached to the non-paralysed part of the body.
(*b*) sensors attached to incompletely paralysed extremities.

It is not difficult to realise that, in completely paralysed paraplegic patients, command sensors can only be used in the upper non-paralysed body. In addition to hand switches, crutch load sensors (ANDREWS *et al.*, 1988) and EMG signals (GRAUPE *et al.*, 1983), joysticks, shoulder and head transducers or voice actuation can also be applied. In incompletely paralysed patients, such as stroke and head injury patients or paraparetic and tetraparetic SCI patients, the command inputs can also be selected on their partially paralysed lower limbs. As well as different foot switches, goniometers and accelerometers can be also used. In incompletely paralysed patients, both categories of command transducers can be used simultaneously, which gives us a very large palette of different control possibilities. By using several sensors, the gait cycle can be divided into as many phases as desired. Each phase of the gait cycle can be characterised by different stimulation sequence.

In this work, we are proposing a combination of two simple command transducers, a crutch hand switch and a crutch tip switch, for the voluntary control of FES-assisted walking in incomplete SCI patients.

Correspondence should be addressed to Professor Tadej Bajd, DSc.
First received 7 February and in final form 25 July 1994

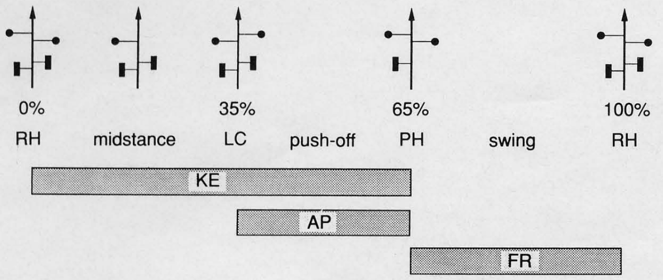

Fig. 1 *Graphic representation of gait control events: loading of crutch (LC); pressing of hand swtich (PH); releasing of hand switch (RH); stimulation sequences delivered to knee extensors (KE), ankle plantarflexors (AP) and triggering the flexion reflex (FR)*

2 Methods

Our previous studies (BAJD *et al.*, 1989) revealed that, in a great number of incomplete patients, one leg was severely paralysed while the other leg was under sufficient voluntary control. Unilateral three-channel stimulation of knee extensors, the peroneal nerve and ankle plantarflexors was proposed as an orthotic aid for this group of patients.

The four-channel stimulator used in the present investigation is designed for clinical and personal home use by both completely and incompletely paralysed SCI subjects. The stimulator enables four-channel unilateral restoration of gait pattern in incomplete SCI subjects, 2 + 2-channel bilateral restoration of gait pattern in complete SCI patients (KRALJ and BAJD, 1989), and four-channel training of atrophied paralysed muscles. Special features of the stimulator are the output stages based on the resonant switching approach and characterised by low energy consumption. The control circuit was developed in sequential digital logic by use of the AC circuit family* and low-consumption EPROM memory. Reprogrammable EPROM enables relatively fast replacement of the existing stimulation protocol with a new one, while the old EPROM can be stored and reused when needed.

Surface electrical stimulation of knee extensors is delivered to the muscles through large (6 × 4 cm) electrodes covered with water-soaked layers of gauze. The peroneal nerve is stimulated with the first electrode (2 cm diameter) near the popliteal fossa and with the second electrode behind the fibular head above the trunk of the superficial peroneal nerve. The stimulation of the peroneal nerve provokes a flexion reflex resulting in simultaneous flexion of hip and knee and ankle dorsiflexion. Ankle plantarflexors are stimulated with two round (6 cm diameter) surface electrodes. The electrical pulses used are rectangular and monophasic. A stimulation frequency of 20 Hz and a pulse duration of 0.3 ms are used. Owing to the preserved pain sensation in incomplete SCI patients, the maximal stimulation amplitudes ranges in most cases from 70 to 90 V.

The voluntary control of the stimulator is realised by the help of two transducers; a crutch hand switch and a crutch tip switch. Three gait control events are obtained from both sensors:

(i) loading of the crutch (LC).
(ii) pressing of the hand switch (PH).
(iii) releasing of the hand switch (RH).

In Fig. 1, the three control events are displayed together with a graphic representatin of the reciprocal four-point gait pattern and three-channel stimulation sequences. The direction of progression is represented by the arrows. The crutches are depicted by the dots and the rectangles indicate both feet. When a foot or a crutch is lifted from the ground, it is omitted from the graphic representation. The three control events divide the gait cycle into three distinct phases: midstance, push-off and swing phase. The duration of each phase, presented as a percentage of the gait cycle (Fig. 1), corresponds to the measurements performed in an incomplete SCI patient. The midstance phase is characterised by the stimulation of knee extensors (KE) providing support to the body. Stimulation of knee extensors and ankle plantarflexors (AP) occurs in the trailing leg during the push-off phase. Stimulation of plantarflexors starts at the landing of the ipsilateral crutch and is discontinued at the pressing of the hand pushbutton (PH). The aim of plantarflexor stimulation is to improve the forward propulsion of the body.

In our preliminary investigation (BAJD *et al.*, 1994), it was observed that there is a delay of about 0.3 s between the start of FES in ankle plantarflexors and maximal vertical reaction force in the trailing leg. Thus, a rather long duration of the push-off phase is chosen in our FES control scheme. During the swing phase, the stimulation of knee extensors and ankle plantarflexors is discontinued and flexion reflex (FR) is triggered, providing swinging of the leg. As the stimulator is used predominantly for gait training in a clinical environment, patients are taught to stop walking at the step performed by the less affected extremity when no FES is applied.

3 Results

The proposed voluntary control over FES-assisted walking was tested on an 18 year old incompletely paralysed patient with C-7 cervical spinal cord lesion. The patient was selected

Fig. 2 *Tetraparetic patient walking with the help of unilateral three-channel FES and crutch support*

* Advanced CMOS Logic, Harris Corporation

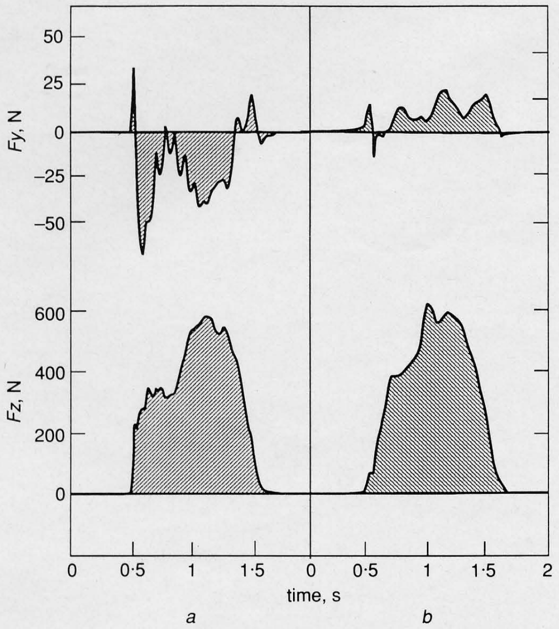

Fig. 3 *Horizontal and vertical ground reaction forces as assessed during gait of tetraparetic patient (a) walking without FES and (b) assisted by stimulation of knee extensors, peroneal nerve and ankle plantarflexors*

from a group of SCI subjects, with one leg almost completely paralysed and the other under voluntary control and sufficiently strong to provide safe standing. Three-channel FES was therefore applied only unilaterally.

Three-channel FES gait training was performed for a period from seven months up to one year after the injury. The patient was walking daily with the help of FES. Fig. 2 shows the tetraparetic patient while walking assisted by FES delivered to the right knee extensors, peroneal nerve and ankle plantarflexors, and supported by crutches instrumental with hand and tip switches.

Our interest is mainly in the push-off phase of the FES synthesised walking. For this purpose, the ground reaction forces are assessed under the severely paralysed extremity. The measurements are taken from two force plates† placed one after another in the direction of walking. In this way, the measured subject succeeds in almost all walking sessions to step appropriately on either of the force places. Special software measures the correct data in the cases when a step is made with a single foot on both force plates simultaneously.

In addition to force plate measurements, the instantaneous horizontal velocity of the centre of mass (COM) of the body is assessed. It is derived by differentiation and filtering (6th-order lowpass digital Chebyshev filter with 0.5 dB of ripple in the passband and cut-off frequency of 2.5 Hz) from the positional data obtained by the use of the contactless OPTOTRAK measuring system§. Our measuring system includes two precalibrated position camera systems which permit measurement of 3-D marker co-ordinates bilaterally. One OPTOTRAK marker is placed in the estimated anatomical position of the COM. In adult humans, the COM is located at the height of the second sacral vertebra. The OPTOTRAK system allows us to acquire data at 50 Hz sampling rate and with an accuracy of 0.35 mm. The force plate and OPTOTRAK data are collected and checked with a DOS 486 computer, and further processed on a UNIX-based HP 9000/700 workstation with commerical Matlab software and custom-written subroutines.

† AMTI, Advanced Mechanical Technology, OR6-5-1, Newton MA 02158, USA

§ Northern Digital Inc, OPTOTRAK/3010, Waterloo, Ontario N2L 3V2, Canada

In Fig. 3*a*, horizontal and vertical ground reaction forces are presented as assessed in the incomplete SCI patients while walking without FES support. In Fig. 3*b*, the same gait parameters are presented for the case when three-channel stimulation was applied. The major changes may be observed in the horizontal reaction force. With FES, the peak values in the horizontal reaction force are lower, which indicates a smoother rolling of the foot during the stance phase. Without FES, most of the curve representing the horizontal force is below the abscissa. By stimulating the ankle plantarflexors, the sign of the curve is changed to predominantly positive values, which is characteristic for adequate push-off. The maximal amplitudes of the horizontal force (around 23N) are considerably lower than in slow normal walking (between 65N and 130N) (WINTER, 1979), which is the consequence of crutch support and insufficient strength in the electrically stimulated plantarflexors. Improvement can be also noticed in the vertical ground reaction force. Owing to the stimulation of the knee extensors, the body weight is accepted to a larger extent by the stimulated leg, which can be observed in higher values of the vertical reaction force in the beginning of the stance phase.

The average walking speed is between 0.2 and 0.25 m s^{-1} and does not significantly alter between with and without FES walking sessions. However, a noticeable difference can be observed in the instantaneous horizontal velocity of the COM. In Fig. 4*a*, the horizontal COM velocity is presented as assessed during steady walking without FES assistance. It can be noticed that the horizontal gait velocity decreased to zero during each gait period. In the case of three-channel FES application (Fig. 4*b*), the instantaneous gait velocity is found to be more continuous and fluid, and approaches a more near normal appearance.

4 Discussion

When designing and developing voluntary control modes for incompletely paralysed patients, we must be aware of several statistical properties of the SCI population (YARKONY *et al.*, 1990). First, there are more incomplete tetraplegic than paraplegic cases. As a consequence, we often deal with more or less paralysed hands. Sophisticated hand transducers, such as joy-sticks, are less appropriate for this group of SCI patients.

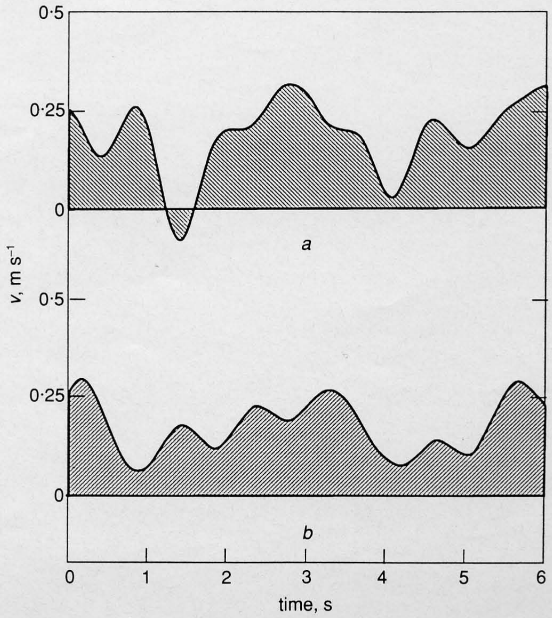

Fig. 4 *Horizontal velocity of centre of mass of patient's body as assessed during gait of tetraparetic patient walking (a) without FES and (b) assisted by three-channel FES*

Secondly, about one-half of incomplete SCI patients recover and need no orthotic aid. Thus, we can talk about two possible applications of FES to incomplete SCI patients:

(*a*) short-term therapeutic treatment in the clinical environment.
(*b*) permanent orthotic use of FES rehabilitative system.

In the beginning of therapeutic FES treatment, cyclical electrical stimulation can be used with the aim of restrengthening the atrophied muscles, increasing the range of motion and reducing spasticity (BAJD *et al.*, 1989; GRANAT *et al.*, 1993). 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 their strength to a useful level. It has been demonstrated that quadriceps strength assessed soon after an accident can be predictive of future ambulation in incomplete SCI patients (CROZIER *et al.*, 1992). The comparison of voluntary and electrically elicited responses soon after an injury yields additional information for prognosis (BAJD *et al.*, 1989).

Here, it should be stressed that multichannel FES represents one of the rare rehabilitative approaches for the incompletely paralysed subject soon after an accident, not only returning them to a vertical position, but also restoring their walking pattern. In the therapeutic FES restoration of walking, a large number of muscle groups should be included in the walking scheme in order to achieve as functional ambulation as possible and at the same time to shorten the patient's stay in the rehabilitation centre. When recovery in 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. Usually, fewer channels of stimulation may suffice in this later permanent phase of FES gait restoration. Owing to greater preserved exteroception and proprioception, most of these patients are excellent candidates for multichannel implanted FES systems which can turn them into community walkers, effectively using the stimulator throughout the day.

Acknowledgments—The authors would like to thank the Republic of Slovenia Ministry of Science and Technology and the National Institute on Disability and Rehabilitation Research, Department of Education, Washington DC, USA, for their financial support.

References

ANDREWS, B. J., BAXENDALE, R. H., BARNETT, R., PHILLIPS, G. F., YAMAZAKI, T., PAUL, J. P., and FREEMAN, P. A. (1988): 'Hybrid FES orthosis incorporating closed loop control and sensory feedback,' *J. Biomed. Eng.*, **10**, pp. 189–195

BAJD, T., KRALJ, A., TURK, R., BENKO, H., and ŠEGA, J. (1989): 'Use of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injuries,' *J. Biomed. Eng.*, **11**, pp. 96–102

BAJD, T., KRALJ, A., KARČNIK, T., ŠAVRIN, R., and OBREZA, P. (1994): 'Significance of FES-assisted plantarflexion during walking of incomplete SCI subjects,' *Gait Posture*, **2**, pp. 5–10

CHIZECK, H. J., KOBETIC, R., MARSOLAIS, E. B., ABBAS, J. J., DONNER, I. H., and SIMON, E. (1988): 'Control of functional neuromuscular stimulation systems for standing and locomotion in paraplegics,' *Proc. IEEE*, **9**, pp. 1155–1165

CROZIER, K. S., CHENG, L. L., GRAZIANI, V., ZORN, G., HERBISON, G., and DITUNNO, J. F. (1992): 'Spinal cord injury: prognosis of ambulation based on quadriceps recovery,' *Paraplegia*, **30**, pp. 762–767

GRANAT, M. H., FERGUSON, A. C. B., ANDREWS, B. J., and DELARGY, M. (1993): 'The role of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injury—observed benefits during gait studies,' *Paraplegia*, **31**, pp. 207–215

GRAUPE, D., KOHN, K., KRALJ, A., and BASSEAS, S. (1983): 'Patient controlled electrical stimulation via EMG signature discrimination for providing certain paraplegics with primitive walking function,' *J. Biomed. Eng.*, **5**, pp. 270–276

KRALJ, A., and BAJD, T. (1989): 'Functional electrical stimulation: Standing and walking after spinal cord injury' (CRC Press Inc., Boca Raton, Florida)

LIBERSON, W. T., HOLMQUEST, H. J., SCOTT, D., and DOW, M. (1961): 'Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients,' *Arch. Phys. Med. Rehab.*, **42**, pp. 101–105

MARSOLAIS, E. B., KOBETIC, R., CHIZECK, H. J., and JACOBS, J. L. (1991): 'Orthoses and electrical stimulation for walking in complete paraplegia,' *J. Neural. Rehab.*, **5**, pp. 13–22

WINTER, D. A. (1979): 'Biomechanics of human movement' (John Wiley & Sons, New York)

YARKONY, G. M., ROTH, E. J., MEYER, P. R., LOVELL, L., HEINEMANN, A. W., and BETTS, H. B. (1990): 'Spinal cord injury care system: fifteen-year experience at the Rehabilitation Institute of Chicago,' *Paraplegia*, **28**, pp. 321–329