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The role of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injury – observed benefits during gait studies

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The benefits of a functional electrical stimulation (FES) gait programme were assessed in a group of 6 incomplete spinal cord injured subjects. Measurements were made of quadriceps spasticity, lower limb muscle strength, postural stability in standing, spatial and temporal values of gait, physiological cost of gait and independence in activities of daily living. The subjects were assessed before commencement of the programme and after a period of gait training using FES. The benefits derived as a result of the FES gait programme included a reduction in quadriceps tone, an increase in voluntary muscle strength, a decrease in the physiological cost of gait and an increase in stride length.

Keywords: functional electrical stimulation (FES); gait; therapeutic benefits; rehabilitation programme; spinal cord injury.

Introduction

Functional electrical stimulation (FES) has been used as an orthotic system, replacing conventional braces with elicited motor responses for standing or walking. Kralj[1] proposed the use of FES for restoring standing and walking in spinal cord injured (SCI) patients. In all lower limb applications the general method for restoration of standing is the application of electrical stimulation to the quadriceps.[2] The restoration and/or improvement of gait has typically involved the stimulation of two sites. These have been the quadriceps, during the stance phase of gait,[3] and the peroneal nerve, producing a patterned flexion response,[4] during the swing phase of the ipsilateral limb.

Bedbrook reported that the proportion of incomplete spinal cord injured (ISCI) patients presenting to spinal injury units has been steadily increasing[5] and attributed this to the widespread use of seat belts and improved early care of the spinal injured patient. FES has greater potential for functional use in ISCI patients due to the preservation of some motor and sensory (in particular proprioception) function.[3,6,7] Several gait programmes for the ISCI subjects have been established.[3,6,8] Bajd *et al*[6,9,10] evaluated the effect of a gait training programme on 10 ISCI patients on voluntary knee moment, maximal stimulated knee moment and stimulated quadriceps fatigue. They suggested that the ISCI population could be divided into three groups; those who had an improvement in both voluntary and stimulated muscle force, those who had an increase in stimulated strength and those in whom there was no effect.

FES has been evaluated mainly in terms of the improvement of gait parameters whilst using FES.[3,11–13] Certain therapeutic effects of the use of FES have been studied where the stimulation regime was designed to have an effect on the specific parameter examined. Vodovnik[14] studied the effect of electrical stimulation (ES) on spasticity, Petrofsky and Chandler[15] examined bone demineralisation, and Levine[16] looked at the effect of stimulation of the glutei on ischial blood flow in reducing pressure sore development. However there has been no clear indication of the beneficial or detrimental effects that may occur as a result of an FES gait programme.

We have recently established an FES gait programme for patients with incomplete spinal cord injury at the West of Scotland Spinal Unit in Philipshill Hospital, Glasgow. The aim of this study was to evaluate the therapeutic effects resulting from an FES gait programme in ISCI patients.

Materials and methods

Six subjects who had sustained an incomplete lesion of the spinal cord were selected. Subject details are given in Table I. All had completed their post injury rehabilitation programme at the Spinal Injury Unit, Philipshill Hospital, Glasgow and were capable of ambulation in orthoses. Of these subjects, 3 walked for exercise only and were dependent on the wheelchair for mobility, whilst the others were independent of the wheelchair.

At the commencement of the study, assessments were made of the subjects' gait and neuromuscular function. From this assessment an individualised muscle conditioning programme using electrical stimulation was devised for each subject. The muscle conditioning programme consisted of a progressive resisted exercise regime for the quadriceps using weights attached at the ankle. The stimulation parameters used were a frequency of 25 Hz, pulse width of 300 μs with a duty cycle of 4 seconds on and 8 seconds off. Other antigravity muscle groups were exercised with stimulation where appropriate. All subjects completed a 6 month exercise programme. FES was then used for gait for all subjects in addition to them continuing their exercise regime.

Using a programmable stimulator[17] individualised stimulation sequences and parameters were used to synthesise gait in the gait laboratory. Muscle groups stimulated included the quadriceps, hip abductors, hamstrings, and erector spinae, as was appropriate for the subjects' requirements. The flexion withdrawal response was elicited by stimulating the common peroneal nerve at the site of the head of fibula, to produce hip and knee flexion and dorsiflexion for the swing phase of gait.

Following optimisation of stimulation patterns, each subject was provided with a stimulator suited to their needs for gait synthesis. Details of the muscle groups stimulated are given in Table II. These FES stimulators were used by each of the subjects, at home, for a minimum period of 3

Table I Patient details

Patient	Age	Years post injury	Lesion level	Frankel grade		Walking aids	Ambulatory status
				At start	At end		
A (M)	20	2	C4 burst fracture	D	D	R AFO One stick	Community walker
B (F)	32	10	L1 acute disc prolapse	D	D	R and L AFO Sticks	Community walker
C (M)	35	4	T12 fracture dislocation	C	C	R and L KAFOs Elbow crutches	Occasional community walking
D (M)	35	18	C3/4 fracture dislocation	D	D	R and L AFOs Sticks	Community walker
E (F)	40	5	T5/6 fracture	C	D	R and L KAFOs Elbow crutches	Exercise only
F (F)	27	5	T12 wedge fracture	C	C	R and L KAFOs Zimmer	Exercise only

M = male
F = female

Table II Muscle groups stimulated by the FES stimulators used by each of the subjects at home

Muscle groups	Subjects A	B	C	D	E	F
R Quads	*			*	*	*
L Quads			*		*	*
R Peroneal	*	*		*	*	*
L Peroneal		*	*		*	*
R Abductors	*					
R Erector spinae	*					
L Erector spinae	*					

months. All subjects were asked to use their stimulators for at least half an hour each day for a minimum of 5 days per week. The physiotherapist (ACBF) regularly assessed subjects in their homes during this period. At completion of this phase all assessment tests were repeated.

Tests to evaluate the outcome of the FES gait programme were carried out at the commencement of the programme and at the end of the gait training phase. These were:

Manual muscle tests (MMT)
All muscle groups in the lower limbs were evaluated using the Oxford scale of muscle strength.[18] Six grades of muscle strength are included in the scale. All of these evaluations were carried out by the same physiotherapist.

Maximum voluntary contraction (MVC)
A quantitative measure of the quadriceps strength was obtained by measuring the moment produced at the knee during a maximum voluntary contraction. The subject was seated in a dynamometer chair system, the knee angle being fixed at 60 degrees of flexion. A ring transducer measured force produced at the ankle. The maximum moment was defined as the best of three attempts at each session.[19]

Upright motor control
The upright motor control test was used to evaluate the integration of preserved voluntary muscle function in the lower limbs.[20] Voluntary flexion and extension of the hip, knee and ankle were assessed whilst the subject was standing in parallel bars. For flexion the subject was asked to maximally flex their leg and the amount of hip and knee flexion and ankle dorsiflexion was graded. Extension was graded according to the ability of the subject to flex and extend their leg whilst weight-bearing on that leg only, thereby performing a partial squat on one leg. All of these evaluations were carried out by the same physiotherapist.

Spasticity
Spasticity was evaluated clinically and biomechanically. Clinical evaluation was performed using the Ashworth scale.[21] This scale has 5 grades of spasticity, ranging from 'no increase in tone' to 'affected part rigid in flexion or extension'. The pendulum test[22,23] was used for the biomechanical evaluation. In this test the subject was placed in the supine position with the knee positioned at the end of the testing couch. The examiner held the lower leg at the ankle and allowed the leg to swing under gravity from 30 degrees of knee flexion. An electrogoniometer recorded the changing angle of the knee. This was repeated 10 times for each session. The degree of spasticity was quantified by the relaxation index which is the ratio of the first minimum angle of the knee (the maximum angle of flexion the leg reaches in the first swing) to the resting angle of the knee. To minimise the short term effects of FES on muscle tone, no electrical stimulation was used by the subject for a period of 24 hours prior to performance of the tests.

Performance of gait
The subjects, using their normal orthoses, walked around a track in the gait laboratory on five separate occasions. This was repeated on five separate days. The length of the track was set according to the individual ability of each subject. During these tests speed, stride length, cadence and heart rate were measured. The physiological cost of

gait was quantified using the physiological cost index (PCI).[24] The PCI was calculated as follows:-

$$\text{PCI} = \frac{\text{walking heart rate} - \text{resting heart rate}}{\text{walking speed}}$$

Postural stability in standing (sway)
Sway was quantified by the movement of the centre of pressure (CofP) underneath the subject's feet whilst standing on a Kistler force platform. Ten measurements of 30 seconds were taken. Data was then filtered[25] and two parameters were calculated and used as indices of sway. These were the average speed of movement of the CofP and the mean radius of excursion of the CofP.[26]

Activities of daily living (ADL)
The modified Barthel index[27] was used to evaluate the degree of independence in areas of mobility and selfcare. This is a questionnaire in which the subject reports the amount of help required to perform 15 defined ADL tasks according to a scoring system. Maximum mobility score for full independence was equal to 53 and for personal care was equal to 47.

Results

The MMT results were analysed using the Wilcoxon matched-pairs sign rank test; each muscle group being evaluated separately. There were significant increases in the strength of the hip flexors ($p < 0.05$) and knee extensors ($p < 0.05$) in the mean value for the group. The results of the hip flexors are shown in Figure 1. A bilateral increase in hip flexor strength was seen in subjects A, B, C and E.

The results of MVC of the quadriceps are shown in Figure 2. The Wilcoxon matched-pairs sign rank test showed that there was a significant increase in strength ($p < 0.05$).

The results of the upright motor control test showed a significant increase ($p < 0.05$) of knee extension strength in the mean value for the subject group. Subject E showed an increase in the strength of flexion and extension of both legs.

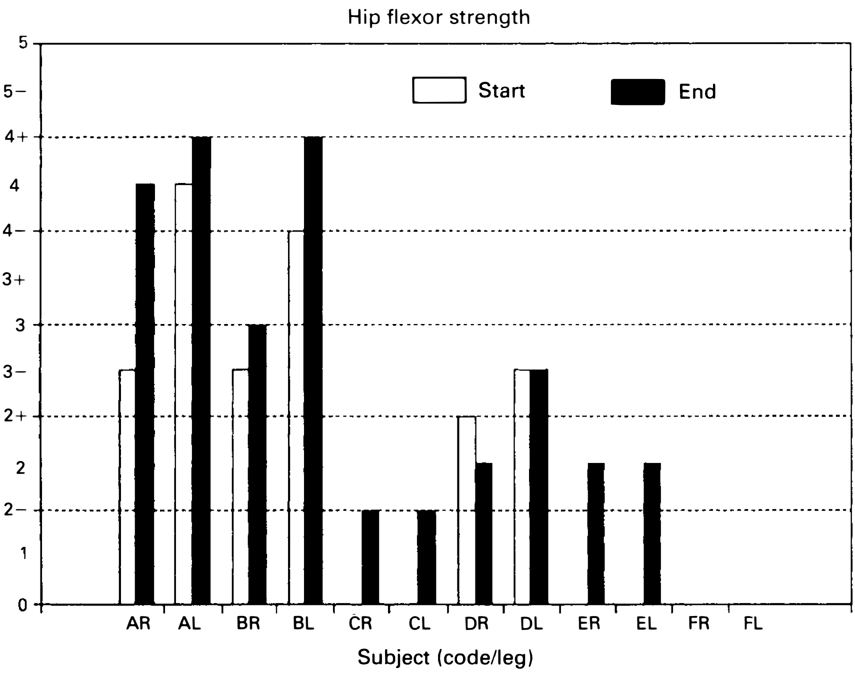

Figure 1 Manual muscle test results for hip flexors at the start and end of the FES gait programme. AR refers to the right leg of subject A.

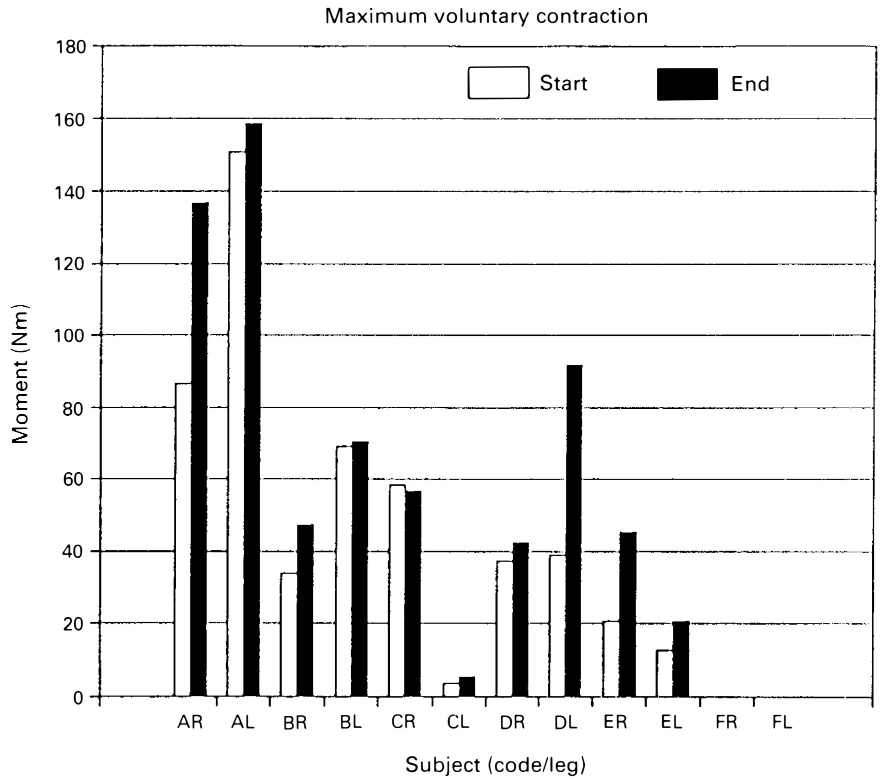

Figure 2 Maximum voluntary contraction for quadriceps at the start and end of the FES gait programme. AR refers to the right leg of subject A. There was no recorded voluntary quadriceps moment for subject F throughout the programme.

The results of a paired *t*-test on the relaxation index (Fig 3) showed an increase in the mean value of the relaxation index (a reduction in spasticity) for the subject group ($p < 0.05$). All changes in spasticity were significant ($p < 0.01$), using the independent *t*-test, subject C showing a significant increase in spasticity in both legs. The results of the Ashworth scale were much more variable and no significant changes were seen.

Intrasubject differences in the gait parameters were tested using a two-tailed independent *t*-test with a significance level of 0.05. Table III shows the PCI of each subject before and after the programme. There was a significant decrease for subjects B, C and E in PCI. Table III shows the values of speed, stride length and cadence. There were significant increases in the speed of gait for subjects D, E, and F. There were significant increases in the stride length for subjects B, C, E and F. There were significant increases in cadence for subjects A, D and F; and a decrease in subject C. Analysis of the mean values of the gait parameters of the whole group using a two-tailed paired *t*-test showed no significant change in speed or cadence, but an increase in stride length.

An analysis of variance was performed to test for changes in the sway parameters. Subjects A, B and C showed a significant decrease in the speed of sway and subject D an increase. Subjects B and C showed a significant decrease in mean radius of sway and D an increase. There was no overall significant change in these parameters.

The only change in the Barthel index score occurred with subject E; this was an increase in the category of mobility from 16 to 27.

Further changes recorded at completion

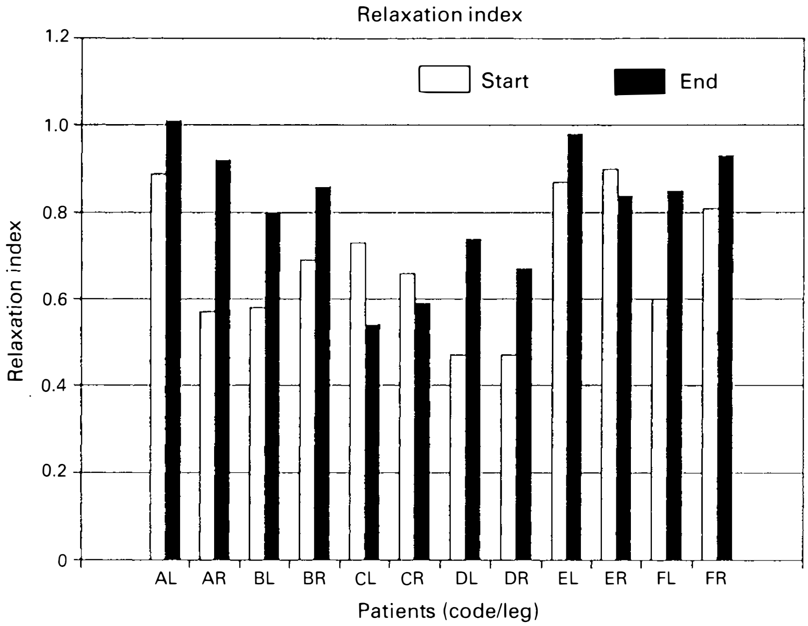

Figure 3 Relaxation index at the start and end of the FES gait programme. AR refers to the right leg of subject A.

of the programme were (a) subject D reported improvement in his standing posture, and there was a gain of full range of extension of his right knee (he had had a 5 degree flexion contracture of 10 years duration); and (b) for the first time since her injury subject E was able to stand and walk independently without orthoses or FES using a zimmer frame for periods in excess of 10 minutes.

Discussion

Most of the work to date on the use of FES in subjects with spinal cord injury has concentrated on gait restoration. The broader role of FES in rehabilitation has received little attention. In the present study we have been able to document several potential benefits of an FES gait programme in subjects with incomplete spinal cord injury.

The results of the MMT, MVC and upright motor control test show that in this group of subjects FES can produce an increase in the voluntary strength of the muscles of the lower limb when the subject has a minimum strength of grade 2 on the Oxford scale. From these results it was not possible to predict improvement in voluntary muscle strength from the initial strength. This would suggest that an FES gait programme may produce muscle strengthening in ISCI subjects where there is some preserved voluntary strength.

The increase in the strength of the hip flexors, which were not directly exercised, could be attributed to the use of the flexion withdrawal response. This would suggest that eliciting a motor response via an afferent pathway could be a means of strengthening certain muscle groups affected by an incomplete spinal cord lesion. Two subjects, A and B, had a bilateral increase in hip flexion strength whereas they only stimulated the right leg (Fig 1). However the increase in grading on the right for subject A was from 3 to 4 which represents a change from being able to move against gravity through less than the full range of motion to being able to move through full range against applied resistance. Increase in grading on the left leg (from 4 to 4+) represents

Table III Means and standard deviations of the parameters speeds stride length, cadence and PCI for the start and end of the FES gait programme

Parameters		Subjects					
		A	B	C	D	E	F
Speed (m/s)	Pre	0.69 (0.03)	0.41 (0.02)	0.22 (0.01)	0.35 (0.01)	0.08 (0.01)	0.06 (0.01)
	Post	0.79 (0.02)	0.42 (0.01)	0.21 (0.01)	0.38 (0.02)	0.09 (0.01)	0.07 (0.00)
Stride length (m)	Pre	1.13 (0.03)	0.85 (0.02)	0.79 (0.03)	1.03 (0.02)	0.32 (0.03)	0.47 (0.02)
	Post	1.20 (0.05)	0.90 (0.02)	0.83 (0.02)	1.03 (0.03)	0.37 (0.01)	0.54 (0.01)
Cadence	Pre	36.9 (1.4)	29.2 (1.0)	16.5 (0.9)	20.4 (0.7)	14.4 (0.7)	7.2 (0.6)
	Post	39.6 (1.6)	28.0 (0.9)	14.7 (0.5)	21.9 (0.9)	14.5 (0.9)	8.3 (0.9)
PCI	Pre	0.50 (0.10)	0.33 (0.08)	0.15 (0.01)	−0.01 (0.01)	0.61 (0.08)	0.21 (0.11)
	Post	0.36 (0.11)	0.16 (0.07)	0.10 (0.06)	−0.01 (0.02)	0.43 (0.13)	0.19 (0.08)

a change in the amount of resistance (applied by the physiotherapist) to full movement against gravity. It is therefore possible that FES could produce some strengthening in the contralateral limb due to crossover effects of FES stimulation to the contralateral side of the spinal cord.

The benefits of the muscle conditioning programme manifested in a variety of ways. The effect of the improved muscle function resulted in increased efficiency of gait in orthoses both in terms of energy expenditure and speed of walking. All subjects had completed an intensive inpatient spinal unit rehabilitation programme at the time of entry to the study. This suggests that in some ISCI patients FES may help maximise muscle recovery.

The results from the biomechanical test of spasticity showed a reduction in spasticity in the quadriceps, which extended for at least 24 hours after the use of FES. The use of FES in reduction of spasticity is not new. Stimulation of the agonist has been investigated[28] as has cyclical stimulation of the agonist and antagonist.[29] The use of dermatomal stimulation has been shown to reduce spasticity more effectively and for longer than the other modalities.[28,30,31] However the effect has been shown to last for only a few hours.[14,31] In this study FES was applied directly to the quadriceps (agonist muscle group), however the hamstrings (antagonists) were also made to contract by means of the flexion withdrawal reflex. Both mechanisms and the long term use of FES may therefore have contributed to the resultant spasticity reduction.

The pendulum test qualifies the hyperactive stretch reflex under standardised conditions whereas the Ashworth scale quantifies the resistance to a slow passive movement. By measuring separate components of spasticity the results may not necessarily be related.

Three of the 4 subjects who showed an increase in stride length also had a bilateral increase in voluntary hip flexor strength (subjects B, C, and E). The increase in voluntary hip flexion strength was associated with a functional gait improvement. The subjects who showed a significant reduction in PCI were those whose lower limb voluntary strength increased most (B, C, and E). It is not possible to relate these two factors as the increase in stride length did not result in a statistically significant increase in the speed of gait which would affect PCI.

Results for sway demonstrate an increase in stability during standing for subjects B and C and a decrease for D. There was no general trend for change in stability.

An increase in the Barthel score for subject E was due to the increase in voluntary strength in the lower limbs. This was sufficient by the end of the programme to enable her to walk without FES or orthoses, independently for periods of 15 minutes. Changes in this index did not occur for the other subjects. However, this subject group by nature of the selection criteria had a higher score than the general population for which this questionnaire was developed.[27,29] The Barthel index only detects larger changes in functional ability than those produced by the FES programme.

There were two groups of subjects, community walkers (subjects A, B and D) and those who walked for exercise only (subjects C, E and F). There were some benefits that both groups derived from the FES gait programme; however an increase in voluntary strength was only possible if there was some motor sparing. There is a wide range of severity in ISCI patients to whom FES has some value.

The use of this programme over a period of time has demonstrated several distinct benefits to the subjects, namely an increase in voluntary strength and stride length, and a reduction in PCI of walking and quadriceps spasticity. There are likely to be selected ISCI patients who may derive functional benefits from an FES gait programme. All these benefits were in addition to those derived by the subjects when using their prescribed FES systems.

Conclusions

This FES gait programme for the ISCI produced therapeutic benefits other than the restoration or improvement in gait by the use of FES. Benefits occurred in all subjects, indicating that FES has potential value in the range of ISCI subjects. Overall there was no deterioration in any of the areas evaluated. The exercise programme can be conducted at home after a short period of instruction and is therefore not time consuming for hospital staff.

We believe that the outcome in this series of subjects supports the use of FES in the post injury rehabilitation of patients with incomplete spinal cord injury. Having demonstrated increases in strength after standard spinal unit rehabilitation, use of FES in the early post trauma phase needs to be evaluated further.

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Addendum

In Figure 1, note that the initial values in subjects C, E and F and the final values for subject F were zero.

Also note that in Table II, the authors of the paper, as is noted in the text, concentrated on the benefits of using FES, and not on the detailed strategy of gait production using FES.