Effects of Functional Electrical Stimulation on Peak Torque and Body Composition in Patients with Incomplete Spinal Cord Injury

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The aim of this study was to investigate the change in body composition, leg girths, and muscle strength of patients with incomplete spinal cord injury (SCI) after functional electrical stimulation cycling exercises (FESCE). Eighteen subjects with incomplete SCI were recruited. Each patient received FESCE three times per week for 8 weeks. Body composition, thigh and calf girths of bilateral legs, muscle strength of bilateral knee flexors and extensors were measured before and after 4 and 8 weeks of FESCE. A significant increase in bilateral thigh girth after 4 weeks of FESCE and significant increase in muscular peak torque of knee flexion and extension were found after 8 weeks of training. Besides, lean body mass increased significantly after complete treatment. FESCE can increase the thigh girth and muscular peak torque of patients with incomplete spinal cord injury.

Key Words: body composition, functional electrical stimulation, peak torque, spinal cord injury

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People with spinal cord injury (SCI) exhibit deficits in volitional motor control and sensation that limit performance of daily tasks as well as the overall activity level [1]. Most patients who suffer from SCI experience some neurologic recovery and regain some muscle strength. Cheng et al [2] reported that the best prognosis is in patients who initially exhibit some spared motor function. But another study showed that patients with incomplete injuries merely recover faster than those with complete injuries, but their degree of recovery is not necessarily greater [3]. The relationship between the extent of strength recovery and spared motor function after injury has not been fully studied.

Poor physical fitness is usually found in persons with SCI due to their sedentary lives [4,5]. Many main long-term issues can be related to the alteration in body composition and metabolic function, including glucose intolerance, an unfavorable lipid profile, a decrease in lean body mass, and reduced physical conditioning [6]. Compared with healthy populations, people with SCI were fatter according to their body mass

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index (BMI) and were significantly less lean with more adipose tissue [7]. A study by Maggioni et al [8] showed that total fat mass in the SCI group was significantly higher than in the able-bodied group (31.1% *vs.* 20.8%). Another study by Spungen et al [9] also indicated that the SCI group was 13 ± 1% fatter per unit of BMI (kg/m^2) compared with the healthy group. Increased incidence of some disorders including diabetes mellitus, hypertension, and hyperlipidemia may be related to adverse changes in body composition that result from immobilization and skeletal muscle denervation because of SCI [10,11]. Therefore, further control of the change in body composition in SCI patients is indicated.

Functional electrical stimulation (FES) is potentially useful in the rehabilitation of patients with SCI. Proven benefits include improvement in bone density, deep venous thrombosis, edema, and amelioration of spasticity [12,13]. Clinical studies have shown that by applying FES to the paralyzed muscles, functional contractions are produced that satisfy the physiologic motor demand as well as maintain the activity of the degenerative target, thus resulting in an improvement in patients' functions [14]. As a result, FES cycling exercises (FESCE) involving the contraction of the muscles of the paralyzed limbs in individuals with SCI may help to decrease muscle atrophy [15]. Erika et al [16] reported that FESCE increases skeletal muscle cross-sectional area with no change in adipose tissue in both the thigh and leg. Timson [17] also reported that this type of exercise induced greater muscle hypertrophy in animals and humans than aerobic exercise. However, few reports have discussed the effect of FESCE on muscular strength and body composition in SCI patients with different grades. Therefore, in the present study, we tried to investigate the effect of FESCE in patients with various degrees of incomplete SCI, and changes in their thigh and calf girth, peak muscular contractile forces, body composition, and BMI. The relationship between strength recovery and the spared motor function was also studied.

Methods

Sample and data sources

Eighteen subjects with age ranging from 26 to 61 years and with incomplete SCI were recruited. The basic data collected (Table 1) were age, gender, weight, time since injury, level of injury, degree of injury (American Spinal Injury Association [ASIA] class) [18] ASIA B: sensory but not motor functional is preserved below the level (6 subjects); ASIA C: motor function is preserved and more than half of the key muscles below

Table 1. Patient characteristics

Subject	Age (yr)	Sex	Weight (kg)	Time since injury (yr)	Neurologic level	ASIA class
1	52	M	64.1	3	T5	C
2	46	M	68.3	5	C4	C
3	32	M	63.2	2	T10	B
4	28	M	61.5	3	T12	C
5	45	M	78.8	4	C4	D
6	29	M	104.4	6	C7	D
7	33	F	62.2	1	T12	B
8	52	M	65.5	2	T5	B
9	46	F	53.4	4	T11	C
10	33	M	67.2	2	T10	C
11	33	M	78.8	5	T12	B
12	54	M	66.6	2	C4	D
13	26	M	77.3	2	L1	B
14	48	M	69.4	3	C3	D
15	61	M	74.4	9	C5	C
16	29	M	87.6	2	C4	D
17	46	M	78.3	1	T12	B
18	27	M	84.6	2	T7	C
Mean	40.0 ± 11.3	M:F (16:2)	73.8 ± 13.9	3.2 ± 2.1	C:T:L (7:10:1)	B:C:D (6:7:5)

Age, weight, and time since injury shown as mean ± standard deviation. ASIA = American Spinal Injury Association; M = male; F = female.

the level have a muscle grade < 3 (7 subjects); ASIA D: motor function is preserved and at least half the key muscles below the level have a muscle grade ≥ 3 (5 subjects). The inclusion criteria for the subjects were: (1) at least 1 year after SCI, to avoid the possibility of the patient still being in the spinal shock stage; (2) subject able to tolerate electrical stimulation; (3) subject has minimal-to-moderate spasticity and no contracture of knees or ankles; (4) radiologic examination of the entire lower extremities was unremarkable, indicating absence of metallic implants, recent fracture, and any other defect; and (5) subject is medically stable with a cooperative attitude. All the participants gave informed consent for the study and the protocol was approved by the Ethical Review Committee of Kaohsiung Medical University.

Outcome measurement

The thigh and calf girths, body weight, BMI, body composition, and muscle peak torque of knee flexors and knee extensors were measured before and after FESCE.

Measurement of body composition and BMI

The assessment of body composition from bioelectrical impedance analysis (BIA) is a recently developed technique. BIA is considered to be a simple, nontraumatic, and reliable method to analyze body composition [19]. An eight-polar tactile-electrode impedance meter (Inbody 3.0, Biospace, Seoul, Korea) was used in this study [20]. This instrument makes use of eight tactile electrodes: two are in contact with the palm and thumb of each hand and two with the anterior and posterior aspects of the sole of each foot. As many SCI subjects did not have enough muscle power to stand unassisted, all the subjects maintained a sitting position to measure the weight and body composition. The total body weight was measured on a standard weight scale before the body composition measurement. The body composition included body fat mass (kg), fat percentage (%), body lean mass (kg), and bone mass (kg). In addition, the height was self-reported and the BMI (kg/m^2) of these subjects were derived from the given data.

Measurement of thigh and calf girths

The measurements of thigh and calf girths were performed as follows: the subject kept a supine position with full relaxation of the lower limb muscles. The thigh girth was measured with a flexible meter at 20 cm above the adductor tubercle, and calf girth was measured at 10 cm below the tibial tubercle [21]. Every measurement was performed at the start of FES to avoid the influence of possible exercise-induced muscle swelling [22]. In order to optimize the accuracy of these measurements, the average of three measurements was taken at each location.

Measurement of isometric peak torque of knee flexors and knee extensors

The voluntary torque capacity was evaluated to measure the peak torque of the knee flexors and knee extensors with the modified isometric mode by using a Kin-Com dynamometer (Kin-Com 505, Chattanooga, TN, USA) under the trigger of electrical stimulation [23,24]. During isometric contraction, the knee muscle maintained a constant length as resistance was applied and no change in joint position occurred. Volitional isometric strength of the bilateral knee flexors and extensors were assessed with the subject seated on the dynamometer with the knee positioned at 100° from the horizontal position [25]. The subjects' hips were positioned at about 85° of flexion. Meanwhile, the trunk, pelvis, thigh, and legs were stabilized with straps. Surface electrodes of the electrical stimulation machine were attached to the muscle belly of bilateral quadriceps and hamstrings. Patients tried to do maximum muscular contraction of knee flexors and extensors on their own, in coordination with being triggered by the electrical stimulation at the same time with the same stimulation current density (140 mA) [26]. Each maximal volitional isometric torque of knee flexors and extensors was recorded as the average of five repeated measurements. The effect of gravity was also corrected for by subtracting the torque generated by the weight of the limb and the lever arm of the apparatus [27]. In order to avoid the extra torque induced by the sporadic spasms, lower stimulation intensities were chosen in these small number of cases. Besides that, in order to minimize possible effects of muscle temperature before and after training, the room temperature was kept constant at 20°C during the testing procedure.

FESCE training

FES-induced cycling exercise was performed by applying 5 × 7 cm surface electrodes to the muscle belly of bilateral quadriceps and hamstrings to achieve a sequential rhythmic cycling motion. The sites of electrode placement were not only easily accessible but also relatively close to the motor points, which needed less stimulation current to generate a satisfactory contraction. The pulse frequency was set at 30 Hz, rectangular pulse duration of 300 μs, and current variation of 10–132 mA, which was controlled by a microprocessor in order to maintain a pedaling rate of 45 rpm [28,29]. Although the equipment contained an arm-crank structure, it could only be used to help establish cycling by an SCI individual and to warm up before electrical stimulation. Patients received the FESCE thrice a week for 8 weeks. Each session lasted 30 minutes with warm-up and cool-down periods of 3 minutes. Evaluations were performed before and after 4 and 8 weeks of training.

Statistical analysis

Paired *t* test was used to analyze changes in thigh and calf girths, body composition, BMI, and muscle peak torque after 4 and 8 weeks of training, respectively. A statistically significant difference was set at $p < 0.05$. Analysis of variance was used to analyze the different percentages of strength recovery among incomplete SCI levels (ASIA B–D). Statistical significance between group means was determined by Scheffe's tests ($p < 0.05$). Furthermore, the relationship between initial strength in the pretraining period and percentage of strength gain after the 8-week training course was performed by Pearson correlations. All analyses were performed with the SPSS program (SPSS Inc., Chicago, IL, USA).

Results

Changes in body composition and BMI

The changes in body composition before and after training are given in Table 2. Total body weight increased from 73.8 ± 13.9 kg to 75.0 ± 14.3 kg ($p = 0.062$). Mild increase in body lean mass (from 51.6 ± 7.1 to 52.8 ± 8.2) was found after 8 weeks of FESCE ($p = 0.03$). However, there were no other marked differences in body composition, including body fat mass, fat percentage, bone mass and BMI.

Changes in upper and lower leg girths

Changes in thigh and calf girths are shown in Table 3. The 18 patients showed significant increase in bilateral thigh girth after 4 weeks of training ($p < 0.05$). Mean thigh girth increased from 48.2 ± 5.5 cm to 49.6 ± 5.2 cm for the right leg, and 47.4 ± 5.9 cm to 49.0 ± 5.4 cm for the left leg. Thereafter, there was only a mild increase

Table 2. Changes in body composition after training in SCI subjects*

	Before FESCE	After 4 wks of FESCE	After 8 wks of FESCE
Total body weight (kg)	73.8 ± 13.9	73.9 ± 13.7	75.0 ± 14.3
Body fat mass (kg)	18.6 ± 8.6	18.7 ± 8.5	18.7 ± 8.4
Body lean mass (kg)	51.6 ± 7.1	52.3 ± 7.5	52.8 ± 8.2†
Percentage fat mass (%)	25.3 ± 7.1	25.4 ± 6.9	24.9 ± 6.6
Bone weight (kg)	3.5 ± 0.4	3.5 ± 0.4	3.6 ± 0.4
BMI (kg/m^2)	25.4 ± 3.9	25.5 ± 3.8	25.7 ± 3.5

*Data are presented as mean ± standard deviation; †significant difference ($p < 0.05$) between the values before FESCE and those after 8 weeks of FESCE. FESCE = functional electrical stimulation cycling exercises; SCI = spinal cord injury.

Table 3. Changes in girth of upper and lower legs (cm) in SCI subjects*

	Before FESCE	After 4 wks of FESCE	After 8 wks of FESCE
Right thigh girth	48.2 ± 5.5	49.6 ± 5.2†	50.3 ± 5.1‡
Left thigh girth	47.4 ± 5.9	49.0 ± 5.4†	49.8 ± 5.2‡
Right calf girth	34.2 ± 3.8	34.5 ± 3.2	34.6 ± 3.3
Left calf girth	33.6 ± 4.9	33.8 ± 3.7	34.1 ± 3.9

*Data are presented as mean ± standard deviation; †significant difference ($p < 0.05$) between the values before FESCE and those after 4 weeks of FESCE; ‡significant difference ($p < 0.05$) between the values before FESCE and those after 8 weeks of FESCE. FESCE = functional electrical stimulation cycling exercises; SCI = spinal cord injury.

when FESCE continued. A slight increase in calf girth from 34.2 ± 3.8 cm to 34.6 ± 3.3 cm in the right leg and 33.6 ± 4.9 to 34.1 ± 3.9 cm in the left leg occurred after 8 weeks of training. However, the slight increase in calf girth was not statistically significant ($p > 0.05$).

Changes in mean peak torque

Changes in isometric peak torque in bilateral knee flexors and knee extensors are shown in Table 4. There was no significant increase in mean peak torque after 4 weeks of FESCE; however, there was significant increase ($p < 0.05$) in mean peak torque of bilateral knee flexors and right knee extensors after 8 weeks of training. Although there was little improvement in peak torque of the left knee extensors after training, the strength of the left knee extensors demonstrated an increasing trend ($p = 0.067$) after 8 weeks of FESCE.

Correlation between SCI severity and FESCE training

Further analysis was performed with reference to the subjects with different grades of motor function (ASIA B–D). The results of isometric peak torques and the percentage of torque gains in bilateral knee flexors and knee extensors of these three groups are shown in Table 5. Although the subjects all had peak torque increase after completing FESCE training, subjects in the ASIA D group had a higher percentage of strength gains in bilateral knee extensors and flexors than those in the ASIA B and C groups ($p < 0.05$)

Table 4. Isometric peak torques of knee extensors and flexors before and after training in SCI subjects*

Peak torque (Nm)	Before FESCE	After 4 wks of FESCE	After 8 wks of FESCE
Right knee extensor	45.9 ± 32.8	47.6 ± 34.8	52.6 ± 40.7†‡
Left knee extensor	37.9 ± 26.8	38.3 ± 32.1	38.9 ± 29.9
Right knee flexor	16.1 ± 11.9	16.5 ± 10.2	17.7 ± 11.6†‡
Left knee flexor	15.1 ± 6.3	15.2 ± 6.1	16.9 ± 6.8†‡

*Data are presented as mean ± standard deviation; †significant difference ($p < 0.05$) between the values after 4 weeks of FESCE and those after 8 weeks of FESCE; ‡significant difference ($p < 0.05$) between the values before FESCE and those after 8 weeks of FESCE. FESCE = functional electrical stimulation cycling exercises; SCI = spinal cord injury.

Table 5. Results of isometric peak torque gains in knee extensors and flexors after training (Nm)*

	ASIA B group ($n = 6$)	ASIA C group ($n = 7$)	ASIA D group ($n = 5$)
Right knee extensor			
Before FESCE	22.1 ± 11.9	44.6 ± 26.3	76.3 ± 36.4
After FESCE	22.8 ± 9.8	47.4 ± 31.4	95.8 ± 39.7
Strength gains (%)	3.2	6.3	25.6‡§
Left knee extensor			
Before FESCE	18.2 ± 6.2	38.7 ± 9.7	52.6 ± 11.3
After FESCE	18.5 ± 5.8	42.5 ± 15.1	58.5 ± 14.4
Strength gains (%)	1.6	9.8†	11.2‡
Right knee flexor			
Before FESCE	11.7 ± 5.6	14.4 ± 11.7	21.1 ± 10.9
After FESCE	12.2 ± 9.1	16.7 ± 13.1	25.9 ± 11.8
Strength gains (%)	4.3	15.9†	22.7‡§
Left knee flexor			
Before FESCE	12.1 ± 6.2	16.2 ± 6.3	16.9 ± 5.5
After FESCE	12.6 ± 5.1	17.5 ± 7.8	21.1 ± 5.9
Strength gains (%)	4.1	8.0	24.9‡§

*Isometric torques presented as mean ± standard deviation; †significant difference ($p < 0.05$) of strength gains (%) between ASIA B group and ASIA C group; ‡significant difference ($p < 0.05$) of strength gains (%) between ASIA B group and ASIA D group; §significant difference ($p < 0.05$) of strength gains (%) between ASIA C group and ASIA D group. ASIA = American Spinal Injury Association; FESCE = functional electrical stimulation cycling exercises.

after 8 weeks of FESCE, and those in the ASIA C group had better results compared with the ASIA B group.

Relationship between changes in muscle peak torque and initial severity of paresis

Correlations between initial peak torque before training and the percentage of changes in knee muscular strength after 8 weeks of training were analyzed to determine the impact of initial motor function on the potential for recovery. Pearson correlation coefficients were 0.86 ($p = 0.013$ for right knee extensor), 0.65 ($p = 0.048$ for left knee extensor), 0.5l ($p = 0.032$ for left knee flexor), and 0.49 ($p = 0.062$ for right knee flexor). These results showed that the percentage of strength gains during FESCE was positively related to the spared muscle function before FESCE, implying that patients who had higher residual muscle strength might achieve better results from training.

Discussion

Many reports on body composition assessment in SCI subjects usually show that total fat mass is significantly higher and total lean mass significantly lower than in healthy people [30,31]. But only a few studies have examined the issue of body composition change in SCI patients after FESCE. Hjeltnes et al [32] reported that lean body mass increased and fat mass decreased for SCI patients after 8 weeks of FESCE. The body composition in their study was evaluated by dual-energy X-ray absorptiometry (DEXA), which showed increase in lean body mass from 66.2 ± 2.6% to 68.2 ± 2.1% ($p < 0.05$), with a decrease in whole body fat content from 29.7 ± 2.6% to 27.8 ± 2.1% ($p < 0.05$) after training. However, those results came from the analysis of a small group of patients ($n = 5$). In the present study, 8 weeks of FESCE resulted in a mild increase in lean body mass from 51.6 ± 7.1 kg to 52.8 ± 8.2 kg ($p < 0.05$), but no significant change in fat body mass. Although there were some differences in the results between the two studies, this possibly resulted from various FES training intensities and differences in the evaluation equipment. Body composition in incomplete SCI subjects always deteriorates as a consequence of both neurologic injury and activity deficiency. Our data suggest that FESCE partially improves lean body mass within 8 weeks of training. In addition, analysis of the relationships between the increment in lean body mass and gains in peak torque of bilateral legs after the 8-week training course were performed. Pearson correlation coefficients were 0.53 ($p = 0.061$) for right knee extensor, 0.41 ($p = 0.093$) for left knee extensor, 0.63 ($p = 0.078$) for right knee flexor, and 0.55 ($p = 0.073$) for left knee flexor. The positive correlation trend demonstrated the possibility that increase in lean body mass may bring about the regaining of muscle strength. Further study for understanding the relationship is warranted.

SCI results in a significant and dramatic loss of muscle mass and muscle strength that can have a harmful impact on the health of the individual. Muscle fiber cross-sectional area starts to decline within 1 month after SCI [33]. Electrical stimulation of the muscular paresis may improve the condition of muscle size and peak contractile forces. Dudley et al [34] demonstrated the effectiveness of a simple program of electrically induced knee extensions, performed twice-weekly over an 8-week period, dramatically reversing the muscle size of the quadriceps muscles in SCI patients. The present results also show that individuals with incomplete SCI responded to the 8-week FES cycling program. The subjects showed significant increases in bilateral thigh girth even after 4 weeks of training. Although calf girth increased after training, this was not statistically significant, probably because the gastrocnemius and soleus muscles were not directly stimulated during the cycling exercise. It demonstrated that an FES training program involving the contraction of the limb muscle with paresis in people with SCI may help not only to decrease muscle atrophy, but increase muscle size as well. Our subjects showed increases in the girth of bilateral thighs, which was compatible with the results that muscle hypertrophy and increase in the number of muscle fibers per motor unit were the reasons for strength gain after the FES cycling exercise [35]. Nevertheless, subjects did not show further increase in muscle mass after 8 weeks of training, probably because the workload was not incrementally increased during the study period.

In general, as the motor and sensory recovery essentially reach a plateau at the end of 1 year, it is logical to base the initial rehabilitation plans on a predicted 1-year recovery period [36]. It is interesting to note that there were substantial increases in the measured strength of the bilateral knee extensors and knee flexors in these SCI patients, whose average postinjury time is about 3.2 years, after 8 weeks of FESCE. The result revealed that exercise by using the FES cycling system can improve muscle strength in patients with SCI postinjury for more than 1 year.

It is well known that the best prognosis is in patients who initially exhibit some spared motor function and in those in whom neurologic recovery occurs early after injury [37]. The effect of FESCE has never been compared and discussed in relation to different degrees of incomplete SCI in previous studies. With regard to the effect of 8 weeks of FESCE on the severity of injury, we found that the average strength increased from 1.6% to 4.3% in ASIA B group, 6.3% to 15.9% in ASIA C group, and 11.2% to 25.6% in ASIA D group in our study. The more residual muscle strength there was, the more percentage of strength was regained. It has been reported that age is an important factor in motor recovery and older patients show less functional motor recovery than younger patients [38]. In our study, each group was controlled by the mean age of SCI patients as far as possible in order to diminish the effect of age on recovery. The findings of our study demonstrated that the initial muscle strength of legs might be an effective predictor of muscle strength recovery after FES cycling training. Besides, FESCE could also provide an effective transitional training for SCI patients in muscle torque increase before the operating electronic device usage at a later stage. There are still some limitations to our study: the permanent effect of FESCE and the other training parameter control such as duration and frequency of FESCE etc, which need further study for more efficiency and convenience for SCI patients. Moreover, in spite of various dietary needs of patients, the subjects' diet intake should be controlled properly in order to avoid the influence on body weight and BMI during the study period.

In conclusion, FES-induced cycling training program resulted in significant increase in thigh muscle mass after a 4-week period and muscle peak torque after 8 weeks of training. Besides, subjects with less muscle power loss have a correspondingly better muscle strength recovery.

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功能性電刺激對不完全脊髓損傷病患力矩與身體組成之影響

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本實驗之目的為研究不完全脊髓損傷病患在接受功能性電刺激踩車訓練後，其身體組成、雙腿腿圍與肌力之變化。本研究共蒐集十八個不完全脊髓損傷病患。每位病患接受每週三次共八週的功能性電刺激踩車訓練。分別紀錄訓練前、訓練四週後，以及訓練八週後的身體組成、雙下肢腿圍及大腿屈肌與伸肌力矩。功能性電刺激踩車訓練四週後，雙下肢大腿腿圍即有明顯增加。訓練八週後，兩側大腿屈肌與大腿伸肌肌力力矩亦顯著增加。此外，八週訓練後瘦肌肉組織也明顯增加。經由本實驗可知，功能性電刺激踩車訓練可增加不完全脊髓損傷病患雙下肢腿圍與肌力力矩。

關鍵詞：身體組成，功能性電刺激，最大力矩，脊髓損傷
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