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Functional electrical stimulation cycling improves body composition, metabolic and neural factors in persons with spinal cord injury

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Abstract

Persons with spinal cord injury (SCI) are at a heightened risk of developing type II diabetes and cardiovascular disease. The purpose of this investigation was to conduct an analysis of metabolic, body composition, and neurological factors before and after 10 weeks of functional electrical stimulation (FES) cycling in persons with SCI. Eighteen individuals with SCI received FES cycling 2–3 times per week for 10 weeks. Body composition was analyzed by dual X-ray absorptiometry. The American Spinal Injury Association (ASIA) neurological classification of SCI test battery was used to assess motor and sensory function. An oral glucose tolerance (OGTT) and insulin-response test was performed to assess blood glucose control. Additional metabolic variables including plasma cholesterol (total-C, HDL-C, LDL-C), triglyceride, and inflammatory markers (IL-6, TNF-α, and CRP) were also measured. Total FES cycling power and work done increased with training. Lean muscle mass also increased, whereas, bone and adipose mass did not change. The ASIA motor and sensory scores for the lower extremity significantly increased with training. Blood glucose and insulin levels were lower following the OGTT after 10 weeks of training. Triglyceride levels did not change following training. However, levels of IL-6, TNF-α, and CRP were all significantly reduced.

Keywords: Functional electrical stimulation; FES cycling; Spinal cord injury; Paralysis

1. Introduction

Advances in emergency care for persons with spinal cord injury (SCI) have resulted in increased rates of survival and more individuals are recovering but with sustained neuromuscular paralysis. SCIs typically occur in persons between the ages of 18–30 years. Thus, the loss of productive years is a major concern if overall health is not maintained across the life span. Muscle paralysis severely limits an individual's participation in activities of daily living, functional independence and exercise. Chronic paralysis can lead to decreases in bone mineral density (Garland et al., 1992) and muscle mass (Castro et al., 1999), increased adipose tissue, and abnormalities of carbohydrate (Elder et al., 2004), lipid, and protein metabolism (Dallmeijer et al., 1997, 1999).

Physical fitness is an important risk factor for all-cause mortality (Paffenbarger et al., 1986; Blair et al., 1989, 1996). The physical de-conditioning resulting from largely sedentary lives of individuals with SCI are well known (Dearwater et al., 1986; Washburn and Figoni, 1998; Bernard et al., 2000; Jacobs and Nash, 2004). Secondary medical complications related to SCI can be life-threatening and often result in short-term or long-term hospitalization. Thus, finding an effective and efficient means to maintain neuromuscular and metabolic health in the SCI population is essential.

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Functional electrical stimulation (FES) cycling can increase muscle volume, strength, endurance, insulin sensitivity, and glucose metabolism (Hjeltnes et al., 1998). Solomonow et al. (1997a,b) demonstrated that approximately 14 weeks of FES walking can improve total cholesterol and low-density lipid levels, hydroxyproline/creatine ratios and reduce spasticity in individuals with paraplegia from SCI. Improvements in motor and sensory ability following the use of FES have been demonstrated in persons paralyzed by stroke (Sheffler and Chae, 2007) but little investigation has been done for the SCI population. Moreover, inflammatory markers which are indications of overall metabolic and cardiovascular health and influence insulin sensitivity have not been measured following FES training.

The purpose of this investigation was to conduct a comprehensive analysis of metabolic, body composition, and neurological profiles before and after 10 weeks of FES cycling in individuals with paralysis from SCI. We hypothesized that 10 weeks of FES cycling would significantly improve glucose metabolism and insulin resistance, increase muscle mass, decrease adipose tissue, lower blood cholesterol and inflammatory markers and improve neurological motor and sensory function of the lower extremity.

2. Methods

2.1. Participants

Eighteen individuals with clinical presentation of either paraplegia or tetraplegia resulting from SCI participated in this study. Study participants were recruited by referral from physicians at Brackenridge Hospital, Austin, TX. Prior to participation, all individuals signed a written informed consent and provided a medical clearance form signed by their personal physician. Potential participants were excluded from the study if they met any one of the following criteria: injury was within 1 year, skin breakdown which limited ability to sit for 30 min, cardiovascular disease, cardiac pacemakers or defibrillators, vasomotor instability, severe loss of range of motion in joints, severe osteoporosis, joint instability, heterotopic ossification, bone fractures, pregnancy, epilepsy, frequent and severe bouts of autonomic dysreflexia, or any other complications that would prevent them from participation as determined by their primary physician. All experimental procedures were approved by the Institutional Review Boards at the University of Texas at Austin and Seton Healthcare Network. Subject demographics (gender, age, injury level, time post-injury, sensory sparing hypersensitivity, initial lower motor scores) are listed in Table 1.

2.2. Protocol

The participants received FES cycling 2–3 times per week for 10 weeks under the supervision of a licensed Occupational Therapist at Brackenridge Hospital, Austin, Texas. The FES cycling was performed on an Ergys2 (Theraputic Alliances, Fairborn, OH) automated recumbent bicycle. Prior to cycling, surface electrodes used for electrical stimulation were applied to the quadriceps, gluteal and hamstring muscles. The stimulation frequency used was constant 50 Hz for all muscle groups.

After a 1-min warm-up with assisted passive movements of the pedals to allow for normalization of tone and the passing of reactive spasms that may occur upon initiation of motion, the stimulation intensity was increased automatically by the Ergys2 computer to promote the participants' cadence to match a target cadence of 49 rpm. The computerized protocol of the Ergys2 is designed to automatically regulate this target cadence (pedaling speed) by adjusting the stimulation level as well as the torque resistance of the flywheel. The stimulation level was set not to exceed 140 mA. At the start of the first session, all participants were oriented with the FES cycle and the intensity levels. Participants were free to request for the maximal stimulation intensity

Table 1
Subject demographics

Rider	Gender	Age (years)	Injury level	Time post-injury (years)	Complete/incomplete	Sensory sparing	Hyper-sensitivity	Lower motor score
1	F	28	T4	8	I	No	No	3
2	M	41	T7	22	C	No	No	0
3	M	25	C4	10	C	No	No	0
4	F	47	C4	2	C	No	No	0
5	M	56	C8	53	I	Yes	Yes	31
6	M	30	C4	10	I	No	No	0
7	M	42	T4	2	I	Yes	Yes	0
8	F	39	T2	14	I	Yes	No	0
9	F	57	T7	2	C	No	No	0
10	M	45	T3	22	C	No	No	0
11	M	48	T6	20	I	No	No	8
12	M	27	T4	1	I	Yes	Yes	0
13	F	43	C4	16	I	Yes	No	0
14	M	35	C4	1	I	No	No	1
15	M	49	T5	2	I	Yes	Yes	34
16	M	29	T5	4	I	No	No	3
17	M	51	C5	5	I	No	No	0
18	M	36	C8	2	I	Yes	No	5
Mean		40		11				5
SE		2.4		3.1				2.6

Table 2
Stimulation intensity

	Pre-fatigue (mA)		Fatigue (mA)[a]	
	Right	Left	Right	Left
Quadriceps				
Week 1	76.18 ± 8.56	76.94 ± 8.42	123.69 ± 6.31	125.41 ± 5.47
Week 10	69.62 ± 7.87	70.64 ± 7.82	119.75 ± 9.52	120.93 ± 6.31
Hamstrings				
Week 1	76.18 ± 8.56	76.94 ± 8.42	123.69 ± 6.31	125.41 ± 5.47
Week 10	69.62 ± 7.87	71.78 ± 7.79	119.75 ± 9.52	122.11 ± 8.78
Gluteals				
Week 1	76.18 ± 8.56	76.94 ± 8.42	123.69 ± 6.31	125.41 ± 5.47
Week 10	69.62 ± 7.87	70.64 ± 7.82	119.75 ± 9.52	120.93 ± 9.21

[a] All fatigue values were significantly greater than pre-fatigue values.

to be adjusted below the 140 mA maximum if they felt it was uncomfortable. The stimulation intensities used at the start (pre-fatigue) and end (fatigue) of the longest ride for each week for all participants are shown in Table 2. The stimulation intensity significantly increased with fatigue for all muscle groups. There were no significant changes in the stimulation intensity required to produce the cadence of 49 rpm following the 10 weeks of training.

When the participant's pedaling speed met or dropped below 35 rpm, the machine automatically started a 2-min cool-down mode with passive pedaling produced by the experimenter. If the participants were unable to pedal for 30 min consecutively, they were allowed to rest for 5 min and then repeat the cycling protocol. However, they were given a maximum of five rides per training session to achieve a total of 30 min of exercise time. If the participant was unable to sustain FES cycling for a total of 30 min within a training session, the therapist manually assisted pedaling while the participant received the maximum electrical stimulation.

On the first day of FES training, the flywheel resistance was set according to the functional status of the participant. The resistance was increased 1 kp during the training period if the individual had three consecutive days of riding for 30 min with no manual assistance from the therapist. If the participant was already riding with resistance, the resistance was increased if the average resistance of each of three consecutive rides was greater than 70% of the set resistance (i.e., 0.7 kp average for a resistance level set at 1 kp). The resistance level was reduced if a higher level of resistance and subsequent stimulation level induced excessive muscle spasticity.

2.3. Pre- and post-testing

Body composition, motor and sensory function and metabolic factors were assessed within 48 h before and after the FES cycling protocol at the University of Texas at Austin. Body composition and bone mass were analyzed by dual X-ray absorptiometry (DEXA) (Lunar Prodigy, GE Health Care, Madison, Wisconsin).

The American Spinal Injury Association (ASIA) neurological classification of SCI test battery (Marino and Graves, 2004) was conducted by the same Occupational Therapist before and after training and was used to describe the status of the motor and sensory components of the CNS. The ASIA is an international standard for the neurologic description for persons with traumatic SCI.

The ability to regulate blood glucose was assessed with an oral glucose tolerance test (OGTT) under fasting conditions. Each participant fasted for 12 h prior to reporting to the laboratory. Upon arriving to the laboratory, they had a 1.5 in. flexible Teflon catheter inserted, under sterile conditions, into a forearm vein. The participants consumed 75 g of dextrose in liquid form. Blood samples (5 ml) were drawn immediately before dextrose consumption and at 30, 60, 120 and 180 min following its consumption. All blood samples were collected in ethylenediaminetetraacetic acid. From each blood draw, approximately 60 μL were removed to analyze blood glucose values using a Basic One Touch blood glucometer (Life Scan Inc., Milpitas, CA). The remaining samples were kept on ice until the OGTT was completed, after which they were centrifuged for 10 min at 1000*g* at 4 °C. Following centrifugation, the plasma was transferred to new 12 × 75 tubes and immediately frozen at −80 °C for later analysis of plasma insulin.

Plasma insulin was determined using a competitive ^{125}I radioimmunoassay (MP Biomedicals, Costa Mesa, CA). Total cholesterol (total-C) was assayed enzymatically (Raichem, Division of Hemagen Dignostics, Inc., San Diego, CA, Catalog No. 85464). HDL-C was assayed following separation of high-density lipoprotein (HDL-C) from low-density lipoprotein (LDL-C) and very low-density lipoprotein by precipitation with magnesium chloride in aqueous dextran sulfate 500 (Raichem, Catalog No. 82051). Plasma triglyceride was measured enzymatically at 37 °C (Raichem, Catalog Nos. 84098 and 85471). C-reactive protein (CRP) was measured using an immunoturbidimetric assay method for quantitative determination of antibody and antigen immunoprecipitation complexes (Raichem, Catalog No. 87545). Tumor necrosis factor-α (TNF-α) and interleuken-6 (IL-6) were analyzed using enzyme-linked immunosorbant assay kits (Biosource International Inc., CA, Catalog No. KHC3011 and KHC0061, respectively) as per the manufacture's protocols. Assays were run at room temperature in the dark and read at the appropriate wavelength using a microplate reader (Bio-Tek Instruments, Inc., Winooski, VT).

2.4. Data analysis

FES cycling power and work performed were computed for each training day and then averaged over each training week. One-way repeated measures analysis of variances (ANOVA) were used to determine if training time had an effect on cycling power and work. Tukey's post-hoc analyses were used to compare the average cycling power and work calculated from the first training week with each subsequent training week. A two-way repeated measures ANOVAs with Tukey's post-hoc analysis (factors: fatigue and training) was used to compare the stimulation intensities for all muscle groups.

One-way repeated measures ANOVA with Tukey post-hoc analyses was used to determine the effects of training on each body mass component (lean muscle, fat, bone, total body mass) and ASIA impairment scores (total, motor and sensory) before and after the training period. A two-way repeated measures ANOVA with Tukey's post-hoc analysis (factors: group and training) was used to compare all variables tested between participants with ASIA lower motor scores of zero ($N = 11$) and those with motor scores above zero ($N = 7$).

Glucose and insulin blood levels analyzed immediately before dextrose consumption and 30, 60, 120 and 180 min following its consumption were each compared with a two-way repeated measures ANOVA (factors: consumption time (0, 30, 60, 120 and 180 min)) and training (pre-test versus post-test) with Tukey post-hoc tests.

The effect of training on all other metabolic variables analyzed from the blood sample immediately drawn before dextrose consumption including total-C, HDL-C, LDL-C, triglyceride, IL-6, TNF-α, and CRP were determined with one-way (pre-test versus post-test) repeated measures ANOVAs. An alpha level of 0.05 was used for all statistical comparisons and significance accepted when $p \leqslant 0.05$. All data are presented as mean ± standard error. There were no significant differences in any of the variables tested between the subjects that had motor scores of zero and those that did not. Thus, the data were collapsed and all data are presented as the results for all 18 participants.

3. Results

3.1. Training load

Training week had a statistically significant effect on the ride time without manually assisted pedaling. Ride times during training weeks 5–10 were statistically greater than during week 1. Group means and standard errors are displayed in Fig. 1. On Day 1, the range of ride times across all participants was 0.22–30 min, with only five participants able to ride for the 30-min limit. By week 10, 12 of the 18 participants rode for 30 min.

Group means and standard errors for cycling power and work per training week are graphically presented in Figs. 2 and 3, respectively. Even though 7/18 participants rode without resistance throughout the duration of the training protocol (cycling power = 0), a statistically significant main effect was found for training time. Only one individual began training with resistance on the FES cycle. This person started at a power of 3.34 W on Day 1 and cycled with a power of 9.92 W on Day 10. The other 10 participants began training with a power of 0 and ended with a range of 0.71–10.51 W. Across all participants, post-hoc testing revealed that both cycling power and work done were greater during training weeks 8, 9 and 10 compared to week 1.

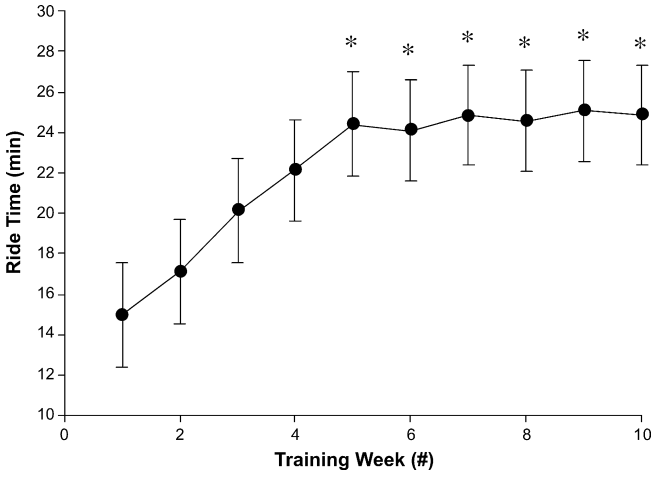

Fig. 1. Mean and standard error for ride time without manually assisted pedaling are plotted for each week for all 18 participants. Unassisted ride time was significantly higher in weeks 5–10 compared to week 1.

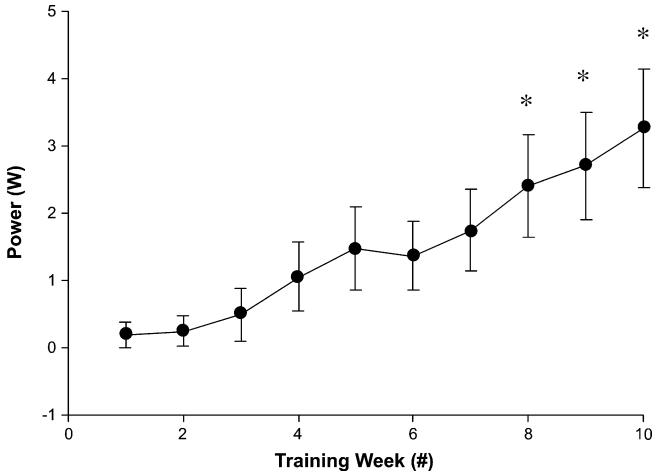

Fig. 2. Average FES cycling power output is plotted with standard error bars for each week for all 18 participants. Cycling power was significantly higher in weeks 8, 9 and 10 compared to week 1.

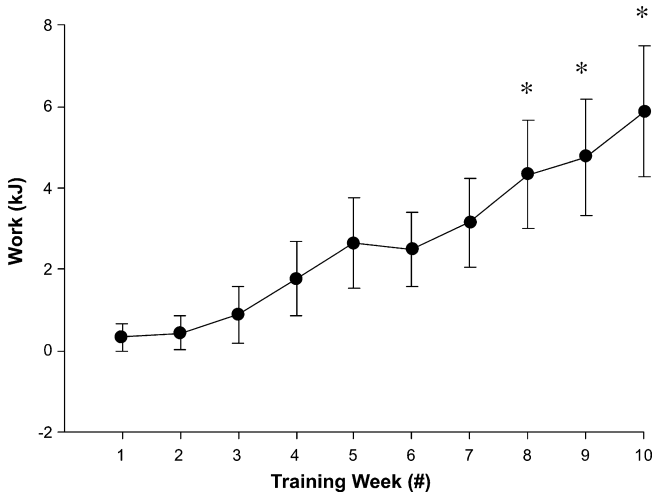

Fig. 3. Average FES cycling work performed is plotted with standard error bars for each week for all 18 participants. Cycling work performed was significantly greater for weeks 8, 9 and 10 compared to week 1.

3.2. Body composition

Group means and standard errors of the components of body mass are located in Table 2. Total body mass, and lean muscle mass significantly increased, while, there was no significant difference in bone or adipose tissue following the 10 weeks of training.

3.3. ASIA impairment scores

Group means and standard errors for the ASIA impairment scores are located in Table 2. One participant was not measured in the past due to personal circumstances and was excluded from the analysis. Lower extremity total ASIA scores and the motor and sensory components of the ASIA test were all significantly higher following training.

3.4. Metabolic risk factors

Group means and standard errors for blood glucose and plasma insulin blood serum levels over the course of dextrose consumption during the pre- and post-tests are presented in Figs. 4 and 5. Glucose levels were influenced by the time after dextrose consumption and training. During the pre-test and post-test, glucose levels were significantly greater at 30, 60 and 120 min after dextrose consumption compared to the baseline value at time 0. Glucose levels at 30, 60 and 120 min after dextrose consumption were significantly lower during the post-test compared to the pre-test.

Insulin levels were also influenced by the time after dextrose consumption and training. During the pre-test and post-test, insulin levels were statistically greater at 30, 60 and 120 min after dextrose consumption compared to the baseline value at time 0. Insulin levels at 60 and 120 min after dextrose consumption were significantly lower during the post-test values compared to the pre-test values.

The group means and standard errors for all other metabolic variables collected pre-dextrose consumption are presented in Table 2. Statistically significant improvements in CRP, IL-6 and TNF-α occurred following training. LDL cholesterol, total cholesterol and triglyceride levels did not change, while HDL cholesterol fell slightly ($p < 0.05$). Only one of the participants started the study with a high total cholesterol level (>200 mg/dL). This individual began the study with a total cholesterol level of 209.68 mg/dL and by week 10, his level decreased to 177.70 mg/dL.

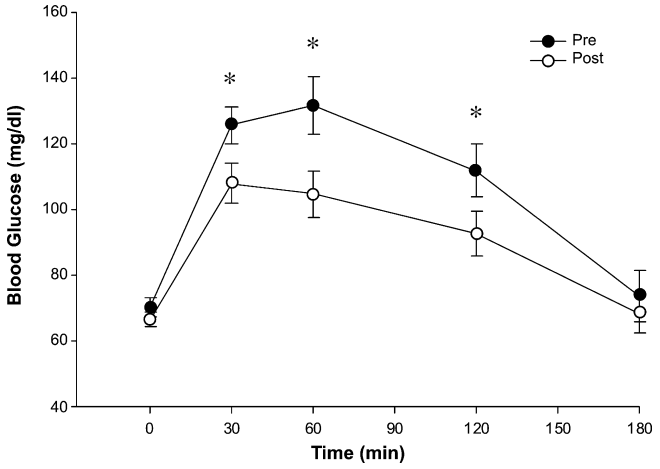

Fig. 4. Mean and standard error for all 18 subjects' blood glucose levels at 0, 60, 120 and 180 min following administration of the oral glucose tolerance test. Glucose levels were significantly lower following the 10 weeks of FES cycling at 30, 60 and 120 min post-OGTT compared to pre-training values.

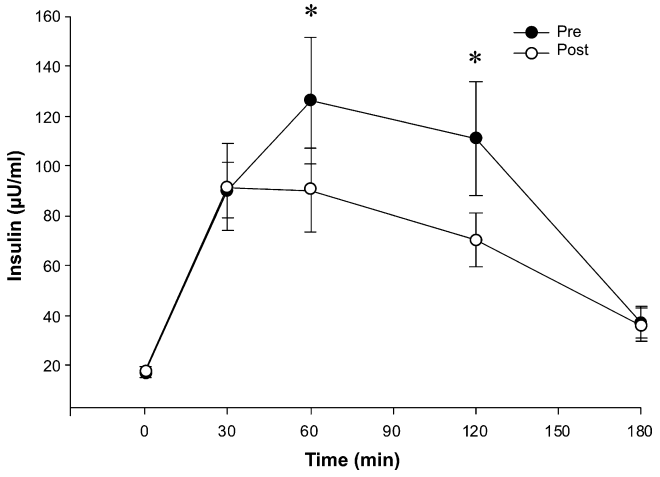

Fig. 5. Mean and standard error for all 18 subjects' insulin levels at 0, 60, 120 and 180 min following administration of the oral glucose tolerance test. Insulin levels were significantly lower following the 10 weeks FES cycling at 60 and 120 min compared to pre-training levels.

4. Discussion

It is imperative that adequate means to sustain overall health are employed to reduce the risks of sedentary lifestyle and early mortality rates in persons paralyzed by SCI. In the present study, we found that 30 min of FES cycling per day, three times per week for 10 weeks significantly improved lean muscle mass, cycling power, work capacity, endurance, glucose tolerance, insulin levels, inflammatory markers, and motor and sensory neurological function. This study is one of the few to use a multidisciplinary approach to investigate metabolic and neurological health factors in a single study and demonstrates that the clinical use of FES cycling can improve overall health benefits to metabolic, cardiovascular and neurological systems.

4.1. Motor control and sensation

In the present study, there were increases in lower extremity motor, sensory and total ASIA scores following training. Very few studies have measured motor or sensory function following FES use in individuals with SCI. One study showed improvements in leg function following 16 months of FES cycling in a single subject design (Donaldson et al., 2000). In individuals with SCI who had partial muscle paralysis of the hand, rehabilitation programs that used electrical stimulation improved voluntary control to a greater degree than rehabilitation programs without it (Popovic et al., 2002). Electrical stimulation excites motor as well as sensory neurons. It is possible that the 10 weeks of electrical stimulation in the present investigation served to strengthen residual pathways that remained after injury.

4.2. Muscle mass, power and endurance

In the present study, mean cycling power progressively increased over the 10 weeks of training. The ability to cycle for approximately 30 min stabilized by the fifth week of FES cycling. It would be expected that greater improvements in health outcome measures could be achieved once this level was met. Participants also significantly increased

the amount of resistance on the flywheel that they were able to cycle with. This resulted in an increase in the amount of work done per week over the training period. Power output ranged from 0 to 11 W following training. This is consistent with the findings of Hjeltnes et al. (1997) who trained five individuals with SCI seven times per week for 8 weeks and found an increase in ride time and power output from 0 to 6–18 W following training.

The increases in muscle power and work done in the present study were accompanied by a 4% significant increase in lean muscle mass. Similarly, Hjeltnes et al. (1997) found an increase in whole body lean mass of 2% following 8 weeks of FES cycling in individuals with SCI. Skold et al. (2002) found a 10% increase in muscle tissue volume after 6 months of FES cycling. Thus, after prolonged inactivity, the muscles of individuals with SCI are still capable of adapting to a stimulus exercise overload.

4.3. Glucose metabolism

Persons paralyzed by SCI are characterized by reduced oral glucose tolerance (Aksnes et al., 1994; Bauman and Spungen, 1994; Elder et al., 2004), and decreased insulin-mediated glucose uptake (Aksnes et al., 1996; Elder et al., 2004), which can lead to an increase type II diabetes and early mortality rates. Individuals with SCI have been shown to have higher rates of type II diabetes than age-matched controls and the risk increases with the level of neurological deficit (Bauman and Spungen, 1994). In the present study, we found significant improvements in the OGTT and insulin response following 10 weeks of FES cycling in persons with SCI. The improvements in glucose tolerance occurred along with an increase in lean muscle mass and no significant change in adipose tissue. An increase in lean body mass following exercise training has been found to correlate with improvements in glucose tolerance (Miller et al., 1984). However, an increase in lean body mass is probably only partially responsible for the improved glucose tolerance and insulin action observed.

Improved glucose clearance and insulin action has been observed following 8 weeks (Hjeltnes et al., 1998; Jeon et al., 2002) and 1 year (Hjeltnes et al., 1998; Jeon et al., 2002) of FES cycling. The improvements were associated with an increase in muscle glucose transporter-4 expression and enzymes that control intracellular glucose disposal (Hjeltnes et al., 1998). FES cycling can also increase the percentage of insulin sensitive type 1 and type IIa fibers and to reduce the percentage of type IIb fibers in the activated muscle (Anderson et al., 1996). These results provide clear evidence that FES cycling is an effective means to maintain adequate blood glucose control and reduce insulin resistance in SCI individuals.

4.4. Adipose

SCI persons are characterized by increased body fat mass and decreased lean body mass (Nuhlicek et al., 1988; Sedlock and Laventure, 1990). By 24 weeks after injury, the average cross-sectional area (CSA) of paralyzed skeletal muscle in SCI persons is just 45–80% of that of age- and weight-matched controls (Castro et al., 1999). Using a cross-sectional approach, Elder et al. (2004) demonstrated that persons with SCI have, on average, only 62% of skeletal muscle CSA of age-, height-, weight- and body mass index-matched able-bodied individuals yet have over three times as much intramuscular fat mass (IMF) (SCI,17.3% IMF; able-bodied, 4.6%). In the present study, FES cycling for 10 weeks did not significantly alter the total body adipose tissue. However, FES cycling three times per week for 8 weeks has been shown to decrease body fat content by 2% (Hjeltnes et al., 1997).

4.5. Plasma lipids

In able-bodied individuals, a healthy cholesterol and triglyceride profile is associated with physical activity (Seals et al., 1984) and with low visceral adiposity (Despres, 1993). Cross-sectional data demonstrates that active men with tetraplegia have a significantly higher HDL-C and lower total-C/HDL-C ratio compared to sedentary men with tetraplegia (Dallmeijer et al., 1997). During the first 2 years after SCI, physical activity can improve the cholesterol profile if total-C and its subfractions are abnormal (Dallmeijer et al., 1999). However, in the present study, we did not observe any improvement in plasma cholesterol levels or triglycerides. In fact, we found a significant reduction in HDL cholesterol. The reason for not finding a significant improvement in plasma lipids was probably due to the fact that total cholesterol, LDL cholesterol and triglyceride levels were well within the normal range prior to training in 17/18 participants. The one individual who started the study with a high cholesterol level was within the normal range by the end of the 10 weeks. In a study of 70 participants with paraplegia, eight of the participants had initially high total cholesterol levels and these individuals decreased their cholesterol levels to within the normal range following 14 weeks of FES walking (Solomonow et al., 1997b). Their LDL levels also decreased and their HDL levels also showed a trend toward a reduction ($p < 0.009$). It is not immediately apparent why HDL cholesterol would declined with exercise training. The response of plasma HDL cholesterol to standardized exercise training, however, is highly variable among individuals and subject to genetic variation (Halverstadt et al., 2003). It is also subject to diet as increases in carbohydrate consumption will reduce HDL cholesterol levels (Wolf and Grundy, 1983). Both genetic variation and changes in the diet of our study participants could possibly account for the decline in plasma HDL cholesterol observed.

4.6. Bone

Spinal cord injury results in a dramatic decline in bone mass and bone mineral density (Garland et al., 1992;

Modlesky et al., 2004) and a marked increase in lower extremity fracture. Muscle volume in SCI persons is strongly correlated with cortical bone volume and bone mineral content (Modlesky et al., 2005). In the present investigation, we observed a 4% increase in lean muscle mass with no significant change in the amount of bone. However, it should be noted that although the DEXA is very accurate, slight changes in bone angulation during the pre- and post-tests can increase the variability of the measurements. Hjeltnes et al. (1997) also found no increase in bone mineral density as a result of 8 weeks of FES cycling in SCI persons, despite a small increase in total body muscle mass. Similarly, no changes in bone mineral density were reported following FES cycling 3 days per week for 6 months (Leeds et al., 1990) or 5 days per week for 5 months (Clark et al., 2007). Increases in bone density have been reported following FES cycling training 5 days per week for 6 months (Belanger et al., 2000) and 3 days per week for 12 months (Mohr et al., 1997). The lack of response in the present study was, therefore, likely due to an insufficient training duration or intensity. However, 14 weeks of FES walking reduced urinary hydroxyproline/creatine ratios which are indicative of bone loss (Solomonow et al., 1997b).

4.7. Inflammatory markers

There is growing evidence that the development of atherosclerotic plaque is associated with inflammation and that the measurement of this inflammation has predictive value in determining risk for future thrombotic events (Ross, 1993; Tracy, 1997; Tracy et al., 1997; Luo et al., 2004). Markers of low-grade inflammation associated with heart disease include CRP, TNF-α and IL-6 (Luo et al., 2004; Chirinos et al., 2005). Individuals with low risk of heart disease have low levels of these markers of inflammation, whereas those with high risk have high levels of these markers. Moreover, individuals who are physically active appear to have reduced inflammation (Tisi et al., 1997; Geffken et al., 2001; Kondo et al., 2005). In the present investigation, significant reductions occurred in all inflammatory markers tested (CRP, IL-6 and TNF-α). This is the first study to demonstrate these improvements in the SCI population and suggests that FES may be an effective mechanism for reducing the incidence of cardiovascular disease in this population. It is also important to acknowledge that elevations in plasma TNF-α have been associated with insulin resistance and type 2 diabetes (Plomgaard et al., 2007). Our finding of an improvement in glucose tolerance and insulin sensitivity following 10 weeks of FES cycling, therefore, could be, in part, due to a lowering of plasma TNF-α (see Table 3).

4.8. Summary

In summary, significant improvements in blood glucose control and inflammatory markers occurred in conjunction with an increase in lean muscle mass and motor and sensory ability following 10 weeks of FES cycling in persons with paralysis from SCI. It is expected that continuous use would be required to maintain the observed health benefits across the life span.

Table 3
Body composition, neural and metabolic measures

	Pre	Post
Body composition		
Total (lb)	153.22 ± 9.32	157.76 ± 9.11*
Muscle (lb)	96.8 ± 5.61	100.0 ± 5.47*
Bone (lb)	6.03 ± 0.37	5.99 ± 0.39
Fat (lb)	50.42 ± 5.10	51.78 ± 4.98
Neural factors		
Total ASIA score	137.94 ± 16.22	147.24 ± 16.83*
Motor score	46.35 ± 4.90	49.35 ± 5.31*
Sensory score	91.59 ± 11.32	97.88 ± 11.52*
Metabolic factors		
HDL cholesterol (mg/dL)	34.27 ± 2.00	30.56 ± 2.11*
LDL cholesterol (mg/dL)	102.65 ± 6.20	105.54 ± 5.49
Total cholesterol (mg/dL)	157.91 ± 6.36	156.32 ± 6.65
Triglyceride (mg/dL)	104.92 ± 26.90	101.07 ± 25.46
CRP (mg/L)	15.92 ± 1.57	12.94 ± 0.78*
IL-6 (pg/ml)	4.91 ± 1.10	3.79 ± 0.52*
TNF-α (pg/ml)	11.82 ± 0.63	11.31 ± 0.62*

* Statistically significant difference at $p < 0.05$.

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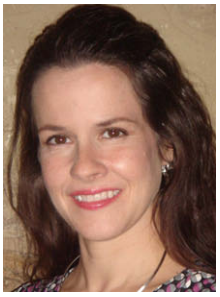

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