References for the use of FES in spinal cord injured clients: Full texts and abstracts of published research results

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  - Hunt KJ1,2, Schauer T1, N. Negård1, W. Stewart2, M. H. Fraser2 (2002) A Pilot Study of Lower-limb FES Cycling in Paraplegia

NOT TO BE COPIED OR PASSED ON!
Severe muscle atrophy occurs rapidly following traumatic spinal cord injury (SCI). Previous research shows that neuromuscular or ‘functional’ electrical stimulation (FES), particularly FES-cycle ergometry (FES-CE) can cause muscle hypertrophy in individuals with chronic SCI (41 year post-injury). However, the modest degree of hypertrophy in these already atrophied muscles has lessened earlier hopes that FES therapy would reduce secondary impairments of SCI. It is not known whether FES treatments are effective when used to prevent, rather than reverse, muscle atrophy in individuals with acute SCI. This study explored whether unloaded isometric FES (FES-IC) or FES-CE decreased subsequent muscle atrophy in individuals with acute SCI (53 months post-injury). Twenty-six subjects, 14 ± 15 weeks post-traumatic SCI, were assigned to control, FES-IC, or FES-CE against progressively increasing resistance. Subjects were involved in the study for 3 or 6 months. Total body lean body mass (TB-LBM), lower limb lean body mass (LL-LBM), and gluteal lean body mass (G-LBM) were measured before the study, and at 3 and 6 months using dual energy X-ray absorptiometry (DEXA). Controls lost an average of 6.1%, 10.1%, 12.4%, after 3 months and 9.5%, 21.4%, 26.8% after 6 months in TB-LBM, LL-LBM, and G-LBM respectively. Subjects in the FES-IC group consistently lost less lean body mass than controls, however, only 6 month G-LBM loss was significantly attenuated in this group relative to the controls. In the FES-CE group, LL-LBM and G-LBM loss were prevented at both 3 and 6 months, and TB-LBM loss was prevented at 6 months. In addition, FES-CE significantly increased G-LBM and LL-LBM after 6 months of training relative to pre-training levels. Within the control group, there was no significant relationship between LL-LBM loss (3 and 6 months) and the number of days between injury and baseline measurement.

In summary, this study shows that FES-CE, but not FES-IC, training prevents muscle atrophy in acute SCI after 3 months of training, and causes significant hypertrophy after 6 months. The magnitude of differences in regionalized LBM between controls and FES-CE subject raises hopes that such treatment may indeed be beneficial in preventing secondary impairments of SCI if employed before extensive post-injury atrophy occurs.

We examined the ability of patients with spinal cord injury to undergo adaptations to chronic exercise training (cycle ergometry) invoked by functional electrical stimulation (FES) of the legs. Nine such patients performed incremental and constant work rate exercise before and after exercise training. Exercise sessions averaged 2.1 +/- 0.4/wk, and consisted of 30 min/session of continuous FES recumbent cycling with increasing work rate as tolerated. Peak VO2 and peak work rate significantly improved with training. Peak VO2 was significantly correlated with peak heart rate both before and after training (r = 0.97 pre and 0.85 post, P < 0.01 for both). The time course of the VO2, VO2C and VE responses to constant-load exercise (unloaded cycling) and in recovery (mean response time MRT) were very long prior to training, and became significantly faster following training. However, there was no correlation between percentage improvement in either MRTon or MRToff for VO2 and the percentage increase in peak VO2. Exercise tolerance in these patients with spinal cord injury appears to be a direct function of the ability to increase heart rate. Further, exercise training can elicit significant improvements in both exercise tolerance and in gas exchange kinetics, even when performed only twice per week. However, these improvements may be accomplished by different mechanisms.

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Study design: Cross-sectional study comparing healthy subjects with age and gender matched subjects with spinal cord injury (SCI, injury levels from C5 to T12).

Objectives: To compare the acute cardiorespiratory responses and muscle oxygenation trends during functional electrical stimulation (FES) cycle exercise and recovery in the SCI and healthy subjects exercising on a mechanical cycle ergometer.

Setting: Seven volunteers in each group participated in one exercise test at the Rick Hansen Center, University of Alberta, Edmonton, Canada.

Methods: Both groups completed a stagewise incremental test to voluntary fatigue followed by 2 min each of active and passive recovery. Cardiorespiratory responses were continuously monitored using an automated metabolic cart and a wireless heart rate monitor. Tissue absorbency, an index of muscle oxygenation, was monitored non-invasively from the vastus lateralis using near infrared spectroscopy.

Results: The healthy subjects showed significant (P<0.05) increases in the oxygen uptake (VO2), heart rate (HR) and ventilation rate (VE) from rest to maximal exercise. The SCI subjects showed a twofold increase in VO2 (P>0.05), a threefold increase in Vdot;E (P<0.05) and a 5 beats/min increase in HR (P>0.05) from the resting value. The SCI subjects demonstrated a lesser degree (P<0.05) of muscle deoxygenation than the healthy subjects during the transition from rest to exercise. Regression analysis indicated that the rate of decline in muscle deoxygenation with respect to the VO2 was significantly (P<0.05) faster in the SCI subjects compared to healthy subjects.

Conclusions: FES exercise in SCI subjects elicits: (a) modest increases in the cardiorespiratory responses when compared to resting levels; (b) lower degree of muscle deoxygenation during maximal exercise, and (c) faster changes in muscle deoxygenation with respect to the VO2 during exercise when compared to healthy subjects.

Chen, CH Lai, WP Chan, MH Huang, HW Tsai, JJJ Chen (2005) ´Increases in bone mineral density after functional electrical stimulation cycling exercises in spinal cord injured patients´  
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Purpose. To assess the change in bone mineral density (BMD) after spinal cord injury (SCI) and to evaluate whether BMD loss can be reversed with the intervention of functional electric stimulation cycling exercises (FESCE).

Methods. Fifteen males with SCI were included. Fifteen able-bodied males were also tested to compare BMD. In the SCI group, the FESCE was performed for six months, and then was discontinued in the subsequent six months. BMD was performed before the FESCE, immediately after six months of the FESCE, and at the end of the subsequent six months.

Results. Before the FESCE, the BMD of the SCI subjects in every site, except the lumbar spine, was lower than that of the able-bodied subjects. After six months of FESCE, BMD of the distal femur (DF) and proximal tibia (PT) increased significantly, and BMD of the calcaneus (heel) showed a trend of increase. However, the BMD in the DF, PT, and heel decreased significantly after the subsequent six months without FESCE. The BMD of the femoral neck (FN) decreased progressively throughout the programme.

Conclusions. Our study showed site-specific BMD changes after FESCE. The BMD loss in the DF and PT was partially reversed after six months of FESCE, but the effect faded once the exercise was discontinued.
Study Design: Longitudinal training.
Objectives: To determine the effects of functional electrical stimulated (FES) leg cycle ergometer training on muscle histochemical characteristics in individuals with motor-complete spinal cord injury (SCI).
Setting: University of Alberta, Edmonton, Alberta, Canada.
Methods: Six individuals with motor-complete SCI (age 31-50 years; 3-25 years post-injury) trained using FES leg cycle ergometry for 30 min, 3 days per week for 8 weeks. Biopsies of the vastus lateralis muscle were obtained pre- and post-training and analyzed for fibre composition, fibre size and capillarization.
Results: The majority of muscle fibres were classified as type 2 pre- and post-training. Average fibre area increased 23% (P<0.05) and capillary number increased 39% (P<0.05) with training. As a result of these proportional increases, capillarization expressed relative to fibre area was unchanged with training.
Conclusions: FES leg cycle ergometer training results in proportional increases in fibre area and capillary number in individuals with SCI.


The effect of early intervention using functional electric stimulation cycle ergometry (FES-CE) on skeletal muscle morphology was evaluated in traumatic spinal cord injured (SCI) patients 4 – 6 weeks after injury. Motor complete SCI patients (n = 10) were assigned to either a SCI control group (IC) or FES-CE group (IE) and compared to uninjured controls (UIC) matched for age, activity, and gender.
Training via FES-CE was performed 3 days/week for 13 weeks. In the FES-CE trained group, power output increased from 2.4 ± .88 Watts to 24.5 ± 3.2 Watts. Muscle biopsies were taken from the vastus lateralis muscle at pre- and posttraining for subsequent morphological analysis. Without intervention, muscle fiber cross sectional area (CSAf) decreased 38% and 65% at 6 and 19 weeks post-SCI, respectively. The loss of CSAf had no impact on myonuclear density. Following 13 weeks of FES-CE training, CSAf increased was 63% greater when compared to the IC group. Results of the present investigation suggest that the initiation of FES-CE in first weeks after traumatic SCI attenuates the loss of muscle mass and power output.
Study design: Single subject pilot.
Objectives: (i) To see whether strength and endurance for recreational cycling by functional electrical stimulation (FES) are possible following spinal cord injury (SCI). (ii) To develop the equipment for FES-cycling.
Setting: England.
Methods: Near-isometric or cycling exercise was performed by the incomplete SCI subject at home.
Results: After training for an average of 21 min per day for 16 months, the stimulated muscles increased in size and the subject was able to cycle for 12 km on the level. Surprisingly, there was a substantial increase in the measured voluntary strength of the knee extensors and the subject reports improved leg function.
Conclusion: FES-cycling may promote recovery after incomplete spinal cord injury. If so, it offers the possibility of being a convenient method for widespread use.
The study investigated the cardiorespiratory (CR) responses at rest and during submaximal (0-W) functional electrical stimulation (FES)-induced leg cycle ergometer (LCE) exercise prior to and following a progressive intensity FES-LCEa exercise training program in spinal cord injured (SCI) subjects. Seven quadriplegics and six paraplegics participated in FES-LCE training three sessions per week for approximately 12 weeks (36 sessions). Monitored CR responses, including oxygen uptake (VO2), pulmonary ventilation (VE), respiratory exchange ratio (RER), arteriovenous O2 difference (a-vO2), blood pressure (BP), heart rate (HR), stroke volume (SV), total peripheral resistance (TPR), and cardiac output (Q), were determined before and after training.

Power output (PO) increased significantly (p < .05) over the duration of the training program, indicating increased in strength and endurance of the paralyzed muscles used. Respiratory responses were not significantly altered by training in both groups. FES-LCE training significantly increased resting HR and SBP in quadriplegics and lowered SBP, DBP, and MAP in paraplegics. In both groups, HR and BP during submaximal exercise significantly decreased and SV and Q significantly increased after completion of the training program.

These results suggest that FES-LCE training improves peripheral muscular and central cardiovascular fitness in SCI subjects. Posttraining HR and BP may also be more stable in quadriplegics and alleviate hypotension. This therapeutic exercise may ultimately lead to improved rehabilitation outcome and reduced stress during activities of daily living, and possibly reduce the risks for secondary CR disabilities.

The purposes of this study were three-fold: (a) to determine acute physiologic responses of spinal cord injured (SCI) subjects to peak levels of leg cycle ergometry utilizing functional neuromuscular stimulation (FNS) of paralyzed leg muscles, (b) to determine the relative contributions of passive and active components of FNS cycling to the peak physiologic responses, and (c) to compare these physiologic responses between persons who have quadriplegia and those who have paraplegia.

Thirty SCI subjects (17 quadriplegics and 13 paraplegics) performed a discontinuous graded FNS exercise test from rest to fatigue on an ERGYS 1 ergometer. Steady-state physiologic responses were determined by open-circuit spirometry, impedance cardiography with ECG, and auscultation.

In the combined statistics of both groups, it was noted that peak FNS cycling significantly increased (from rest levels) mean oxygen uptake by 255%, arteriovenous O2 difference VO2 and VE, Q and a-vO2 and VCO by 69%, and stroke volume by 45%, while total peripheral vascular resistance decreased by 43%. Mean peak power output for paraplegics (15 W) was significantly higher than for quadriplegics (9 W), eliciting higher peak levels of pulmonary ventilation and sympathetically mediated hemodynamic responses such as cardiac output, heart rate, and systolic and diastolic arterial blood pressure. Passive cycling without FNS produced no statistically significant increases in physiologic responses above the resting level in either group.
STUDY DESIGN: A longitudinal training study.

OBJECTIVES: To assess if contractile speed and fatigability of paralysed quadriceps muscles in individuals with spinal cord injury (SCI) can be altered by functional electrical stimulation leg cycle ergometry (FES-LCE) training.

SETTINGS: The Sint Maartenskliniek rehabilitation centre and the University of Nijmegen, Nijmegen, the Netherlands.

METHODS: Contractile properties of the quadriceps muscle were studied in seven people with motor-complete SCI who participated in a FES-LCE training program. Subjects trained for 30 min, three times per week for 6 weeks. Contractile speed and fatigue characteristics of electrically stimulated isometric contractions were compared before and after 6 weeks of FES-LCE.

RESULTS: Fatigue resistance improved following FES-LCE training as indicated by the higher forces maintained in response to repetitive electrical stimulation. In contrast with an improved fatigue resistance, the maximal rate of force rise was unaffected, the speed of relaxation increased and the fusion of a 10 Hz force signal decreased. Furthermore, the force-frequency relationship shifted to the right at low stimulation frequencies, indicated by a decline in the ratio of 1 and 100 Hz force responses as well as the ratio of 10 and 100 Hz force responses.

CONCLUSION: FES-LCE training can change the physiological properties of the quadriceps muscle in people with SCI. Even after a short period of training, the stimulated muscles become more resistant to fatigue. Furthermore, the increased speed of relaxation and associated decreased fusion and altered force-frequency relationship following training may be related to adaptations in the calcium handling processes, which reflect an early response of long-term disused muscles.

OBJECTIVE: To test whether a short period of training leads to adaptations in the cross-sectional area of large conduit arteries and improved blood flow to the paralyzed legs of individuals with spinal cord injury (SCI).

DESIGN: Before-after trial.

SETTING: Rehabilitation center, academic medical center.

PARTICIPANTS: Nine men with spinal cord lesions.

INTERVENTION: Six weeks of cycling using a functional electrically stimulated leg cycle ergometer (FES-LCE).

MAIN OUTCOME MEASURES: Longitudinal images and simultaneous velocity spectra were measured in the common carotid (CA) and femoral (FA) arteries using quantitative duplex Doppler ultrasound examination. Arterial diameters, peak systolic inflow volumes (PSIVs), mean inflow volumes (MIVs), and a velocity index (VI), representing the peripheral resistance, were obtained at rest. PSIVs and VI were obtained during 3 minutes of hyperemia following 20 minutes of FA occlusion.

RESULTS: Training resulted in significant increases in diameter (p < .01), PSIVs (p < .01), and MIVs (p < .05), and reduced VI (p < .01) of the FA, whereas values in the CA remained unchanged. Postocclusive hyperemic responses were augmented, indicated by significantly higher PSIVs (p < .01) and a trend toward lower VI.

CONCLUSION: Six weeks of FES-LCE training increased the cross-sectional area of large conduit arteries and improved blood flow to the paralyzed legs of individuals with SCI.
The purpose of this study was to assess the physiologic training effects of functional electrical stimulation leg cycle ergometer (FES-LCE) exercise in persons with spinal cord injury (SCI) who were previously untrained in this activity. Ten persons with quadriplegia (C5 to C7) and eight with paraplegia (T4 to T11) performed FES-LCE training on an ERGYS I ergometer 10 to 30 minutes per day, 2 or 3 days per week for 12 to 16 weeks (36 total sessions). Training session power output (PO) ranged from 0.0W (no external resistance) to 30.6W. Each subject completed discontinuous graded FES-LCE and arm crank ergometer (ACE) tests before and after training for determinations of peak lower and upper extremity metabolic, pulmonary, and hemodynamic responses.

Compared with pretraining, this SCI group exhibited significantly (p less than or equal to .05) higher posttraining peak PO (+45%), oxygen uptake ([O2], +23%), pulmonary ventilation (+27%), heart rate (+11%), cardiac output ([Qt], +13%) and significantly lower total peripheral resistance ([TPR], -14%) during FES-LCE posttests. There were no significant changes in peak stroke volume (+6%), mean arterial pressure ([MAP], -5%), or arteriovenous oxygen difference ([a-vO2diff], +10%) during posttraining FES-LCE tests. In addition, no significant differences were noted for the peak level of any monitored variable during ACE posttests after FES-LCE training. The rise in total vascular conductance, implied by the significant decrease in posttraining TPR during FES-LCE tests, denotes that a peripheral circulatory adaptation developed in the persons with SCI during FES-LCE exercise training.

Eight males with spinal cord injury (SCI) participated in an exercise training program using neuromuscular electrical stimulation (NMES) leg cycle ergometry. Each subject completed a minimum of 24 (mean +/- SD = 38.1 +/- 17.2) 30-minute training sessions over a 19-week period. The initial work rate (WR) of 0 watts (W) of unloaded cycling was increased when appropriate with subjects exercising at 11.4 +/- 3.7 W (range = 6.1 W-18.3 W) at the end of the training program. Randomized block repeated measures ANOVA was used to compare pretraining and posttraining peak physiologic responses during graded NMES leg cycle tests and subpeak physiologic responses during 10 minutes of NMES leg cycle exercise at an absolute WR (0 W).

A significant (P < or = 0.05) increase was observed for peak VO2; (+10%, 1.29 +/- 0.30 to 1.42 +/- 0.39 1.min-1). No other statistically significant differences were noted for any other peak variable (VCO2, VO2 ml.kg-1 min-1, VE, WR, HR, RER) pre- to posttraining. During submaximal NMES leg cycle testing, a significant decrease was noted for RER (-9.2%, 1.19 +/- 0.14 to 1.08 +/- 0.09). No other submaximal variable (VO2 1.min-1, ml.kg-1.min-1, VCO2, HR, VE) showed significant changes as a result of the training. Although the improvement in peak VO2 was not as dramatic as those reported in previous studies, it appears that NMES leg cycle training performed two times per week can significantly enhance cardiorespiratory fitness.
Spinal cord injury can restrict exercise participation. As a consequence, fitness can reduce and the risk of health complications and illness are likely to increase. In this study, a group of subjects with complete lower-limb paralysis trained intensively (5 hours per week) using adapted recumbent tricycles at their homes. The cycles incorporate controlled functional electrical stimulation of the paralysed leg muscles: this is known as FES-cycling. The subjects also participated in mobile, recreational cycling sessions outdoors and in leisure facilities. These activities culminated in the first international FES sports festival, held in Cardiff in June 2006.

Regular clinical measurements during the 1-year cycle-training programme showed important improvements in cardiopulmonary fitness, bone density, and muscle bulk and strength. There were no significant changes in seating pressure, tissue oxygenation, or spasticity. Collaboration with a medical technology company has led to certification and commercial availability of FES-cycling systems. In addition, a new start-up company has been founded with the aim of widening FES exercise options. We regard this as a major success of the project: individuals with spinal cord injury are now able to purchase and use FES-cycling systems at home, and for recreational purposes in leisure facilities and outdoors; clinical centres will now be able to offer these systems to patients during primary rehabilitation. Until now, FES-cycling systems were only available to patients through participation in research studies.

Thus, we have demonstrated the practicality of FES-cycling as a recreational activity, we have provided clinical evidence of the positive contribution FES-cycle training can make to fitness and health, and we have succeeded in bringing the technology to market. These developments are important and necessary contributions towards increasing participation in exercise and promoting health maintenance in people with spinal cord injury.

The aim of this work was to develop the engineering methods and apparatus for FES cycling, and to achieve regular periods of mobile FES cycling over significant distances with paraplegic subjects. The study utilised a commercial recumbent tricycle, which was instrumented for stimulation control. Three subjects with a complete spinal cord lesion at level T7-T10 were recruited for the study. After four months of participation in the study the subjects were able to cycle outdoors for distances of up to 3km in a single session. The subjects are also able to cycle continuously and reliably on an indoor cycle trainer for periods of up to 1 h. We conclude that mobile FES cycling over useful distances outdoors is a realistic option for the paraplegic population, even with a low-intensity training regime. Future work will involve FES cycling exercise tests to document changes in cardio-pulmonary fitness in SCI subjects.

Lower limb paralysis after spinal cord injury (SCI) typically leads to musculoskeletal problems, including disuse atrophy, osteoporosis, and reduced joint mobility. The atrophy of the paralyzed muscles can subsequently permit an accompanying loss of support of the skeletal system that, when combined with osteoporosis, can result in fractures and other injuries. Thus, it would be desirable to provide appropriate exercise for the paralyzed lower limbs to prevent or reverse these problems. Functional electrical stimulation (FES) is presently the only available technique that can accomplish this goal, since voluntary arm exercise does not markedly benefit lower limb integrity.


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To examine the importance of blood-borne vs. neural mechanisms for hormonal responses and substrate mobilization during exercise, six spinal cord-injured tetraplegic (C5-T1) males (mean age: 35 yr, range: 24-55 yr) were recruited to perform involuntary, electrically induced cycling [functional electrical stimulation (FES)] to fatigue for 24.6 +/- 2.3 min (mean and SE), and heart rate rose from 67 +/- 7 (rest) to 107 +/- 5 (exercise) beats/min. Voluntary arm cranking in tetraplegics (ARM) and voluntary leg cycling in six matched, long-term immobilized (2-12 mo) males (Vol) served as control experiments.

In FES, peripheral glucose uptake increased [12.4 +/- 1.1 (rest) to 19.5 +/- 4.3 (exercise) mumol.min-1.kg-1; P < 0.05], whereas hepatic glucose production did not change from basal values [12.4 +/- 1.4 (rest) vs. 13.0 +/- 3.4 (exercise) mumol.min-1.kg-1]. Accordingly, plasma glucose decreased [from 5.4 +/- 0.3 (rest) to 4.7 +/- 0.3 (exercise) mmol/l; P < 0.05]. Plasma glucose did not change in response to ARM or Vol. Plasma free fatty acids and beta-hydroxybutyrate decreased only in FES experiments (P < 0.05). During FES, increases in growth hormone (GH) and epinephrine and decreases in insulin concentrations were abolished. Although subnormal throughout the exercise period, norepinephrine concentrations increased during FES, and responses of heart rate, adrenocorticotropic hormone, beta-endorphin, renin, lactate, and potassium were marked.

In conclusion, during exercise, activity in motor centers and afferent muscle nerves is important for normal responses of GH, catecholamines, insulin, glucose production, and lipolysis. Humoral feedback and spinal or simple autonomic nervous reflex mechanisms are not sufficient. However, such mechanisms are involved in redundant control of heart rate and neuroendocrine activity in exercise.

Spinal cord injured persons have limited possibilities to perform physical training. By use of computerized, feed-back controlled electrical stimulation of the gluteal, the hamstrings and the quadriceps muscles cycle ergometry can be performed by the spinal cord injured individual. The cardiovascular demands of this training is higher than with voluntary upper body training using the intact innervated muscles. The inactivity related conditions caused by the spinal cord injury are reversed in part by regular electrically stimulated training. An increase is seen in maximal oxygen consumption, in the insulin stimulated glucose uptake and in the muscular mass and bone mineral content of the lower extremities. Electrically induced cycle ergometry is thoroughly investigated, relatively safe, but time consuming. As this training in addition results in the same well being as seen by training in able bodied individuals it can be recommended for motivated patients.


Purpose: Individuals with spinal cord injuries (SCI) have an increased prevalence of insulin resistance and type 2 diabetes mellitus. In able-bodied individuals, training with large muscle groups increases insulin sensitivity and may prevent type 2 diabetes mellitus. However, individuals with SCI cannot voluntarily recruit major muscle groups, but by functional electrical stimulation (FES) they can now perform ergometer bicycle training.

Methods: Ten subjects with SCI (35 +/- 2 yr (mean +/- SE), 73 +/- 5 kg, level of lesion C6-Th4, time since injury: 12 +/- 2 yr) performed 1 yr of FES cycling (30 min[dot]d-1, 3 d[wk]-1 (intensive training)). Seven subjects continued 6 months with reduced training (1 d[wk]-1 (reduced training)). A sequential, hyperinsulinemic (50 mU[middle dot]m-2 (step 1) and 480 mU[middle dot]m-2 (step 2)), euglycemic clamp, an oral glucose tolerance test (OGTT), and determination of GLUT 4 transporter protein in muscle biopsies were performed before and after training.

Results: Insulin-stimulated glucose uptake rates increased after intensive training (from 4.9 +/- 0.5 mg[middle dot]kg-1 (P < 0.008) (step 1) and from 9.0 +/- 0.8 mg[middle dot]kg-1 (P = 0.103) (step 2)). With the reduction in training, insulin sensitivity decreased to a similar level as before training (P > 0.05). GLUT 4 increased by 105% after intense training and decreased again with the training reduction. The subjects had impaired glucose tolerance before and after training, and neither glucose tolerance nor insulin responses to OGTT were significantly altered by training.

Conclusions: Electrically induced bicycle training, performed three times per week increases insulin sensitivity and GLUT 4 content in skeletal muscle in subjects with SCI. A reduction in training to once per week is not sufficient to maintain these effects. FES training may have a role in the prevention of the insulin resistance syndrome in persons with SCI.

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Spinal cord injured (SCI) individuals have a substantial loss of bone mass in the lower limbs, equaling approximately 50% of normal values in the proximal tibia, and this has been associated with a high incidence of low impact fractures. To evaluate if this inactivity-associated condition in the SCI population can be reversed with prolonged physical training, ten SCI individuals [ages 35.3 ± 2.3 years (mean ± standard error [SE]); post injury time: 12.5 ± 2.7 years, range 2–24 years; level of lesion: C6–Th4; weight: 78 ± 3.8 kg] performed 12 months of Functional Electrical Stimulated (FES) upright cycling for 30 min per day, 3 days per week, followed by six months with only one weekly training session. Bone mineral density (BMD) was determined before training and 12 and 18 months later. BMD was measured in the lumbar spine, the femoral neck, and the proximal tibia by dual energy absorptiometry (DEXA, Nordland XR 26 MK1).

Before training, BMD was in the proximal tibia (52%), as well as in the femoral neck, lower in SCI subjects than in controls of same age (P < 0.05). BMD of the lumbar spine did not differ between groups (P > 0.05). After 12 months of training, the BMD of the proximal tibia had increased 10%, from 0.49 ± 0.04 to 0.54 ± 0.04 g/cm² (P < 0.05). After a further 6 months with reduced training, the BMD in the proximal tibia no longer differed from the BMD before training (P > 0.05). No changes were observed in the lumbar spine or in the femoral neck in response to FES cycle training.

It is concluded that in SCI, the loss of bone mass in the proximal tibia can be partially reversed by regular long-term FES cycle exercise. However, one exercise session per week is insufficient to maintain this increase.
OBJECTIVE: To determine the magnitude of changes in muscle mass and lower extremity body composition that could be induced with a regular regimen of functional electrical stimulation (FES)-induced lower-extremity cycling, as well as the distribution of changes in muscle mass among the thigh muscles in persons with spinal cord injury (SCI).

STUDY DESIGN: Thirteen men with neurologically complete motor sensory SCI underwent a 3-phase, FES-induced, ergometry exercise program: phase 1, quadriceps strengthening; phase 2, progressive sequential stimulation to achieve a rhythmic pedaling motion (surface electrodes placed over the quadriceps, hamstrings, and gluteal muscles); phase 3, FES-induced cycling for 30 minutes. Participants moved from one phase to the next when they met the objectives for the current phase.

MEASURES: Computed tomography of legs to assess muscle cross-sectional area and proportion of muscle and adipose tissue. Scans were done at baseline (before subjects started the program), at first follow-up, typically after 65.4+/−5.6 (SD) weekly sessions, and at second follow-up, typically after 98.1+/−9.1 sessions.

RESULTS: Increases in cross-sectional areas were found in the following muscles: rectus femoris (31%, p<.001), sartorius (22%, p<.025), adductor magnus-hamstrings (26%, p<.001), vastus lateralis (39%, p = .001), vastus medialis-intermedius (31%, p = .025). Cross-sectional area of adductor longus and gracilis muscles did not change. The ratio of muscle to adipose tissue increased significantly in thighs and calves. There was no correlation among the total number of exercise sessions and the magnitude of muscle hypertrophy.

CONCLUSIONS: Muscle cross-sectional area and the muscle to adipose tissue ratio of the lower extremities increased during a regular regimen of 2.3 FES-induced lower extremity cycling sessions weekly. The distribution of changes was related to the proximity of muscles to the stimulating electrodes.
Objective: To assess the time course of arterial adaptations during 6 weeks of functional electric stimulation (FES) training and 6 weeks of detraining in subjects with spinal cord injury (SCI).

Design: Intervention study (before-after trial).

Setting: University medical center.

Participants: Volunteer sample of 9 subjects with SCI.

Interventions: Six weeks of twice weekly FES cycling and 6 weeks of detraining.

Main Outcome Measures: Vascular characteristics were measured by plethysmography (baseline and peak blood flow of the thigh) and echo Doppler (diameter of the femoral artery and flow-mediated dilation [FMD]).

Results: After 2 weeks of FES training, arterial characteristics changed significantly; there was an increase in baseline and peak thigh blood flow, an increase in femoral artery diameter, and a decrease in FMD of the femoral artery. Detraining reversed baseline and peak thigh blood flow, vascular resistance, and femoral diameter toward pretraining values within 1 week. However, detraining did not restore the FMD of the femoral artery, even after 6 weeks.

Conclusions: Two weeks of hybrid FES training (4 exercise bouts) is sufficient to improve peak leg blood flow and arterial diameter, and to normalize FMD. In addition, detraining results in rapidly reversed vascular characteristics within 1 week.
The purpose of this collective review on functional electrical stimulation (FES) cycle ergometer training is to describe the pathologic effects of spinal cord injury (SCI) and the structure and function of the FES cycle ergometers, which reverse the devastating systemic and life-threatening effects of SCI. The pathophysiologic consequences of SCI include diminished cardiopulmonary and circulatory function as well as lower extremity muscle atrophy and bone mass reduction. Clinical studies have demonstrated that the two FES cycle ergometers offer promise in reversing these devastating consequences which can shorten patients’ lives. On the basis of this collective review, it is recommended that all patients with SCI have the benefits of this potentially life-sustaining clinical modality.