FES Cycle Ergometry for Spinal Cord Injury– Evidence Library

Contents

Muscle atrophy is prevented in patients with acute spinal cord injury using functional electrical stimulation.

Baldi J.C.; Jackson R.D.; Moraille R.; Mysiw W.J. (1998).

Spinal Cord, 36(7): 463-469.

Abstract

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 (> 1 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 contractions (FES-IC) or FES-CE decreased subsequent muscle atrophy in individual with acute SCI (< 3 months post-injury). Twenty-six subjects, 14-15 weeks post-traumatic SCI, were assigned to control, FES-IC, or FES-CE against progessively 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 determined 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.

Cardiorespiratory and power adaptations to stimulated cycle training in paraplegia.

Berry H.R.; Perret C.; Saunders B.A.; Kakebeeke T.H.; Donaldson N.; de N.; Allan D.B.; Hunt K.J. (2008).

Medicine and Science in Sports and Exercise, 40(9): 1573-1580.

Abstract

PURPOSE: The extent to which cardiorespiratory fitness and cycling power can be improved in individuals with paraplegia by progressive, high-volume, home-based, electrically stimulated (ES) cycle training was investigated using a novel, sensitive method and protocol that allowed high-resolution power output analyses to be performed for the first time in ES cycling.
METHODS: Nine male and two female individuals with paraplegia trained progressively at home for up to five 60-min sessions x wk(-1) for 12 months. Peak power and cardiorespiratory parameters were estimated during quarterly feedback-controlled incremental work rate tests in the laboratory.
RESULTS: Cycle training endurance increased from 10 to 60 min of continuous pedaling for all subjects. Peak power output (POpeak) increased by 132% (P = 0.001), peak oxygen uptake (VO2peak) increased by 56% (P < 0.001), and oxygen pulse increased by 34% (P = 0.002). All significant adaptations occurred during the first 6 months of training when training load was progressive and duration compliance (90%) and frequency compliance (88%) were at their highest. A strong positive relationship between the total training duration and the magnitude of improvements

in both POpeak (r2 = 0.84, P < 0.001) and VO2peak (r2 = 0.52, P= 0.012) was found during the first 6 months only.
CONCLUSIONS: High-volume, home-based ES cycle training using the current training and the ES strategies can significantly improve cardiorespiratory fitness and cycling power output in paraplegia but only while training is progressive. The training plateau reached by 6 months may be physiological in nature or due to the ES strategy used.

A clinical exercise system for paraplegics using functional electrical stimulation.

Bremner L.A.; Sloan K.E.; Day R.E.; Scull E.R.; Ackland T. (1992).
Paraplegia, 30: 647-655.

Abstract

A low cost clinical exercise system was developed for the spinal cord injured, based on a bicycle ergometer and electrical stimulation. A pilot project was conducted, using the system, to examine the effects of stimulation induced cycling in long term paraplegics. The project comprised 2 phases of exercise, a strengthening phase involving a 12 week programme of electrical stimulation to the quadriceps and hamstrings and a 12 week cycling phase. Physiological, morphological and biochemical parameters were measured for each subject, at the beginning of the programme and following each phase. Results showed that a programme of stimulation induced lower limb exercise increased the exercise tolerance of all patients, as determined by a progressive increase in exercise time, cycling rate and exercise load. The enhanced exercise tolerance was a result of increases in local muscle strength and endurance. Increases in thigh muscle area and joint range of motion were recorded and all incomplete subjects reported an improvement in functional capabilities and general wellbeing.

Effect of lower extremity functional electrical stimulation pulsed isometric contractions on arm cycling peak oxygen in spinal cord injured individuals.

Burok B.; Torhaug T.; Karlsen T.; Leivseth G.; Helgerud J.; Hoff J. (2013).
Journal of Rehabilitation Medicine, 45(3): 254-259.

Abstract

Objective: To compare peak oxygen uptake (VO2peak) between: (i) functional electrical stimulation lower extremity pulsed isometric muscle contractions combined with arm cycling (FES iso hybrid), (ii) functional electrical stimulation cycling combined with arm cycling (FES hybrid cycling), and (iii) arm cycling exercise (ACE) in individuals with spinal cord injury with level of injury above and below T6.

Design: Cross-over repeated measures design.

Methods/participants: Individuals with spinal cord injury (n = 15) with level of injury between C4 and T12, were divided into groups; above (spinal cord injury – high, n = 8) and below (spinal cord injury – low, n = 7) T6 level. On separate days, VO2peak was compared between: (i) ACE, (ii) FES iso hybrid, and (iii) FES hybrid cycling.

Results: In the SCI–high group, FES iso hybrid increased VO2peak (17.6 (standard deviation (SD) 5.0) to 23.6 (SD 3.6) ml/kg/min; p = 0.001) and ventilation (50.4 (SD 20.8) to 58.2 (SD 20.7) l/min; p = 0.034) more than ACE. Furthermore, FES hybrid cycling resulted in a 6.8 ml/kg/min higher VO2peak (p = 0.001) and an 11.0 litres/minute (p = 0.001) higher ventilation. ACE peak workload was 10.5 W (p = 0.001) higher during FES hybrid cycling compared with ACE. In the spinal cord injury – low group, no significant differences were found between the modalities.
Conclusion: VO2peak increased when ACE was combined with FES iso hybrid or FES hybrid cycling in persons with spinal cord injury above the T6 level. Portable FES may serve as a less resource-demanding alternative to stationary FES cycling, and may have important implications for exercise prescription for spinal cord injury.

An upper body exercise system incorporating resistive exercise and neuromuscular electrical stimulation (NMS).

Cameron, T; Broton J.G.; Needham-Shropshire B.; Klose K.J. (1998).
The Journal of Spinal Cord Medicine, 21(1): 1-6.

Abstract

A device is described which combines arm crank ergometry and neuromuscular electrical stimulation (NMS) delivered at different phases of the crank cycle. Details of the device including circuit schematics are shown. The device was evaluated by non-paralyzed subjects for its operational safety and by tetraplegic subjects for its effectiveness as a muscle-strengthening tool. All subjects showed improvement in one or more of their manual muscle scores. The most dramatic increased motor score occurred in the triceps muscle group. There was an average increase in the manual muscle score of 1.1 +/- 0.2 for the left triceps and 0.7 +/- 0.1 for the right triceps after eight weeks of NMS assisted exercise. No adverse effects were experienced and it appears to meet safety considerations necessary for this group of individuals. Preliminary observations indicate that an eight-week exercise protocol that utilizes this device can be beneficial for this population.

The use of functional electrical stimulation in children and adolescents with spinal cord dysfunction: A pilot study.

Castello F.; Louis B.; Cheng J.; Armento M.; Santos A.M. (2012).
Journal of Pediatric Rehabilitation Medicine, 5(4):261-273.

Abstract

BACKGROUND AND METHODS: Children who experience spinal cord injuries (SCI) may develop many complications, including loss of bone mass, osteoporosis, and pathological fractures. Additionally, patients with SCI often rate their quality of life as poor compared to non-injured peers. We examined the effect of functional electrical stimulation (FES) cycle exercise on bone mineral density (BMD) and quality of life (QOL) in six patients ranging in age from 9 to 20 years. BMD was determined using Dual X-ray Absorptiometry scans, and QOL was measured using the Pediatric Quality of Life Inventory (PedsQL™ 4.0).

RESULTS: While patients experienced difficulty in attending sessions consistently, we found a tendency toward improved BMD and QOL associated with the number of months using the FES cycles. In addition, a positive relation was seen between improved BMD and the total number of cycling sessions, as well as between the final rating of QOL and time from injury.

CONCLUSION: FES cycle exercise has the potential to increase BMD, possibly leading to a decrease in pathologic fractures, as well as to improve QOL, in children and adolescents with SCI. Further investigation is warranted on a larger population of children with SCI in order to establish the full benefits of FES cycle exercise.

Histochemical changes in muscle of individuals with spinal cord injury following functional electrical stimulated exercise training.

Chilibeck P.D.; Jeon J.; Weiss C.; Bell G.; Burnham R. (1999).
Spinal Cord, 37(4): 264-268.

Abstract

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.

Arm-cranking exercise assisted by Functional Electrical Stimulation in C6 tetraplegia: a pilot study.

Coupard S; Gollee H; Hunt K.J.; Fraser M.H.; Allan D.B; McLean A.N. (2008).
Technology and Health Care, 16 (6). pp. 415-427.

Abstract

Tetraplegic volunteers undertook progressive exercise training, using novel systems for arm-cranking exercise assisted by Functional Electrical Stimulation (FES). The main aim was to determine potential training effects of FES-assisted arm-crank ergometry (FES-ACE) on upper limb strength and cardiopulmonary {fitness} in tetraplegia. Surface FES was applied to the biceps and triceps during exercise on an instrumented ergometer. Two tetraplegic volunteers with C6 Spinal Cord Injury (SCI) went through muscle strengthening, baseline exercise testing and three months of progressive FES-ACE training. Repeat exercise tests were carried out every four weeks during training, and post-training, to monitor upper-limb strength and cardiopulmonary fitness. At each test point, an incremental test was carried out to determine peak work rate, peak oxygen uptake, gas exchange threshold and oxygen uptake-work rate relationship during FES-ACE. Peak oxygen uptake for Subject A increased from 0.7 l/min to 1.1 l/min, and peak power output increased from 7 W to 38 W after FES-ACE training. For Subject B, peak oxygen uptake was unchanged, but peak power output increased from 3 W to 8 W. These case studies illustrate potential benefits of FES-ACE in tetraplegia, but also the differences in exercise responses between individuals.

Cardiorespiratory, metabolic, and biomechanical responses during functional electrical stimulation leg exercise: health and fitness benefits.

Davis G.M.; Hamzaid N.A.; Fornusek C. (2008).
Artificial Organs, 32(8): 625-629.

Abstract

Functional electrical stimulation (FES)-induced leg exercise offers the potential for individuals with lower-limb paralysis to otherwise gain some benefits conferred by leg exercise. Although its original intent is to reactivate the leg muscles to produce functional upright mobility, as a rehabilitation therapy, FES-evoked exercise increases the whole-body metabolism of individuals with spinal cord injury (SCI) so that they may gain general and localized health and fitness benefits. The physiological and psychosocial responses during FES-evoked cycling, standing, rowing, leg extension, or stepping have been extensively explored for over 20 years. Some of the advantages of such exercise include augmented cardiorespiratory fitness, promotion of leg blood circulation, increased activity of specific metabolic enzymes or hormones, greater muscle volume and fiber size, enhanced functional exercise capacity such as strength and endurance, and altered bone mineral density. Positive psychosocial adaptations have also been reported among SCI individuals who undergo FES exercise. This article presents a position review of the available literature on the effects of FES-evoked exercise since the earliest date until 2007, to warrant a conclusion about the current status and potential of FES-evoked exercise for paralyzed people.

Feasibility of home-based functional electrical stimulation cycling: case report.

Dolbow, D.R.; Gorgey, A.S.; Cifu D.X.; Moore, J.R. and Gater, D.R. (2011).
Spinal Cord, 50: 170-171.

Abstract

Study design: Single-subject (male, 64 years of age) case.

Objectives: To determine the feasibility of a home-based FES-LEC (functional electrical stimulation lower extremities cycling) program and effects on body composition, quality of life (QOL) and seat pressure mapping in an older individual with spinal cord injured (SCI).

Setting: Home-based FES-LEC with internet connection. Southeastern United States.

Methods: FES-LEC three sessions per week for 9 weeks in the participant's home and monitored by the research staff via internet connection. Pre- and post-exercise program testing of seat pressure mapping, QOL and body composition including percent body fat (%BF), fat mass (FM), lean mass (LM) and bone mineral density (BMD).

Results: The participant completed 25 of 27 recommended exercise sessions over 9 weeks for a 93% compliance rate. Cycling distance increased from 3.98 to 9.00 km (126%). Total body LM increased from 48.94 to 53.02 kg (8.3%). The %BF decreased from 29.6 to 28.4(−1.2%). Total body weight, FM and BMD remained unchanged. Average static seat pressure decreased from 55.5 to 52.59 mm Hg (5%), whereas maximum seat pressure decreased from 120.76 to 91.5 mm Hg (24%). The psychological domain (perception of body image, appearance and self-esteem) of the QOL questionnaire improved from 12.67 to 14.

Conclusion: Positive changes in this study regarding body composition, QOL and seat pressure mapping support results of clinical studies using FES-LEC training on younger adults with SCI. The high percentage of exercise adherence and positive results on body composition, QOL and seat pressure provide support for the feasibility of home-based FES-LEC.

Exercise adherence during home-based functional electrical stimulation cycling by individuals with spinal cord injury.

Dolbow D.R.; Gorgey A.S.; Ketchum J.M.; Moore J.R.; Hackett L.A.; Gater D.R. (2012a).

American Journal of Physical Medicine and Rehabilitation, 91(11): 922-930.

Abstract

Objective: The typically sedentary spinal cord injured population has limited physical activity options because of muscle paralysis, difficulties in transportation, and barriers to access rehabilitation/wellness facilities. It is important to investigate physical activity alternatives to increase physical activity levels and decrease the risk of inactivity-derived diseases. The goal of this study was to determine the effects of a home-based functional electrical stimulation cycling program on exercise adherence of those with spinal cord injury.

Design: Seventeen Veterans with posttraumatic C4–T11 American Spinal Injury Association Impairment Scale A–C spinal cord injury participated in two 8-wk exercise periods of home-based functional electrical stimulation lower extremity cycling. Exercise adherence and the effects of six factors thought to influence exercise adherence were studied during both exercise periods.

Results: Exercise adherence rates for exercise periods 1 and 2 were 71.7% and 62.9%, respectively. Age, history of exercise, and pain not associated with the exercise activity were determined to have significant impact on exercise adherence rates.

Conclusions: Exercise adherence rates were well above the reported 35% in the able-bodied population, which provides evidence for the feasibility of a home-based functional electrical stimulation lower extremity cycling program. Younger adults with a history of being physically active have the highest potential for exercise adherence.

Report of practibility of a 6 month home-based functional electrical stimulation cycling program in an individual with tetraplegia.

Dolbow D.R.; Gorgey A.S.; Moore J.R.; Gater D.R. (2012b).

The Journal of Spinal Cord Medicine, 35(3): 182-186.

Abstract

Background: Sedentarism is common among people with spinal cord injury (SCI). However, new technologies such as functional electrical stimulation cycles with internet connectivity may provide incentive by removing some of the limitations and external barriers.

Objective: To determine the effectiveness of a long-term home-based functional electrical stimulation lower extremities cycling (FES-LEC) program on exercise adherence, body composition, energy expenditure, and quality

of life (QOL) in an adult with chronic tetraplegia.

Participant: A 53-year-old man, 33 years post-motor complete C4 SCI participated in FES-LEC in his home, three sessions per week for 24 weeks.

Methods: Exercise adherence was calculated as the percentage of performed cycling sessions relative to the recommended number of cycling sessions. Body composition was measured by dual-energy X-ray absorptiometry. Energy expenditure was measured using a COSMED K4b2 and QOL via the World Health Organization Quality of Life (WHO-QOL) Brief Questionnaire. Testing was performed before and after the 24-week exercise program.

Results: The participant cycled 59 out of a recommended 72 sessions which is an exercise adherence rate of 82%. Body composition displayed increases in total body lean mass (LM) with an increase of 3.3% and an increase in leg LM of 7.1%. Energy expenditure increased by 1.26 kcal/minute or greater than 200%. The physical and psychological domain scores of QOL increased by 25 and 4.5%, respectively.

Conclusion: This case study provides encouragement concerning the practicality of a home-based FES-LEC program for those with SCI.

Seat Pressure Changes After Eight Weeks of Functional Electrical Stimulation Cycling: A Pilot Study.

Dolbow DR.; Gorgey AS.; Dolbow JD.; Gater DR. (2013a).

Topics in Spinal Cord Injury Rehabilitation, 19(3): 222-228.

Abstract

Background: Pressure ulcers (PUs) are a common secondary condition associated with spinal cord injury (SCI). PUs can potentially interfere with activities of daily living, occupational duties, and rehabilitation programs, and in severe cases they may threaten life. Functional electrical stimulation (FES) cycling has been proposed as an activity that may decrease the risk of PUs through the promotion of increased blood flow and thickening of the gluteus maximus. The purpose of this pilot study was to measure the effects of home-based FES cycling on the average and maximal seat pressure of wheelchair-reliant individuals with SCI.

Method: Eight male veterans with C5-T6 SCI participated in FES cycling 3 times per week. Cycling parameters were individualized depending on the comfort of the participants and the amount of current needed to perform the cycling activity. Pressure mapping was completed immediately before and after the 8 weeks of FES cycling with the measurement performed by a force sensitive application (FSA) 4 pressure mapping system.

Results: The mean average seat pressure decreased by 3.69 ± 4.46 mm Hg (35.57 ± 11.99 to 31.88 ± 13.02), while the mean maximum seat pressure decreased by 14.56 ±18.45 mm Hg (112 ± 34.73 to 98.36 ± 25.89). Although neither measurement was statistically significant, there was a strong trend toward a reduction in average and maximal seat pressure (P = .052 and P = .061, respectively).

Conclusion: The positive trend of decreased seat pressure in our study creates incentive for further investigation of the effects of electrical stimulation activities on seat pressure and the prevention of PUs.

The Effects of Aging and Electrical Stimulation Exercise on Bone After Spinal Cord Injury.

Dolbow JD.; Dolbow DR.; Gorgey AS.; Adler RA.; Gater DR. (2013b).

Aging and Disease, 4(3): 141-153.

Abstract

Age related bone loss predisposes adults to osteoporosis. This is especially true for individuals with spinal cord injury (SCI). The effects of decreased bone loading with older age and paralysis significantly contribute to decreased bone mass and increased risk for fragility fractures. Loading bone via volitional muscle contractions or by using electrical stimulation are common methods for helping to prevent and/or decrease bone loss. However the effectiveness and safety of

electrical stimulation activities remain unclear. The purpose of this review is to investigate the factors associated with aging and osteoporosis after SCI, the accuracy of bone measurement, the effects of various forms of bone loading activities with a focus on electrical stimulation activities and the safety of physical exercise with a focus on electrical stimulation cycling. Osteoporosis remains a disabling and costly condition for older adults and for those with paralysis. Both dual energy x-ray absorptiometry and peripheral quantitative computed tomography are valuable techniques for measuring bone mineral density (BMD) with the latter having the ability to differentiate trabecular and cortical bone. Physical activities have shown to be beneficial for increasing BMD however, the extent of the benefits related to aging and paralysis remain undetermined. Electrical stimulation activities administered appropriately are assumed safe due to thousands of documented safe FES cycling sessions. However, specific documentation is needed to verify safety and to development formal guidelines for optimal use.

Muscle and bone plasticity after spinal cord injury: review of adaptations to disuse and to electrical muscle stimulation.

Dudley-Javoroski S. & Shields R.K. (2008).
Journal of Rehabilitation Research and Development, 45(2): 283-296.

Abstract

The paralyzed musculoskeletal system retains a remarkable degree of plasticity after spinal cord injury (SCI). In response to reduced activity, muscle atrophies and shifts toward a fast-fatigable phenotype arising from numerous changes in histochemistry and metabolic enzymes. The loss of routine gravitational and muscular loads removes a critical stimulus for maintenance of bone mineral density (BMD), precipitating neurogenic osteoporosis in paralyzed limbs. The primary adaptations of bone to reduced use are demineralization of epiphyses and thinning of the diaphyseal cortical wall. Electrical stimulation of paralyzed muscle markedly reduces deleterious post-SCI adaptations. Recent studies demonstrate that physiological levels of electrically induced muscular loading hold promise for preventing post-SCI BMD decline. Rehabilitation specialists will be challenged to develop strategies to prevent or reverse musculoskeletal deterioration in anticipation of a future cure for SCI. Quantifying the precise dose of stress needed to efficiently induce a therapeutic effect on bone will be paramount to the advancement of rehabilitation strategies.

Long-term intensive electrically stimulated cycling by spinal cord-injured people: effect on muscle properties and their relation to power output.

Duffell L.D.; Donaldson N.; Perkins T.A.; Rushton D.N.; Hunt K.J.; Kakebeeke T.H.; Newham D.J. (2008).
Muscle & Nerve, 38(4): 1304-1311.

Abstract

Inactivity and muscular adaptations following spinal cord injury (SCI) result in secondary complications such as cardiovascular disease, obesity, and pressure sores. Functional electrically stimulated (FES) cycling can potentially reduce these complications, but previous studies have provided inconsistent results. We studied the effect of intensive long-term FES cycle training on muscle properties in 11 SCI subjects (mean ± SEM: 41.8 ± 2.3 years) who had trained for up to 1 hour/day, 5 days/week, for 1 year. Comparative measurements were made in 10 able-bodied (AB) subjects. Quadriceps maximal electrically stimulated torque increased fivefold (n = 5), but remained lower than in AB individuals. Relative force response at 1 HZ decreased, relaxation rate remained unchanged, and fatigue resistance improved significantly. Power output (PO) improved to a lesser extent than quadriceps torque and not to a greater extent than has been reported previously. We need to understand the factors that limit PO in order to maximize the benefits of FES cycling.

Functional Electrical Stimulation Leg Cycle Ergometer Exercise: training effects

on cardiorespiratory responses of spinal cord injured subjects at rest and during submaximal exercise.

Faghri P.D.; Glaser R.M.; Figoni S.F. (1992).
Archives of Physical Medicine & Rehabilitation, 73(11): 1085-1093.

Abstract

This 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.

Cardiorespiratory responses during functional electrical Stimulation cycling and electrical stimulation isometric exercise.

Fornusek, C.; Gwinn, TH.; Heard, R. (2014)
Spinal Cord, 52: 635-639.

Abstract

Study design: Prospective experimental.

Objectives: To compare the cardiorespiratory responses with electrical stimulation (ES) producing either dynamic leg cycling or intermittent isometric leg contractions using the same ES protocol.

Setting: Sydney, Australia.

Methods: Eight paraplegics (T4–T11) performed ES exercise sessions on two separate days. On day 1, cardiorespiratory responses were measured during 5 min of rest followed by 35 min of cycling, and finally 15 min of intermittent isometric exercise using the same ES parameters. On the second day, after 5 min of rest, 35 min of isometric exercise was performed followed by 15 min of cycling.

Results: There were no significant differences during the first 35 min of exercise on each day comparing the two modes of exercise for average rate of oxygen consumption (cycling, 534±128 ml min−1; isometric 558±146 ml min−1; P=0.451), the average heart rate (cycling, 93±15 b.p.m.; isometric 95±17 b.p.m.; P=0.264) or minute ventilation (cycling, 23.0±6.5 l min−1; isometric 23.8±6.7 l min−1; P=0.655). In addition, there were no significant differences between exercise modes for any peak cardiorespiratory values recorded during the initial 35 min of exercise or the following 15 min crossover exercise phase.

Conclusion: The current data found that intermittent ES leg isometric exercise elicited a similar cardiorespiratory response compared with functional ES leg cycling, suggesting it should be investigated as a viable alternative intervention for increasing whole body metabolic rate during sustained exercise training sessions for individuals with paralyzed muscles.

High-volume FES-cycling partially reverses bone loss in people with chronic spinal cord injury.

Frotzler, A.; Coupaud, S.; Perret, C.; Kakebeeke, T.H.; Hunt, K.J.; Donaldson, N.; Eser, P. (2008).
Bone, 43(1): 169–176.

Abstract

Spinal cord injury (SCI) leads to severe bone loss in the paralysed limbs and to a resulting increased fracture risk thereof. Since long bone fractures can lead to comorbidities and a reduction in quality of life, it is important to improve bone strength in people with chronic SCI. In this prospective longitudinal cohort study, we investigated whether functional electrical stimulation (FES) induced high-volume cycle training can partially reverse the loss of bone substance in the legs after chronic complete SCI. Eleven participants with motor-sensory complete SCI (mean age 41.9 ± 7.5 years; 11.0 ± 7.1 years post injury) were recruited. After an initial phase of 14 ± 7 weeks of FES muscle conditioning, participants performed on average 3.7 ± 0.6 FES-cycling sessions per week, of 58 ± 5 min each, over 12 months at each individual's highest power output. Bone and muscle parameters were investigated in the legs by means of peripheral quantitative computed tomography before the muscle conditioning (t1), and after six (t2) and 12 months (t3) of high-volume FES-cycle training.

After 12 months of FES-cycling, trabecular and total bone mineral density (BMD) as well as total cross-sectional area in the distal femoral epiphysis increased significantly by 14.4 ± 21.1%, 7.0 ± 10.8% and 1.2 ± 1.5%, respectively. Bone parameters in the femoral shaft showed small but significant decreases, with a reduction of 0.4 ± 0.4% in cortical BMD, 1.8 ± 3.0% in bone mineral content, and 1.5 ± 2.1% in cortical thickness. These decreases mainly occurred between t1 and t2. No significant changes were found in any of the measured bone parameters in the tibia. Muscle CSA at the thigh increased significantly by 35.5 ± 18.3%, while fat CSA at the shank decreased by 16.7 ± 12.3%. Our results indicate that high-volume FES-cycle training leads to site-specific skeletal changes in the paralysed limbs, with an increase in bone parameters at the actively loaded distal femur but not the passively loaded tibia. Thus, we conclude that high-volume FES-induced cycle training has clinical relevance as it can partially reverse bone loss and thus may reduce fracture risk at this fracture prone site.

Intensive exercise program after spinal cord injury ("FULL-ON"): study protocol for a randomized controlled trial.

Galea MP, Dunlop SA,Davis GM,Nunn A, Geraghty T, Hsueh YS, Churilov L. (2013).
Trials, 14(1): 1-9.

Abstract

Background: Rehabilitation after spinal cord injury (SCI) has traditionally involved teaching compensatory strategies for identified impairments and deficits in order to improve functional independence. There is some evidence that regular and intensive activity-based therapies, directed at activation of the paralyzed extremities, promotes neurological improvement. The aim of this study is to compare the effects of a 12-week intensive activity-based therapy program for the whole body with a program of upper body exercise. Methods/Design: A multicenter, parallel group, assessor-blinded randomized controlled trial will be conducted. One hundred eighty-eight participants with spinal cord injury, who have completed their primary rehabilitation at least 6 months prior, will be recruited from five SCI units in Australia and New Zealand. Participants will be randomized to an experimental or control group. Experimental participants will receive a 12-week program of intensive exercise for the whole body, including locomotor training, trunk exercises and functional electrical stimulation-assisted cycling. Control participants will receive a 12-week intensive upper body exercise program. The primary outcome is the American Spinal Injuries Association (ASIA) Motor Score. Secondary outcomes include measurements of sensation, function, pain, psychological measures, quality of life and cost effectiveness. All outcomes will be measured at baseline, 12 weeks, 6 months and 12 months by blinded assessors. Recruitment

commenced in January 2011. Discussion: The results of this trial will determine the effectiveness of a 12-week program of intensive exercise for the whole body in improving neurological recovery after spinal cord injury.

Altered contractile properties of the quadriceps muscle in people with spinal cord injury following functional electrical stimulated cycle training.

Gerrits H.L.; de Haan A.; Sargeant A.J.; Dallmeijer A.; Hopman M.T. (2000).
Spinal Cord, 38(4): 214-223.

Abstract

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.

A report of anticipated benefits of functional electrical stimulation after spinal cord injury.

Gorgey A.S.; Harrish C.R.; Daniels J.A.; Dolbow D.R.; Keeley A.; Moore J.; Gater D.R. (2012).
The Journal of Spinal Cord Medicine, 35(2): 107-112.

Abstract

Background: Functional electrical stimulation (FES) has been regularly used to offset several negative body composition and metabolic adaptations following spinal cord injury (SCI). However, the outcomes of many FES trials appear to be controversial and incoherent.

Objective: To document the potential consequences of several factors (e.g. pain, spasms, stress and lack of dietary control) that may have attenuated the effects on body composition and metabolic profile despite participation in 21 weeks of FES training.

Participant: A 29-year-old man with T6 complete SCI participated in 21 weeks of FES, 4 days per week.

Methods: Prior to and following training, the participant performed arm-crank-graded exercise testing to measure peak VO2. Tests conducted included anthropometrics and dual energy X-ray absorptiometry body composition assessments, resting energy expenditure, plasma lipid profiles and intravenous glucose tolerance tests.

Results: The participant frequently reported increasing pain, stress and poor eating habits. VO2 peak decreased by 2.4 ml/kg/minute, body mass increased by 8.5 kg, and body mass index increased from 25 to 28 kg/m2. Waist and abdominal circumferences increased by 2–4 cm, while %fat mass increased by 5.5%.

Absolute increases in fat mass and fat-free mass of 8.4 and 1 kg, respectively, were reported. Fasting and peak plasma glucose increased by 12 and 14.5%, while lipid panel profiles were negatively impacted.

Conclusion: Failure to control for the listed negative emerging factors may obscure the expected body composition and metabolic profile adaptations anticipated from FES training.

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

Griffin L.; Decker M.J.; Hwang J.Y.; Wang B.; Kitchen K.; Ding Z.; Ivy J.L. (2009).

Journal of Electromyograhy and Kinesiology, 19(4): 614-622.

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.

Exercise responses during Functional Electrical Stimulation Cycling in individuals with spinal cord injury.

Hasnan,N; Ektas,N; Tanhoffer, AL; Tanhoffer, R; Fornusek, C; Middleton, JW; Husain, R; Davis, GM. (2013).

Medicine and Science in Sports and Exercise, 45(6): 1131-1138.

Abstract

PURPOSE: This study compared acute exercise responses during arm cranking, functional electrical stimulation (FES)-assisted leg cycling, and combined arm and leg ("hybrid") cycling in individuals with spinal cord injury during maximal and submaximal exercise.

METHODS: Nine male subjects with long-standing neurological lesions from C7 to T12 were recruited. All subjects performed arm crank ergometry (ACE), FES leg cycle exercise (FES-LCE), combined ACE + FES-LCE, and cycling on a hybrid FES tricycle (HYBRID). They were assessed for their peak exercise responses in all four modalities. Subsequently, their submaximal heart rates (HR), cardiac outputs (Q), stroke volumes (SV), and arteriovenous oxygen extractions (Ca-Cv)O2 were measured at 40%, 60%, and 80% of mode-specific $V\dot{O}2$peak.

RESULTS: Arm exercise alone and arm + leg exercise resulted in significantly higher $V\dot{O}2$peak and HRpeak compared with FES-LCE ($P < 0.05$). Submaximal $V\dot{O}2$ during FES-LCE was significantly lower than all other modalities across the range of exercise intensities ($P < 0.05$). ACE elicited 70%-94% higher steady-state $V\dot{O}2$, and HYBRID evoked 99%-148% higher $V\dot{O}2$ compared with FES-LCE. Steady-state FES-LCE also produced significantly lower Q, HR, and (Ca-Cv)O2. ACE evoked 31%-36% higher Q and 19%-47% greater HR than did FES-LCE. HYBRID elicited 31%-49% greater Q and 23%-56% higher HR than FES-LCE.

CONCLUSIONS: Combined arm and leg exercise can develop a higher oxygen uptake and greater cardiovascular demand compared with ACE or FES-LCE alone. These findings

suggested that combined arm + leg FES training at submaximal exercise intensities may lead to greater gains of aerobic fitness than would arm exercise alone. These data also proffered that FES leg cycling exercise by itself may be insufficient to promote aerobic fitness in the spinal cord injury population.

Improved body composition after 8 wk of electrically stimulated leg cycling in tetraplegic patients.

Hjeltnes N.; Aksnes A.K.; Birkeland K.I.; Johansen J.; Lannem A.Wallberg-Henriksson H. (1997).
American Journal of Physiology, 273(3): R1072-R1079.

Abstract

The practical aspects of utilizing electrically stimulated leg cycling (ESLC) to counteract alterations in body composition were investigated in five tetraplegic subjects with long-standing complete spinal cord injuries (C5-C7). After a 2-wk adaptation period, the subjects performed seven ESLC sessions per week for 8 wk. No adverse reactions were noted in response to the ESLC program. The ESLC sessions were accompanied by higher lactate concentrations compared with arm exercise. Heart rate and blood pressure response revealed clear, but not serious, signs of autonomic dysreflexia in the beginning of the ESLC sessions. Body temperature increased moderately during the ESLC sessions. Peak oxygen uptake (Vo2) during an ESLC session increased by 70% (P < 0.05) after 8 wk of training. Body composition, evaluated by dual-energy X-ray absorptiometry (DEXA), demonstrated an increase in lean body mass (LBM) from 66.2 +/- 2.6 to 68.2 +/- 2.1% (P < 0.05), with a concomitant decrease in whole body fat (BF) content from 29.7 +/- 2.6 to 27.8 +/- 2.1% (P < 0.05) after training. The cross-sectional area of quadriceps, hamstrings, gluteus maximus, and gluteus medius muscles, measured by computer tomographic scans, increased from 267 +/- 27 to 324 +/- 27 cm2 (P < 0.05) after the training. In conclusion, daily ESLC sessions during a 2-mo period resulted in increased LBM, decreased BF content, and increased muscular endurance in tetraplegic subjects without any noticeable adverse effects.

Physiological-Responses to Prolonged Electrically Stimulated Leg-Cycle Exercise in the Spinal-Cord Injured.

Hooker S.P.; Figoni S.F.; Glaser R.M.; Rodgers M.M.; Ezenwa B.N.; Faghri P.D. (1990).
Archives of Physical Medicine and Rehabilitation, 71(11): 863-869.

Abstract

This study determined the physiologic responses to prolonged functional neuromuscular stimulation (FNS) leg-cycle exercise in seven quadriplegic and seven paraplegic subjects. Each subject completed 30 minutes of continuous FNS leg cycling during which open-circuit spirometry, impedance cardiography, auscultation, and fingertip capillary blood sampling were used to assess metabolic and hemodynamic responses. Compared with resting values, oxygen uptake, carbon dioxide production, respiratory exchange ratio (RER), pulmonary ventilation, heart rate (HR), left ventricular stroke volume (SV), cardiac output (Qt), and blood lactate (La) concentration were significantly (p less than.05) elevated, whereas plasma volume, bicarbonate concentration, and pH were significantly decreased in both groups during prolonged FNS leg-cycle exercise. Mean arterial pressure remained unchanged in quadriplegic and paraplegic subjects during the prolonged FNS leg-cycle exercise bout. Persons with quadriplegia elicited significantly lower MAP and tended to have lower SV and Qt responses than persons with paraplegia, probably due to a higher degree of sympathetic dysfunction and circulatory hypokinesis during FNS leg-cycle exercise. All other physiologic variables responded similarly between groups. We speculate that the relative increases observed for HR (33% to 60%), SV (45% to 69%), and Qt (113% to 142%) during prolonged FNS leg-cycle exercise create a sufficient cardiac-volume load to promote central cardiovascular conditioning in persons with both quadriplegia and paraplegia. The La accumulation (4.7 to 5.2 mmol.L-1) in the spinal cord injured during prolonged FNS leg cycling is unusually high for the power output attained (5.2W and 6.1W for quadriplegia and paraplegia, respectively).

Physiologic effects of electrical stimulation leg cycle exercise training in spinal cord injured persons.

Hooker S.P.; Figoni S.F.; Rodgers M.M.; Glaser R.M.; Mathews T.; Suryaprasad A.G.; Gupta S.C. (1992).

Archives of Physical Medicine & Rehabilitation, 73(5): 470-476.

Abstract

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 ($p \leq .05$) 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-Math EqO2diff],+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. An increase in total vascular conductance was accompanied by an elevation in peak Q̇t that supported the heightened peak O2 and maintained peak MAP; this enabled a moderate widening of the a-Math EqO2diff to partially support the enhanced peak aerobic power. The lack of augmentation of posttraining peak V̇O2 or Q̇t with untrained upper extremity muscle groups may be due to (1) the specificity of the lower limb training, (2) local fatigue of the upper extremity musculature, or (3) peripheral rather than central circulatory training adaptations in persons with SCI during the short-term FES-LCE training program implemented in this study.

Peak and submaximal physiologic responses following electrical stimulation leg cycle ergometer training.

Hooker S.P.; Scremin A.M.; Mutton D.L.; Kunkel C.F.; Cagle G. (1995).

Journal of Rehabilitation Research and Development, 32(4): 361—366.

Abstract

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.

Improved glucose tolerance and insulin sensitivity after electrical stimulation-assisted cycling in people with spinal cord injury.

Jeon J.Y.; Weiss C.B.; Steadward R.D.; Ryan E.; Burnham R.S.; Bell G.; Chilibeck P.; Wheeler G.D. (2002).
Spinal Cord, 40(3): 110-117.

Abstract

DESIGN: Longitudinal training.

OBJECTIVES: The purpose was to determine the effect of electrical stimulation (ES)-assisted cycling (30 min/day, 3 days/week for 8 weeks) on glucose tolerance and insulin sensitivity in people with spinal cord injury (SCI).

SETTING: The Steadward Centre, Alberta, Canada.

METHODS: Seven participants with motor complete SCI (five males and two females aged 30 to 53 years, injured 3-40 years, C5-T10) underwent 2-h oral glucose tolerance tests (OGTT, n=7) and hyperglycaemic clamp tests (n=3) before and after 8 weeks of training with ES-assisted cycling.

RESULTS: Results indicated that subjects' glucose level were significantly lower at 2 h OGTT following 8 weeks of training (122.4+/-10 vs 139.9+/-16, P=0.014). Two-hour hyperglycaemic clamps tests showed improvement in all three people for glucose utilisation and in two of three people for insulin sensitivity.

CONCLUSIONS: These results suggested that exercise with ES-assisted cycling is beneficial for the prevention and treatment of Type 2 diabetes mellitus in people with SCI.

Outcomes of a home cycling program using functional electrical stimulation or passive motion for children with spinal cord injury: a case series.

Johnston T.E.; Smith B.T.; Oladeji O.; Betz R.R.; Lauer R.T. (2008).
The Journal of Spinal Cord Medicine, 31(2): 215-221.

Abstract

Background/Objective: Children with spinal cord injury (SCI) are at risk for musculoskeletal and cardiovascular complications. Stationary cycling using functional electrical stimulation (FES) or passive motion has been suggested to address these complications. The purpose of this case series is to report the outcomes of a 6-month at-home cycling program for 4 children with SCI.

Methods: Two children cycled with FES and 2 cycled passively at home for 1 hour, 3 times per week.

Outcome Measures: Data collected included bone mineral density of the left femoral neck, distal femur, and proximal tibia; quadriceps and hamstring muscle volume; stimulated quadriceps and hamstring muscle strength; a fasting lipid profile; and heart rate and oxygen consumption during incremental upper extremity ergometry testing.

Results: The 2 children cycling with FES and 1 child cycling passively exhibited improved bone mineral density, muscle volume, stimulated quadriceps strength, and lower resting heart rate. For the second child cycling passively, few changes were realized. Overall, the lipid results were inconsistent, with some positive and some negative changes seen.

Conclusions: This case series suggests that cycling with or without FES may have positive health benefits and was a practical home exercise option for these children with SCI.

Changes in spastic muscle tone increase in patients with spinal cord injury using functional electrical stimulation and passive leg movements.

Krause P.; Szecsi J.; Straube A. (2008).
Clinical Rehabilitation, 22(7): 627-634.

Abstract

Objective: Comparison of cycling interventions to reduce spastic muscle tone increase in patients with spinal cord injury.

Setting: Neuroprosthetic outpatient clinic in a university hospital.
Methods: Five patients with spinal cord injury took part in a crossover study in which the lower limbs (1) were stimulated by functional neuromuscular electrical stimulation (FES) to induce leg cycling movements and (2) were passively moved by an ergometer machine. Patients sat in a comfortable chair fastened to the ergometer while FES was done to induce leg cycling (active session). During the passive leg movement session the ergometer moved their legs for the same period of time at the same velocity and frequency.
Main outcome measures: The change in spastic muscle tone increase before and after each training session was tested with the modified Ashworth Scale and the pendulum test of spasticity (relaxation index and peak velocity).
Results: The averaged data of the relaxation index increased after FES by about 68%. Compared with the slight increase after the passive movement training of 12%, this is statistically significant (P = 0.01). Peak velocity increased after FES by around 50%, while it was nearly unchanged after the passive intervention (1%); this is also significant (P = 0.01). This was similar with the peak velocity and the modified Ashworth Scale.
Conclusion: The study presents further interesting aspects of the usefulness of FES in patients with spinal cord injury to reduce spastic muscle tone.

Effects of Functional Electrical Stimulation Cycling Exercise on Bone Mineral Density Loss in the Early Stages of Spinal Cord Injury.

Lai, C.-H., Chang, W.H.-S., Chan, W.P., Peng, C.-W., Shen, L.-K., Chen, J.-J.J. & Chen, S.-C. (2010).
Journal of Rehabilitation Medicine, 42: 150-154.

Abstract

OBJECTIVE: To determine whether bone mineral density loss after spinal cord injury can be attenuated by an early intervention with functional electrical stimulation cycling exercises (FESCE) and to ascertain whether the effect persists after FESCE is discontinued.
DESIGN: A prospective study.
SUBJECTS: Twenty-four individuals with spinal cord injury, 26-52 days after spinal cord injury, were divided into FESCE or control groups.
METHODS: FESCE was applied in the initial 3 months and then suspended in the subsequent 3 months. Bone mineral density in the femoral neck and distal femur was measured using dual energy X-ray absorptiometry before training, immediately after the initial 3 months of training, and at the end of the subsequent 3 months.
RESULTS: The bone mineral density decrease rate in the distal femur in the FESCE group was significantly less than that in the control group during the initial 3 months. However, there was no significant difference in the subsequent 3 months.
CONCLUSION: FESCE in the early stages of spinal cord injury can partly attenuate bone mineral density loss in the distal femur. However, bone mineral density loss in the distal femur cannot be ameliorated completely by FESCE. In addition, the effect on the attenuation of bone loss in the distal femur faded once FESCE was discontinued.

Effects of cycling and/or electrical stimulation on bone mineral density in children with spinal cord injury

Lauer, R.T., Smith, B.T., Mulcahey, M.J., Betz, R.R. & Johnston, T.E. (2011).
Spinal Cord, 49: 917–923

Abstract

STUDY DESIGN: Randomized clinical trial.
OBJECTIVES: To determine the effect of cycling and/or electrical stimulation on hip and knee bone mineral density (BMD) in children with spinal cord injury (SCI).
SETTING: Children's hospital specializing in pediatric SCI.
METHODS: A total of 30 children, aged 5-13 years, with chronic SCI were randomized to one of three interventions: functional electrical stimulation cycling (FESC), passive cycling (PC), and non-cycling, electrically

stimulated exercise (ES). Each group exercised for 1 h, three times per week for 6 months at home. The hip, distal femur and proximal tibia BMD were examined via dual-energy X-ray absorptiometry (DXA) pre- and post-intervention.
RESULTS: In all, 28 children completed data collection. The FESC group exhibited increases in hip, distal femur and proximal tibia BMD of 32.4, 6.62 and 10.3%, respectively. The PC group exhibited increases at the hip (29.2%), but no change at the distal femur (1.5%) or proximal tibia (-1.0%). The ES group had no change at the hip (-0.24%) and distal femur (3.3%), but a loss at the proximal tibia (-7.06%). There were no differences between groups or within groups over time. Significant negative correlations were found between baseline BMD and the amount of BMD change.
CONCLUSION: Although not achieving statistical significance, hip BMD changes observed were greater than the reported 0.9-10% gains after exercise for children with and without disability. Thus, cycling with and without electrical stimulation may be beneficial for skeletal health in pediatric SCI, but further research is needed with a larger sample size.

Long-term adaptation to electrically induced cycle training in severe spinal cord injured individuals.

Mohr T.; Andersen J.L.; Biering-Sorensen F.; Galbo H.; Bangsbo J.; Wagner A.; Kjaer M. (1997).

Spinal Cord, 35(1): 1-16.

Abstract

Spinal cord injured (SCI) individuals most often contract their injury at a young age and are deemed to a life of more or less physical inactivity. In addition to the primary implications of the SCI, severe SCI individuals are stigmatized by conditions related to their physically inactive lifestyle. It is unknown if these inactivity related conditions are potentially reversible and the aim of the present study was, therefore, to examine the effect of exercise on SCI individuals. Ten such individuals (six with tetraplegia and four with paraplegia; age 27-45 years; time since injury 3-23 years) were exercise trained for 1 year using an electrically induced computerized feedback controlled cycle ergometer. They trained for up to three times a week (mean 2.3 times), 30 min on each occasion. The gluteal, hamstring and quadriceps muscles were stimulated via electrodes placed on the skin over their motor points. During the first training bouts, a substantial variation in performance was seen between the subjects. A majority of them were capable of performing 30 min of exercise in the first bout; however, two individuals were only able to perform a few minutes of exercise. After training for 1 year all of the subjects were able to perform 30 min of continuous training and the work output had increased from 4±1 (mean±SE) to 17±2 Kilo Joules per training bout ($P<0.05$). The maximal oxygen uptake during electrically induced exercise increased from 1.20±0.08 litres per minute measured after a few weeks habituation to the exercise to 1.43±0.09 litres per minute after training for 1 year ($P<0.05$). Magnetic resonance cross sectional images of the thigh were performed to estimate muscle mass and an increase of 12% (mean, $P<0.05$) was seen in response to 1 year of training. In biopsies taken before exercise various degrees of atrophy were observed in the individual muscle fibres, a phenomenon that was partially normalized in all subjects after training. The fibre type distribution in skeletal muscles is known to shift towards type IIB fibres (fast twitch, fast fatiguable, glycolytic fibres) within the first 2 years after the spinal cord injury. The muscle in the present investigation contained of 63% myosin heavy chain (MHC) isoform IIB, 33% MHC isoform IIA (fast twitch, fatigue resistant) and less than 5% MHC isoform I (slow twitch) before training. A shift towards more fatigue resistant contractile proteins was found after 1 year of training. The percentage of MHC isoform IIA increased to 61% of all contractile protein and a corresponding decrease to 32% was seen in the fast fatiguable MHC isoform IIB, whereas MHC isoform I only comprised

7% of the total amount of MHC. This shift was accompanied by a doubling of the enzymatic activity of citrate synthase, as an indicator of mitochondrial oxidative capacity. It is concluded that inactivity-associated changes in exercise performance capacity and skeletal muscle occurring in SCI individuals after injury are reversible, even up to over 20 years after the injury. It follows that electrically induced exercise training of the paralysed limbs is an effective rehabilitation tool that should be offered to SCI individuals in the future.

Insulin action and long-term electrically induced training in individuals with spinal cord injuries.

Mohr T; Dela F; Handberg A; Biering-Sorensen F; Galbo H; Kjaer M. (2001).

Medicine and Science in Sports and Exercise, 33(8): 1247-1252.

Abstract

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 x d(-1), 3 d x wk(-1) (intensive training)). Seven subjects continued 6 months with reduced training (1 d x wk(-1) (reduced training)). A sequential, hyperinsulinemic (50 mU x min(-1) x m(-2) (step 1) and 480 mU x min(-1) x 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 x min(-1) x kg(-1) to 6.2 +/- 0.6 mg x min(-1) x kg(-1) ($P < 0.008$) (step 1) and from 9.0 +/- 0.8 mg x min(-1) x kg(-1) to 10.6 +/- 0.8 mg x min(-1) x 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.

Physiologic responses during functional electrical stimulation leg cycling and hybrid exercise in spinal cord injured subjects.

Mutton D.L.; Scremin A.M.; Barstow T.J.; Scott M.D.; Kunkel C.F.; Cagle T.G. (1997).

Archives of Physical Medicine & Rehabilitation, 78(7): 712-718.

Abstract

Objectives: (1) To determine if a hybrid exercise (leg plus arm) training program performed immediately after functional electrical stimulation (FES) leg cycle exercise (LCE) training would further improve aerobic capacity when compared with FES leg cycle training alone, and (2) to compare the submaximal responses occurring during both FES-LCE alone and hybrid exercise in the same SCI subjects.
Design: Nonrandomized control trial whereby subjects act as their own control.
Setting: Outpatient rehabilitation in a primary care hospital.
Patients: A volunteer sample (n = 11) of men 20 to 50 years old with complete spinal cord injury, free from cardiovascular and metabolic disease with spasticity.
Interventions: Three phases of exercise training: phase 1, progressive FES-LCE to 30 minutes of exercise (n = 11); phase 11, 35.2 ± 16.2 sessions of FES-LCE (n = 11); phase III, 41.4 ± 17.7 30-minute sessions of hybrid exercise (n = 8).

Main Outcome Measures: (1) Aerobic capacity—a further increase after hybrid exercise when compared with FES-LCE alone; (2) submaximal physiologic parameters (oxygen uptake [V̇O2], heart rate [hr], blood lactate [BLa−])—measurement of these during constant work rate exercise and a training effect.
Results:V̇O2 (the body's ability to utilize oxygen) significantly improved ($p < .05$) after both FES-LCE and then further after hybrid training. Hybrid exercise training resulted in significantly ($p < .05$) greater work rates and V̇O2 values than both FES-LCE at baseline and training work rates.
Conclusion: These subjects demonstrated that hybrid exercise performed twice a week provided sufficient intensity to improve aerobic capacity and provide a medium whereby patients with SCI can burn more calories than via FES-LCE alone. This has important implications for improving the health and fitness levels of individuals with SCI and may ultimately reduce their risk of cardiovascular disease.

Lower extremity blood flow and responses to occlusion ischemia differ in exercise-trained and sedentary tetraplegic persons.

Nash, M.S.; Montalvo B.M.; Applegate B. (1996).
Archives of Physical Medicine & Rehabilitation, 77(12): 1260-1265.

Abstract

Objective: To test whether lower extremity blood flow and hyperemic responses to vascular occlusion differ among electrically stimulated exercise trained and sedentary tetraplegic persons and subjects without tetraplegia (control).
Design: Blinded cross-sectional comparison, control group.
Setting: Academic medical center.
Participants: Ten sedentary tetraplegic men, 10 tetraplegic persons previously habituated to electrically stimulated cycling exercise for 0.4 to 7 years, and 10 nondisabled controls.
Outcome Measures: Subjects underwent quantitative Doppler ultrasound examination of the common femoral artery (CFA). End-diastolic arterial images and arterial flow-velocity profiles obtained at rest and following five minutes of suprasystolic thigh occlusion were computer digitized for analysis of heart rate (HR), CFA peak systolic velocity (PSV), CFA cross-sectional area (CSA), flow velocity integral (FVI), and computed CFA inflow volume (IV).
Results: No group main effects were observed for resting HR or FVI. At rest, trained tetraplegic men had 14.9% greater PSV, 29.8% larger CSA, and 51.3% greater IV (p values $<$ .05) than sedentary tetraplegic subjects. Resting PSV and IV of the trained subjects did not differ from controls, although CSA was smaller than controls ($p < .05$). Following occlusion, PSV, CSA, and IV averaged 16.5%, 33.4%, and 65.1% greater for trained tetraplegics persons, respectively, than sedentary tetraplegic subjects (p values $< .05$). Only CSA differed between the control and the trained groups ($p < .05$).
Conclusion: Tetraplegic persons conditioned by electrically stimulated cycling have greater lower extremity blood flow and hyperemic responses to occlusion than do their sedentary counterparts.

Improved motor function in tetraplegics following neuromuscular stimulation-assisted arm ergometry.

Needham-Shropshire B.M.; Broton J.G.; Cameron T.L.; Klose K.J. (1997)
The Journal of Spinal Cord Medicine, 20(1):49-55.

Abstract

The effectiveness of neuromuscular stimulation (NMS)-assisted arm ergometry for strengthening triceps brachii was evaluated in 34 cervical spinal cord injured persons. Group I (n = 12) received eight weeks of NMS-assisted ergometry. Group II (n = 11) received four weeks of NMS-assisted ergometry followed by four weeks of arm ergometry alone. Group III (N = 11) received only arm ergometry (control group). Seventeen of 24 muscles in Group I subjects had improved manual muscle test scores after eight weeks, compared with 10 of 22 Group II muscles and five of 22 Group III muscles. Including only muscles with initial scores < or = 3, Group I demonstrated significant improvements versus Group III after four weeks ($p <.003$) and

after eight weeks (p <.0005) of exercise. A difference was also found between Groups II and III (p <.03) after eight weeks. These results suggest that NMS-assisted ergometry is effective for strengthening voluntary triceps muscle contractions in tetraplegics.

Review: Clinical Benefits of Functional Electrical Stimulation Cycling Exercise for Subjects with Central Neurological Impairments.

Peng, C.-W.; Chen, S.-C.; Lai, C.-H.; Chen, C.-J., Chen, C.-C., Mizrahi, J. & Handa, Y. (2011).
Journal of Medical and Biological Engineering, 31(1): 1-11.

Abstract

Functional electrical stimulation (FES) cycling ergometer has been utilized in recent decades for rehabilitation by sequentially stimulating the large leg-actuating muscles of paralyzed leg muscles to produce cyclical leg motion. A number of studies reported physiological adaptations after regular FES-cycling exercise (FESCE) training in subjects with spinal cord injury, stroke, cerebral palsy and other conditions. This article provides a comprehensive overview of general aspects of FES cycling systems and clinical applications of FESCE. The studies cited in this article provide supportive findings for the potential clinical efficacy of FESCE for reducing the risk of secondary medical complications in subjects with paralysis. The potential therapeutic benefits of FESCE include conditioning the cardiopulmonary, muscular, and skeletal systems, and improving other physiological and psychological performances. Our recent pilot study also indicated that the decrease of leg spasticity in subjects with cerebral palsy is one of the acute effects of FESCE. In conclusion, we recommend that FESCE is of benefit in a variety of aspects to improve the general condition and to prevent deterioration in subjects with central neurological impairments.

The effect of electrically induced lower extremity ergometry on an ischial pressure ulcer: a case study.

Pollack, S.F., K.T. Ragnarsson, et al. (2004).
The Journal of Spinal Cord Medicine, 27(2): 143-147.

Abstract

BACKGROUND: Individuals with spinal cord injury (SCI) are at an increased risk of pressure ulcer development. Electrical stimulation of adjacent muscles may be underutilized as a tool for pressure ulcer healing in individuals with SCI.
METHOD: Single case study.
SUMMARY: A 27-year-old man with C4 tetraplegia developed a left ischial pressure ulcer that for 23 months responded slowly and inconsistently to conventional treatment. Electrically induced lower extremity ergometry (EILEE) was introduced to facilitate wound healing. The pressure ulcer healed completely in 6.5 months.
CONCLUSION: This case illustrates the potential important contribution of EILEE in the healing of an ischial pressure ulcer in individuals with SCI.

The effects of Upper Extremity Functional Electrically Stimulated Exercise training on Upper Limb Function in Individuals with tetraplegia.

Ptasinski, J. (2010).
Masters Thesis – Brock University. Available from < https://dr.library.brocku.ca/handle/10464/3081>

Abstract

Functional Electrically Stimulated (FES) ami cycle ergometry is a relatively new technique for exercise in individuals with impairments of the upper limbs. The purpose of this study was to determine the effects of 12 weeks of FES arm cycle ergometry on upper limb function and cardiovascular fitness in individuals with tetraplegia. F!ve subjects (4M/1F; mean age 43.8 ± 15.4 years) with a spinal cord injury of the cervical spine (C3- C7; ASIA B-D) participated in 12 weeks of3 times per week FES arm cycle ergometry training. Exercise performance measures (time to fatigue, distance to fatigue, work rate) were taken at baseline, 6 weeks, and following 12 weeks of training. Cardiovascular measures (MAP, resting HR, average and peak HR during exercise, cardiovascular efficiency) and self reported upper limb function (as determined

by the CUE, sf-QIF, SCI-SET questionnaires) were taken at baseline and following 12 weeks of training. Increases were found in time to fatigue (84.4%), distance to fatigue (111.7%), and work rate (51.3%). These changes were non-significant. There was a significant decrease in MAP (91.1 ± 13.9 vs. 87.7 ± 14.7 mmHg) following 12 weeks ofFES arm cycle ergometry. There was no significant change in resting HR or average and peak HR during exercise. Cardiovascular efficiency showed an increase following the 12 weeks ofFES training (142.9%), which was non-significant. There were no significant changes in the measures of upper limb function and spasticity. Overall, FES arm cycle ergometry is an effective method of cardiovascular exercise for individuals with tetraplegia, as evidenced by a significant decrease in MAP, however it is unclear whether 12 weeks of thrice weekly FES arm cycle ergometry may effectively improve upper limb function in all individuals with a cervical SCI.

The effects of functional electrically stimulated (FES)-arm ergometry on upper limb function and resting cardiovascular outcomes in individuals with tetraplegia: A pilot study.

Ptasinski, J; Sharif H.; Ditor D. (2013).

Open Journal of Therapy and Rehabilitation, 1(2): 17-21.

Abstract

Background: Functional electrically stimulated (FES)-arm ergometry has been shown to increase peak power output and aerobic capacity in individuals with cervical SCI. However, the functional benefits remain unknown. Objective: To determine the effects of FES-arm ergometry on exercise performance, upper limb function and resting cardiovascular function in individuals with tetraplegia. Methods: Five individuals (43.8 ± 15.4 years old) with SCI (C3-C5, AIS C-D, 14.0 ± 11.1 years post-injury) completed 12 weeks FES-arm ergometry. Exercise performance (time and distance to fatigue), perceived upper limb function [Capabilities of Upper Extremity Questionnaire (CUE), short form-Quadriplegia Index of Function Questionnaire (sf-QIF) and Spinal Cord Injury Spasticity Evaluation Tool (SCI-SET)] and resting mean arterial pressure (MAP) and heart rate (HR) were measured pre and post. Results: Following training, MAP significantly decreased (91.1 ± 14.0 to 87.7 ± 14.7 mmHg; p = 0.04), and there was a trend for an increased time to fatigue (804.6 ± 359.4 to 1483.8 ± 1110.2 sec; p = 0.08), distance to fatigue (3508.4 ± 3524.5 to 7412.6 ± 7773.1 m, p = 0.08) and the CUE scores pertaining to hand function (31.6 ± 12.8 to 38.0 ± 17.7; p = 0.07). Conclusion: Twelveweek FES-arm ergometry was associated with decreased resting MAP in individuals with tetraplegia, and may show promise as a means to increase exercise performance and hand function. Further research is required to verify these preliminary findings.

Physiologic Effects of Functional Electrical Stimulation-Induced Exercises in Spinal Cord-Injured Individuals.

Ragnarsson K.T. (1988).

Clinical Orthopaedics and Related Research, 233: 53-63.

Abstract

Spinal cord injury (SCI) results in multiple degenerative changes that may in part be related to physical inactivity. There are indications that some of these changes may be reversed by exercise and fitness training. Computerized functional electrical stimulation (FES) allows active exercise of limbs paralyzed by upper motor neuron lesions. Thirty SCI subjects safely participated in an FES-induced exercise program for lower extremity strengthening and endurance training. Increased strength, endurance, and bulk of stimulated muscles were noted. The subjects were able to perform a greater amount of work on a lower extremity ergometer, both per unit of time and per length of time, indicating a training effect. A multistage stress test showed evidence that the subjects had increased their aerobic metabolism during the training program. Twitch time tests showed slowing of muscle contraction, and computed tomography showed increased muscle density.

Cardiorespiratory responses to arm cranking and electrical stimulation leg cycling in people with paraplegia.

Raymond J.; Davis G.M.; Climstein M.; Sutton J.R. (1999).

Medicine and Science in Sports and Exercise, 31(6): 822-828.

Abstract

PURPOSE: The purpose of this study was to assess the cardiorespiratory responses during arm exercise with and without concurrent electrical stimulation-induced leg cycling in people with paraplegia.
METHODS: On separate days, 10 subjects with spinal cord injuries (T5-T12) performed either arm cranking (ACE), or simultaneous arm cranking + electrical stimulation-induced leg cycling (ACE+ES-LCE) graded exercise tests.
RESULTS: During submaximal, steady-state exercise, ACE+ES-LCE elicited significantly higher VO2, (by 0.25-0.28 L x min(-1)) stroke volume (by 13 mL), and VE(BTPS) (by 9.4 L x min(-1)) compared with ACE alone. In contrast, there were no significant differences of submaximal HR, cardiac output, or power output between the exercise modes. At maximal exercise, ACE+ES-LCE elicited significantly higher VO2 (by 0.23 L x min(-1)) compared with ACE alone, but there were no differences in power output, HR, or VE(BTPS).
CONCLUSIONS: These results demonstrate that during submaximal or maximal exercise there was a greater metabolic stress elicited during ACE+ES-LCE compared with during ACE alone. The higher stroke volume observed during submaximal ACE+ES-LCE, in the absence of any difference in HR, implied a reduced venous pooling and higher cardiac volume loading during ACE+ES-LCE. These results suggest that training incorporating ACE+ES-LCE may be more effective in improving aerobic fitness in people with paraplegia than ACE alone.

Lower extremity functional electrical stimulation cycling promotes physical and functional recovery in chronic spinal cord injury.

Sadowsky C.; Hammond E.; Strohl A.; Damiano DL; Commean P; Eby S; Wingert J.R.; McDonald J.W. (2013).

The Journal of Spinal Cord Medicine, 36(6): 623-631.

Abstract

Objective: To examine the effect of long-term lower extremity functional electrical stimulation (FES) cycling on the physical integrity and functional recovery in people with chronic spinal cord injury (SCI).
Design: Retrospective cohort, mean follow-up 29.1 months, and cross-sectional evaluation.
Setting: Washington University Spinal Cord Injury Neurorehabilitation Center, referral center.
Participants: Twenty-five people with chronic SCI who received FES during cycling were matched by age, gender, injury level, and severity, and duration of injury to 20 people with SCI who received range of motion and stretching.
Intervention: Lower extremity FES during cycling as part of an activity-based restorative treatment regimen.
Main outcome measure: Change in neurological function: motor, sensory, and combined motor–sensory scores (CMSS) assessed by the American Spinal Injury Association Impairment scale. Response was defined as ≥1 point improvement.
Results: FES was associated with an 80% CMSS responder rate compared to 40% in controls. An average 9.6 CMSS point loss among controls was offset by an average 20-point gain among FES subjects. Quadriceps muscle mass was on average 36% higher and intra/inter-muscular fat 44% lower, in the FES group. Hamstring and quadriceps muscle strength was 30 and 35% greater, respectively, in the FES group. Quality of life and daily function measures were significantly higher in FES group.
Conclusion: FES during cycling in chronic SCI may provide substantial physical integrity benefits, including enhanced neurological and functional performance, increased muscle size and force-generation potential, reduced spasticity, and improved quality of life.

Increasing muscle mass in spinal cord injured persons with a functional electrical stimulation exercise program.

Scremin A.M.; Kurta L.; Gentili A.; Wiseman B.; Perell K.; Kunkel C.; Scremin O.U. (1999).
Archives of Physical Medicine & Rehabilitation, 80(12): 1531-1536.

Abstract

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 idone 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.

Effects of functional electrical stimulation training for six months on body composition and spasticity in motor complete tetraplegic spinal cord injured individuals.

Skold C.; Lonn L.; Harms-Ringdahl K.; Hultling C.; Levi R.; Nash M.; Seiger A. (2002).
Journal of Rehabilitation Medicine, 34(1): 25-32.

Abstract

The effect of functional electrical stimulation (FES) training on body composition, assessed by computed tomography, and the effect of spasticity, assessed by both objective and subjective measures, are evaluated. Fifteenmotor-complete spinal-cord-injured men participated in the study. Eight of the 15 subjects undertook FES cycling 3 times weekly for 6 months. Whole body computed tomography scans evaluated changes in body composition. Simultaneous Modified Ash-worth Scale and electromyography (EMG) measurements, resistive torque (Kin-Com) and EMG measurements, and self-ratings with Visual Analogue Scale during four consecutive days were used to evaluate changes in spasticity. Lower extremity muscle volume increased by an average of 1300 cm3 ($p < 0.001$) in the training group compared to the control group, who experienced no change. Otherwise no changes in body composition were seen. Significant correlations (Spearman) were found between individual EMG activity recordings and movement-provoked Modified Ash-worth Scale ratings in 26% of the test situations, irrespective of group and time. The objective and subjective evaluation of movement-provoked passive (viscoelastic) and active (spasticity-related) resistance remained unchanged.

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