FES Cycling Literature – Evidence Library

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Intensive training of subjects with chronic hemiparesis on a motorized cycle combined with functional electrical stimulation (FES): a feasibility and safety study.

Alon G.; Conroy V.M.; Donner T.W. (2010).
Physiotherapy Research International, 16(2): 81-91.

Abstract

Background and Purpose. This study tested the safety and ability of subjects with chronic hemiplegia to tolerate intensive training using a motorized cycle combined with functional electrical stimulation (FES) system.

Methods. A case series of 10 subjects with chronic stroke participated in 30-minute three times per week cycling on a stationary motorized cycling system combined with FES (RT300TM). The stimulation activated the dorsal and plantar flexors, the quadriceps and the hamstrings using four channels and a stimulation pattern that assisted cycling motion of the paretic lower limb. Patients were instructed to cycle as close as possible to 60 rpm and the resistance to cycling was gradually increased using a computer-based algorism. The training lasted eight weeks.

Results. All 10 participants completed the training without adverse reactions to the training or the FES. The kcal utilized during the training increased significantly ($p = 0.0003$) between session 1 (2.2 ± 0.47), session 12 (4.3 ± 1.2) and session 24 (7.5 ± 1.8). Peak pedaling power increased from 6.5 ± 0.5 W pre-training to 18.0 ± 5.4 W post-training. Locomotion variables that improved significantly were time to complete the get up and go test (45.4 ± 54.9 seconds vs. 34.0 ± 31.8 seconds) a 24.6% improvement ($p = 0.03$) and gait velocity, which increased 25.0% from 0.4 ± 0.3 m/sec to 0.5 ± 0.4 m/sec ($p = 0.01$).

Conclusion. Using a motorized cycle combined with FES intensive training appears safe and can be tolerated by patients with chronic stroke of wide age range, diverse severity of cardio-pulmonary deconditioning, motor loss and locomotor deficits.

A pilot study investigating arm and leg FES-assisted cycling as an intervention for improving ambulation after Incomplete Spinal Cord Injury

Alvardo, L. (2013).
Masters Thesis, University of Alberta, Available from [https://era.library.ualberta.ca/files/4f16c326m/Alvarado%20Pacheco_Laura_%20Spring%202013.pdf].

Abstract

People with incomplete spinal cord injury (iSCI) have the potential for recovering walking through plasticity-induced changes in the remaining neural circuitry.Current rehabilitation for walking attempts to induce such changes by providing relevant sensory inputs and motor commands through repetitive practice.Current rehabilitation fails to actively incorporate arm movements despite being naturally involved in human walking. The overall goal of my thesis was to demonstrate that active arm involvement through arm and leg FES-assisted cycling improvesovergroundwalking afteriSCI. Specifically, my pilot studyevaluated the changes in walking after 12 weeks of the intervention in individuals with chronic iSCI. Arm and leg FES-assisted cyclingwas effective in improving walking speed and endurance. Balance, motorand sensory scores,and gait kinematics improved in most cases. The reflex modulation improved in every case suggesting that neuronal reorganization (plasticity)was involved. Hence, arm and leg FESassisted cycling is worthy of further investigation.

Cycling induced by electrical stimulation improves activation and symmetry during pedaling in hemiparetic patients.

Ambrosini E.; Ferrante S.; Ferrigno G.; Molteni F.; Pedrocchi A. (2012).
Neural Systems and Rehabilitation Engineering, IEEE Transactions on, 20(3): 320-330.

Abstract

A randomized controlled trial, involving 35 post-acute hemiparetic patients, demonstrated that a four-week treatment of cycling induced by functional electrical stimulation (FES-cycling) promotes motor recovery. Analyzing additional data acquired during that study, the present work investigated whether these improvements were associated to changes in muscle strength and motor coordination. Participants were randomized to receive FES-cycling or placebo FES-cycling. Clinical outcome measures were: the Motricity Index (MI), the gait speed, the electromyography activation of the rectus femoris and biceps femoris, and the mechanical work produced by each leg during voluntary pedaling. To provide a comparison with normal values, healthy adults also carried out the pedaling test. Patients were evaluated before, after training, and at follow-up visits. A significant treatment effect in favor of FES-treated patients was found in terms of MI scores and unbalance in mechanical works, while differences in gait speed were not significant (ANCOVA). Significant improvements in the activation of the paretic muscles were highlighted in the FES group, while no significant change was found in the placebo group (Friedman test). Our findings suggested that improvements in motor functions induced by FES-cycling training were associated with a more symmetrical involvement of the two legs and an improved motor coordination.

Cycling induced by electrical stimulation improves motor recovery in post acute hemiparetic patients: a randomized controlled trial.

Ambrosini E.; Ferrante S.; Pedrocchi A.; Ferrigno G.; Molteni F. (2011).
Stroke, 42: 1068-1073.

Abstract

Background and Purpose—This study assessed whether cycling induced by functional electrical stimulation (FES) was more effective than passive cycling with placebo stimulation in promoting motor recovery and walking ability in postacute hemiparetic patients.

Methods—In a double-blind, randomized, controlled trial, 35 patients were included and randomized to receive FES-induced cycling training or placebo FES cycling. The 4-week treatment consisted of 20 sessions lasting 25 minutes each. Primary outcome measures included the leg subscale of the Motricity Index and gait speed during a 50-meter walking test. Secondary outcomes were the Trunk Control Test, the Upright Motor Control Test, the mean work produced by the paretic leg, and the unbalance in mechanical work between paretic and nonparetic legs during voluntary pedaling. Participants were evaluated before training, after training, and at 3- to 5-month follow-up visits.

Results—No significant differences were found between groups at baseline. Repeated-measures ANOVA (P<0.05) revealed significant increases in Motricity Index, Trunk Control Test, Upright Motor Control Test, gait speed, and mean work of the paretic leg after training and at follow-up assessments for FES-treated patients. No outcome measures demonstrated significant improvements after training in the placebo group. Both groups showed no significant differences between assessments after training and at follow-up. A main effect favoring FES-treated patients was demonstrated by repeated-measures ANCOVA for Motricity Index (P<0.001), Trunk Control Test (P=0.001), Upright Motor Control Test (P=0.005), and pedaling unbalance (P=0.038).

Conclusions—The study demonstrated that 20 sessions of FES cycling training significantly improved lower extremity motor functions and accelerated the recovery of overground locomotion in postacute hemiparetic patients. Improvements were maintained at follow-up.

Outcomes After Functional Electrical Stimulation Cycle Training in Individuals with Multiple Sclerosis Who Are Nonambulatory

Backus, D., Burdett, B., Hawkins, L., Manella, C., McCully, K.K. & Sweatman, M. (2017).
International Journal of MS Care, 19(3): 113-121.

Abstract

Background: Exercise is safe and beneficial for people with multiple sclerosis (MS). Functional electrical stimulation (FES) cycling offers people with significant weakness and mobility challenges an option for exercise. We sought to evaluate the safety of FES cycling and its potential to improve fatigue, pain, spasticity, and quality of life in people with moderate-to-severe MS.

Methods: Sixteen participants with MS who were nonambulatory cycled for 30 minutes two to three times a week for 1 month. Outcomes assessed included MS Quality of Life Inventory (MSQLI) subscales, Modified Ashworth Scale (MAS), and manual muscle test (MMT).

Results: Fourteen participants (six women and eight men) with MS completed the training. All were able to maintain or increase their cycle time; half increased the resistance while cycling. Participants demonstrated a significant decrease in the Physical (P = .02) and Psychosocial (P < .01) subscales of the Modified Fatigue Impact Scale. There was no significant change in the other MSQLI subscale scores. There was no change in MAS and MMT scores. Type of MS and the use of antispasticity medications, disease-modifying therapies, or dalfampridine did not seem to

influence response to training. There were no adverse events.

Conclusions: Functional electrical stimulation cycling may be a viable and effective exercise option for people with moderate-to-severe MS. Further study is required to examine the parameters of FES cycling that are most effective for people with different MS symptoms and to fully explore the potential benefits of optimizing function and improving health in people with MS.

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.

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.

Functional electrical stimulation does not improve mobility in people with acquired brain injury and its effects on strength are unclear: a randomised trial.

De Sousa, D.G., Harvey, L.A., Dorsch, S., Leung, J. & Harris, W. (2016).
Journal of Physiotherapy, 62: 203-208

Abstract

Question: Does 4 weeks of active functional electrical stimulation (FES) cycling in addition to usual care improve mobility and strength more than usual care alone in people with a sub-acute acquired brain injury caused by stroke or trauma?

Design: Multi centre, randomised, controlled trial.

Participants: Forty patients from three Sydney hospitals with recently acquired brain injury and a mean composite strength score in the affected lower limb of 7 (SD 5) out of 20 points.

Intervention: Participants in the experimental group received an incremental, progressive, FES cycling program five times a week over a 4-week period. All participants received usual care.

Outcome measures: Outcome measures were taken at baseline and at 4 weeks. Primary outcomes were mobility and strength of the knee extensors of the affected lower limb. Mobility was measured with three mobility items of the Functional Independence Measure and strength was measured with a hand-held dynamometer. Secondary outcomes were strength of the knee extensors of the unaffected lower limb, strength of key muscles of the affected lower limb and spasticity of the affected plantar flexors.

Results: All but one participant completed the study. The mean between-group differences for mobility and strength of the knee extensors of the affected lower limb were –0.3/21 points (95% CI –3.2 to 2.7) and 7.5 Nm (95% CI –5.1 to 20.2), where positive values favoured the experimental group. The only secondary outcome that suggested a possible treatment effect was strength of key muscles of the affected lower limb with a mean

between-group difference of 3.0/20 points (95% CI 1.3 to 4.8).

Conclusion: Functional electrical stimulation cycling does not improve mobility in people with acquired brain injury and its effects on strength are unclear.

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.

Body composition changes after 12 months of FES cycling: case report of a 60-year-old female with paraplegia.

Dolbow, D.R., Gorgey, A.S., Gater, D.R. & Moore, J.R. (2014).
Spinal Cord, 52:S3-S4.

Abstract

Study design: Single-subject (female, 60 years of age) case. Objectives: The purpose of this case report is to document body composition changes in a 60-year-old female with chronic paraplegia after 12 months of home-based functional electrical stimulation lower extremities cycling (FES-LEC).

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

Methods: FES-LEC three sessions per week for 12 months in participant's home and monitored by the research staff via internet connection. Pre- and post-exercise program testing for body composition including percent body fat, fat mass (FM), lean mass (LM) and whole-body bone mineral density (BMD) via dual-energy x-ray absorptiometry (DXA).

Results: There was a 7.7% increase in total body LM and a 4.1% increase in legs LM. There was a 1.2% decrease in total body FM and a 9.9%decrease in legs FM. Percent body fat decreased from 48.4 to 46.3 and whole-body BMD was increased from 0.934 to 1.023, which resulted in an improvement in the DXA T-score from −2.4 to −1.3.

Conclusion: Positive body compositional changes during this study support the idea that long-term FES-LEC can help restore healthier ratios of LM and FM and possibly decrease the risk of associated diseases. Increased whole-body BMD provides hope that long-term FES-LEC may be beneficial regarding bone health.

Effects of a fifty-six month electrical stimulation cycling program after tetraplegia: case report

Dolbow, D.R., Gorgey, A.S., Khalil, R.K. & Gater, D.R. (2016).
The Journal of Spinal Cord Medicine, Published Online,
http://dx.doi.org/10.1080/10790268.2016.1234750

Abstract

Background: Functional electrical stimulation cycling is a common clinical treatment for individuals with spinal cord injury and other paralytic conditions, however, the long term effects of home-based functional electrical stimulation cycling remains unreported.

Objective: To determine the effectiveness of a long-term home-based functional electrical stimulation lower extremities cycling (FES-LEC) program on body composition.

Participant: An adult male 52.7 years of age at pre-intervention and 57.3 years of age at post-intervention with chronic C4 spinal cord injury and American Spinal Injury Association Impairment Scale C.

Methods: Dual-energy X-ray absorptiometry scans were performed on the participant before and after the FES cycling program to determine body composition changes. An RT300 FES cycle was issued to the participant with the recommendation to cycle three times per week for general conditioning and the maintenance of physical health.

Results: Total body lean mass (LM) increased from 39.13 kg to 46.35 kg, an 18.5% increase

while total body fat mass (FM) increased by just 3.7% from 20.85 kg to 21.64 kg. Legs LM increased by 10.9% (10.93 kg to 12.12 kg). There was a negligible decrease in total body bone mineral content (BMC) with a pre-training measure of 2.09 kg compared to a post-training measure of 1.98 kg. Lower extremities FM increased by less than 1% from 3.51 kg to 3.54 kg.

Conclusion: Natural limitations of a single subject case report disallow a causal conclusion. However, for this particular older adult with chronic tetraplegia, home-based FES-LEC appears to have resulted in cardio-metabolic protective body composition changes.

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.

Cycling induced by functional electrical stimulation improves the muscular strength and the motor control of individuals with post-acute stroke.

Ferrante S.; Pedrocchi A.; Ferrigno G.; Molteni F. (2008)

Europa Medicophysica-SIMFER 2007 Award Winner. *European Journal of Physical and Rehabilitation Medicine*, 44: 159-167.

Abstract

AIM: The aim of this study was to investigate the effectiveness of cycling induced by functional electrical stimulation (FES) in patients with postacute stroke.

METHODS: Twenty postacute inpatients were recruited and were randomly shared in a control group (56+/-9.2 years old, 50.8+/-24.5 days post-stroke) performing the standard rehabilitation (SR) and a FES group (51+/-12 years old, 56.1+/-22.8 days post-stroke) performing FES cycling in addition to SR. Both the groups performed 3 hours of rehabilitation per day for 4 weeks. The FES cycling was applied daily for 35 minutes and quadriceps, hamstring, gluteus maximus and tibialis anterior of both the legs were stimulated. The two groups were compared by the following outcome measurements before and after treatment: maximum isometric voluntary contraction (MVC) of quadriceps, walking and sit-to-stand ability, motricity index, upright motor control test and trunk control test.
RESULTS: After the treatment, the U-Mann-Whitney test demonstrated that the FES group produced a significantly higher increase of the muscular force produced by both the quadriceps during MVC with respect to the control group (P<0.05). Seventy percent of FES patients learned how to perform the sit to stand movement with three different rising speeds while no control patients develop the ability to perform the task properly.

CONCLUSION: Rehabilitation including FES cycling was more effective in promoting muscle strength and motor recovery of the lower extremity than therapist-assisted SR alone. Tests on an enlarged number of patients are necessary for generalization before proposing FES cycling in the clinical rehabilitation of post-acute stroke patients.

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.

Neuromuscular Electrical Stimulation Cycling Exercise for Persons with Advanced Multiple Sclerosis.

Fornusek, C; Hoang, P. (2014).
Journal of Rehabilitation Medicine, 46(7): 698-702.

Abstract

Objective: To investigate the feasibility of neuromuscular electrical stimulation cycling modified to suit persons with advanced multiple sclerosis.

Subjects: Eight women with secondary progressive multiple sclerosis.

Methods: Subjects participated in an 18-session (40 min) neuromuscular electrical stimulation cycling program. A pedaling cadence of 10 rev•min−1 was employed and stimulation intensity was not modulated to control cadence, but increased gradually throughout each session. The outcomes included the stimulation intensity tolerated, thigh circumference changes, and power output and cardiorespiratory response during cycling. Participants were interviewed about perceived benefits of the treatment including changes in transfer ability.

Results: Seven participants (Expanded Disability Status Scale 6.5–8.5) (mean 7.4 (standard deviation 0.7)) completed the training program over an average of 10 weeks. Greater stimulation intensities were tolerated than previously reported for persons with multiple sclerosis. Increases were found in thigh volume. Perceived benefits included improvements in transfer ability, leg circulation, spasticity and strength.

Conclusion: Modifying neuromuscular electrical stimulation cycling allowed persons with advanced multiple sclerosis to tolerate greater stimulation intensities and exercise their muscles more intensely than previous studies. The benefits reported, which were solely due to neuromuscular electrical stimulation cycling, demonstrate that persons with preserved sensation and muscle paralysis/paresis might benefit from neuromuscular electrical stimulation exercise when it is adjusted appropriately.

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.

Acute Responses of Functional Electrical Stimulation Cycling on the Ventilation-to-CO_2 Production Ratio and Substrate Utilization After Spinal Cord Injury

Gorgey, A.S. & Lawrence, J. (2016).
PM&R, 8(3): 225-234.

Abstract

Background: Ventilation-to-carbon dioxide ratio is comparable with peak oxygen uptake in the prognosis of cardiovascular disorders. Currently, there are no established indices to determine the submaximal effects of functional electrical stimulation on cardiovascular performance in persons with spinal cord injury.

Objective: To determine the effects of an acute bout of functional electrical stimulation-lower extremity cycling on ventilation, carbon dioxide production, ventilation-to-carbon dioxide ratio, and substrate utilization in people with motor complete spinal cord injury.

Design: Observational cross-sectional design.

Setting: Clinical laboratory setting.

Participants: Ten individuals with motor complete spinal cord injury.

Methods: Participants were allowed to cycle until fatigue. The effects of functional electrical stimulation on ventilation, carbon dioxide production, ventilation-to-carbon dioxide ratio, and substrate utilization were measured with a portable metabolic cart (COSMED K4b2). Body composition was determined with bioelectrical impedance.

Results: Resting and warm-up ventilation were 8.15 ± 3.5 L/min and 8.15 ± 2.8 L/min, respectively. Functional electrical stimulation increased ventilation significantly (14.5 ± 6.4 L/min), which remained significantly elevated (13.3 ± 4.3 L/min) during the recovery period. During resting and warm-up phases, the ventilation-to-carbon dioxide ratios were 41 ± 4.8 and 38 ± 5.4, respectively. Functional electrical stimulation decreased the ventilation-to-carbon dioxide ratio significantly to 31.5 ± 4, which remained significantly reduced during the recovery period (34.4 ± 3). Functional electrical stimulation relied primarily on carbohydrate utilization (188 ± 160 g/day to 574 ± 324 g/day; $P = .001$) with no changes in fat utilization (77.5 ± 28 g/day to 93.5 ± 133.6 g/day; $P = .7$) from resting to exercise periods. Significant relationships were noted between carbohydrate utilization during functional electrical stimulation and carbon dioxide ($r = 0.98$; $P = .00010$) production. The percentage whole body fat-free mass was negatively related to the exercise ventilation-to-carbon ratio ($r = −0.66$; $P = .045$).

Conclusions: An acute bout of functional electrical stimulation resulted in a significant drop in the ventilation-to-carbon ratio, accompanied with a reliance on carbohydrate utilization and a diminished capacity to utilize fat as a substrate. Fat-free mass may be associated with a decrease in ventilation to carbon dioxide ratio and an increase in carbohydrate utilization in persons with spinal

cord injury.

Effect of adjusting pulse durations of functional electrical stimulation cycling on energy expenditure and fatigue after spinal cord injury

Gorgey, A.S., Poarch, H.J., Dolbow, D.R., Castillo, T. & Gater, D.R. (2014).

Journal of Rehabilitation Research and Development; Washington, 51(9): 1455-1467.

Abstract

The purpose of the current study was to determine the effects of three different pulse durations (200, 350, and 500 microseconds [P200, P350, and P500, respectively]) on oxygen uptake, cycling performance, and energy expenditure (EE) percentage of fatigue of the knee extensor muscle group immediately and 48 to 72 h after cycling in persons with spinal cord injury (SCI). A convenience sample of 10 individuals with motor complete SCI participated in a repeated-measures design using a functional electrical stimulation (FES) cycle ergometer over a 3 wk period. There was no difference among the three FES protocols on relative oxygen uptake or cycling EE. Delta EE between exercise and rest was 42% greater in both 500 and P350 than in P200 ($p = 0.07$), whereas recovery oxygen uptake was 23% greater in P350 than in P200 ($p = 0.03$). There was no difference in the outcomes of the three pulse durations on muscle fatigue. Knee extensor torque significantly decreased immediately after ($p < 0.001$) and 48 to 72 h after ($p < 0.001$) FES leg cycling. Lengthening pulse duration did not affect submaximal or relative oxygen uptake or EE, total EE, and time to fatigue. Greater recovery oxygen updake and delta EE were noted in P350 and P500 compared with P200. An acute bout of FES leg cycling resulted in torque reduction that did not fully recover 48 to 72 h after cycling.

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.

Functional electrical stimulation as a component of activity based restorative therapy may preserve function in persons with multiple sclerosis.

Hammond, E.R., Recio, A.C., Shadowsky, C.L. & Becker, D. (2014).

The Journal of Spinal Cord Medicine, 38(1): 68-75.

Abstract

Objective - To examine the effect of functional electrical stimulation (FES) cycling on disability progression in persons with multiple sclerosis (MS).
Design - Retrospective cohort, 40 participants with mean follow-up of 15 months.
Setting - International Center for Spinal Cord Injury at Kennedy Krieger Institute in Baltimore, a rehabilitation referral center.
Participants - Forty consecutive persons with MS undergoing rehabilitation from 2007 to 2011, with at least two evaluations based on the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI).
Interventions - FES cycling as part of activity-based restorative therapy interventions.
Outcome measures - Change in Expanded Disability Status Scale (EDSS) and ISNCSCI motor, light touch, and pin prick scores from baseline to latest evaluation.
Results - In 71% of patients, activity-based rehabilitation included FES cycling. There was no disability progression on the EDSS. Lower extremity motor scores improved or stabilized in 75% of patients with primary progressive MS (PPMS), 71.4% with secondary progressive MS (SPMS), and 54.5% with relapsing remitting MS (RRMS). Among patients with improved or stabilized lower extremity motor function, PPMS recorded a mean 9% improvement, SPMS 3% and RRMS 6%. In PPMS, use of FES showed trend towards improvement in motor scores (P = 0.070).
Conclusions - FES as part of activity-based rehabilitation may help preserve or improve neurological function in patients with MS.

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˙O2peak.

RESULTS: Arm exercise alone and arm + leg exercise resulted in significantly higher V˙O2peak and HRpeak compared with FES-LCE ($P < 0.05$). Submaximal V˙O2 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˙O2, and HYBRID evoked 99%-148% higher V˙O2 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 $\dot{Q}t$ 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 $\dot{V}O2$ or $\dot{Q}t$ 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.

Effects of electric stimulation-assisted cycling training in people with chronic stroke.

Janssen T.W.; Beltman J.M.; Elich P.; Koppe P.A.; Konijnenbelt H.; de Haan A.; Gerrits K.H. (2008).
Archive of Physical Medicine and Rehabilitation, 89(3): 463-469.

Abstract

Objective: To evaluate whether leg cycling training in subjects with chronic stroke can improve cycling performance, aerobic capacity, muscle strength, and functional performance and to determine if electric stimulation (ES) to the contralateral (paretic) leg during cycling has additional effects over cycling without ES.

Design: A randomized controlled trial, with a partial double-blind design.

Setting: A rehabilitation center.

Participants: Twelve stroke patients (range, 18–70y), more than 5 months poststroke, with lower-extremity hemiparesis.

Intervention: Subjects were randomly assigned to groups that performed cycling exercise, one with ES evoking muscle contractions and a control group with ES not evoking muscle contractions. Subjects, blinded for group assignment, trained twice a week for 6 weeks.

Main Outcome Measures: Changes in aerobic capacity and maximal power output, functional performance, and lower-limb muscle strength.

Results: Aerobic capacity and maximal power output significantly increased by 13.8%±19.1% and 38.1%±19.8%, but muscle strength was not significantly enhanced after training. Functional performance improved (ie, scores on the Berg Balance Scale increased by 6.9%±5.8% (P=.000) and the six-minute walk test improved by 14.5%±14.1% (P=.035). There was no significant effect on the Rivermead Mobility Index (P=.165). Training-induced changes were not significantly different between the 2 groups. Changes in cycling performance and aerobic capacity were not significantly related to changes in functional performance.

Conclusions: This study showed that a short cycling training program on a semirecumbent cycle ergometer can markedly improve cycling

performance, aerobic capacity, and functional performance of people with chronic stroke. The use of ES had no additional effects in this specific group of subjects with chronic stroke.

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.

Musculoskeletal Effects of 2 Functional Electrical Stimulation Cycling Paradigms Conducted at Different Cadences for People With Spinal Cord Injury: A Pilot Study.

Johnston, T.E., Marino, R.J., Oleson, C.V., Schmidt-Read, M., Leiby, B.E., Sendecki, J., Singh, H. & Modlesky, C.M. (2016)
Archives of Physical Medicine and Rehabilitation, 97(9): 1413-1422.

Abstract

Objective: To compare the musculoskeletal effects of low cadence cycling with functional electrical stimulation (FES) with high cadence FES cycling for people with spinal cord injury (SCI).

Design: Randomized pre-post design.

Setting: Outpatient rehabilitation clinic.

Participants: Participants (N=17; 14 men, 3 women; age range, 22–67y) with C4-T6 motor complete chronic SCI were randomized to low cadence cycling (n=9) or high cadence cycling (n=8).

Interventions: Low cadence cycling at 20 revolutions per minute (RPM) and high cadence cycling at 50 RPM 3 times per week for 6 months. Cycling torque (resistance per pedal rotation) increased if targeted cycling cadence was maintained.

Main Outcome Measures: Dual-energy x-ray absorptiometry was used to assess distal femur areal bone mineral density, magnetic resonance imaging was used to assess to assess trabecular bone microarchitecture and cortical bone macroarchitecture and thigh muscle volume, and biochemical markers were used to assess bone turnover. It was hypothesized that subjects using low cadence cycling would cycle with greater torque and therefore show greater musculoskeletal improvements than subjects using high cadence cycling.

Results: A total of 15 participants completed the study. Low cadence cycling obtained a maximal average torque of 2.9±2.8Nm, and high cadence cycling obtained a maximal

average torque of 0.8±0.2Nm. Low cadence cycling showed greater decreases in bone-specific alkaline phosphatase, indicating less bone formation (15.5% decrease for low cadence cycling, 10.7% increase for high cadence cycling). N-telopeptide decreased 34% following low cadence cycling, indicating decreased resorption. Both groups increased muscle volume (low cadence cycling by 19%, high cadence cycling by 10%). Low cadence cycling resulted in a nonsignificant 7% increase in apparent trabecular number (*P*=.08) and 6% decrease in apparent trabecular separation (*P*=.08) in the distal femur, whereas high cadence cycling resulted in a nonsignificant (*P*>.3) 2% decrease and 3% increase, respectively.

Conclusions: This study suggests that the greater torque achieved with low cadence cycling may result in improved bone health because of decreased bone turnover and improved trabecular bone microarchitecture. Longer-term outcome studies are warranted to identify the effect on fracture risk.

Cycling with Functional Electrical Stimulation Before and After a Distal Femur Fracture in a Man with Paraplegia.

Johnston, T.E., Marino, R.J., Oleson, C.V., Schmidt-Read, M., & Modlesky, C.M. (2015a)

Topics in Spinal Cord Injury Rehabilitation, 21(4): 275-281.

Abstract

Case Presentation: A man with chronic paraplegia sustained a distal femur fracture following an unrelated fall while enrolled in a study examining musculoskeletal changes after 6 months of cycling with functional electrical stimulation (FES). After healing, he restarted and completed the study.

Management and Outcome: Study measures included areal bone mineral density, trabecular bone microarchitecture, cortical bone macroarchitecture, serum bone formation/resorption markers, and muscle volume. The patient made small gains in bone- and muscle-related measures. Bone markers had not returned to baseline prior to restarting cycling, which may have impacted results.

Discussion: This case shows that cycling with FES may be safely resumed after distal femur fracture.

Cycling With Functional Electrical Stimulation After Spinal Cord Injury: What's in It for Me?

Johnston, T.E., Forst, N., Jones, K. & Backus, D. (2015b)

Archives of Physical Medicine and Rehabilitation, 96(8):1553-1554.

Abstract

Functional electrical stimulation (FES) is an intervention that uses an electrical current to activate weak or paralyzed muscles. The combination of FES with a bike, or cycle, is called FES cycling. The goal is to help people with paralysis or weakness to perform cycling. Sometimes the FES is needed to turn on muscles for motion because the limbs are completely paralyzed; in other cases it may mean that the FES will help weak muscles to get stronger contractions to make it easier to cycle. -

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Health and fitness in pediatric spinal cord injury: Medical issues and the role of exercise.

Johnson T.E.; McDonald C,M. (2013).

Journal of Pediatric Medicine, 6(1): 35-44.

Abstract

Children with spinal cord injury (SCI) are at risk for the same health related complications experienced by adults with SCI; however, children are likely at increased risk due to the

young age at which the injury was sustained. Common health related complications impact the cardiovascular, respiratory, and musculoskeletal systems, increasing the risk of cardiovascular disease, metabolic syndrome, and fractures, as well as impacting the ability to complete everyday tasks. The available literature shows that children and adults with SCI have a high prevalence of metabolic syndrome and decreased muscle mass, resting energy expenditure, peak oxygen consumption, and bone mineral density. Exercise may have an impact on these complications, thus increasing overall health and fitness. Some literature is available on the effects of exercise for adults with SCI, but few studies have examined these effects for children. Pediatric and adult studies have shown some positive effects on muscle mass, resting energy expenditure, peak oxygen consumption, and bone mineral density. However, more research is needed to develop optimal exercise programs that adequately address long-term health in children who have a long lifetime ahead.

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.

Cycling with functional electrical stimulation in an adult with spastic diplegic cerebral palsy.

Johnston T.E.; Wainwright S.F. (2011).

Physical Therapy, 91(6): 970-982.

Abstract

Background and Purpose: Adults with cerebral palsy (CP) are at risk for decreased mobility and health complications, and exercise may combat some of these negative changes. Because people with CP have difficulty generating sufficient muscle force, exercise augmented with functional electrical stimulation (FES) is an option for increasing exercise intensity. This mixed-method (quantitative-qualitative) case report describes the effects—across the International Classification of Functioning, Disability and Health (ICF) model—of cycling with FES (FES cycling) in an adult with CP.

Case Description: An ambulatory 49-year-old man with spastic diplegic CP cycled with FES at home for 30 minutes, 3 times per week, for 12 weeks. Volitional efforts were augmented by FES of the bilateral quadriceps, gastrocnemius, and gluteal muscles. Testing was performed before and after the intervention and 4 weeks after intervention withdrawal.

Outcomes: After training, quadriceps muscle strength (force-generating capacity) improved

by 22.2%, hamstring muscle strength improved by 18.5%, and the Timed “Up & Go” Test time decreased from 11.9 to 9.0 seconds. The patient reported increased performance and satisfaction for self-identified goals at the ICF level of participation, and his score on the Medical Outcomes Study 36-Item Health Survey questionnaire increased from 62.1 to 77.6. However, he reported increased back pain, which he attributed to positioning while cycling. Qualitative interviews provided context (the patient's perspective) for some of the quantitative results.

Discussion: The patient made gains in body structure and function, activity, and participation (ICF levels) after FES cycling. The mixed-method approach provided insight into his experiences and perceptions about the measures assessed quantitatively. Further investigation on FES cycling in this population as well as positioning during cycling is warranted.

Activity-Based Therapy for Recovery of Walking in Individuals with Chronic Spinal Cord Injury: Results from a Randomized Clinical Trial

Jones, M.L., Evans, N., Tefertiller, C., Backus, D., Sweatman, M., Tansey, K., and Morrison, S. (2014)

Archives of Physical Medicine and Rehabilitation, doi: 10.1016/j.apmr.2014.07.400

Abstract

OBJECTIVE: To examine the effects of activity-based therapy (ABT) on neurologic function, walking ability, functional independence, metabolic health, and community participation.
DESIGN: Randomized controlled trial with delayed treatment design.
SETTING: Outpatient program in a private, nonprofit rehabilitation hospital.
PARTICIPANTS: Volunteer sample of adults (N=48; 37 men and 11 women; age, 18-66y) with chronic (≥12mo postinjury), motor-incomplete (ASIA Impairment Scale grade C or D) spinal cord injury (SCI).
INTERVENTIONS: A total of 9h/wk of ABT for 24 weeks including developmental sequencing; resistance training; repetitive, patterned motor activity; and task-specific locomotor training. Algorithms were used to guide group allocation, functional electrical stimulation utilization, and locomotor training progression.
MAIN OUTCOME MEASURES: Neurologic function (International Standards for Neurological Classification of Spinal Cord Injury); walking speed and endurance (10-meter walk test, 6-minute walk test, and Timed Up and Go test); community participation (Spinal Cord Independence Measure, version III, and Reintegration to Normal Living Index); and metabolic function (weight, body mass index, and Quantitative Insulin Sensitivity Check).
RESULTS: Significant improvements in neurologic function were noted for experimental versus control groups (International Standards for Neurological Classification of Spinal Cord Injury total motor score [5.1±6.3 vs 0.9±5.0; P=.024] and lower extremity motor score [4.2±5.2 vs -0.6±4.2; P=.004]). Significant differences between experimental and control groups were observed for 10-meter walk test speed (0.096±0.14m/s vs 0.027±0.10m/s; P=.036) and 6-minute walk test total distance (35.97±48.2m vs 3.0±25.5m; P=.002).
CONCLUSIONS: ABT has the potential to promote neurologic recovery and enhance walking ability in individuals with chronic, motor-incomplete SCI. However, further analysis is needed to determine for whom ABT is going to lead to meaningful clinical benefits.

FES cycling reduces spastic muscle tone in a patient with multiple sclerosis.

Krause P.; Szecsi J.; Straube A. (2007).

Neurorehabilitation, 22(4): 335-337.

Abstract

We report on a multiple sclerosis patient who received functional electrical stimulation to reduce spastic muscle tone of the lower limbs. Stimulation by means of surface electrodes applied to the thigh muscles induced cycling leg movements. Spastic muscle tone was measured clinically using the modified Ashworth scale and semiautomatically by pendulum testing of spasticity. This was done before and directly after stimulation. The

patient was able to endure the stimulation for ca. 30 minutes; there was a significant reduction of spasticity after each stimulation session. We conclude, that this type of stimulation could be another potential treatment modality for multiple sclerosis patients, especially those with a high score in the expanded disability Status scale.

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.

The effects of assisted ergometer training with a functional electrical stimulation on exercise capacity and functional ability in subacute stroke patients.

Lee S.Y.; Kang S.Y.; Im S.H.; Kim B.R.; Kim S.M.; Yoon H.M.; Han E.Y. (2013).
Annals of Rehabilitation Medicine, 37(5): 619-627.

Abstract

Objective: To determine if assistive ergometer training can improve the functional ability and aerobic capacity of subacute stroke patients and if functional electrical stimulation (FES) of the paretic leg during ergometer cycling has additional effects.
Methods: Sixteen subacute stroke patents were randomly assigned to the FES group (n=8) or the control group (n=8). All patients underwent assistive ergometer training for 30 minutes (five times per week for 4 weeks). The electrical stimulation group received FES of the paretic lower limb muscles during assistive ergometer training. The six-minute walk test (6MWT), Berg Balance Scale (BBS), and the Korean version of Modified Barthel Index (K-MBI) were evaluated at the beginning and end of treatment. Peak oxygen consumption (Vo2peak), metabolic equivalent (MET), resting and maximal heart rate, resting and maximal blood pressure, maximal rate pressure product, submaximal rate pressure product, submaximal rate of perceived exertion, exercise duration, respiratory exchange ratio, and estimated anaerobic threshold (AT) were determined with the exercise tolerance test before and after treatment.
Results: At 4 weeks after treatment, the FES assistive ergometer training group showed significant improvements in 6MWT (p=0.01), BBS (p=0.01), K-MBI (p=0.01), Vo2peak (p=0.02), MET (p=0.02), and estimated AT (p=0.02). The control group showed improvements in only BBS (p=0.01) and K-MBI (p=0.02). However, there was no significant

difference in exercise capacity and functional ability between the two groups.
Conclusion: This study demonstrated that ergometer training for 4 weeks improved the functional ability of subacute stroke patients. In addition, aerobic capacity was improved after assisted ergometer training with a FES only.

Effects of a functional electrical stimulation-assisted leg-cycling wheelchair on reducing spasticity of patients after stroke.

Lo H.C.; Tsai K.H.; Su F.C.; Chang G.L.; Yeh C.Y. (2009).

Journal of Rehabilitation Medicine, 41(4), 242-246.

Abstract

Objective: To determine whether short-term propulsion of a functional electrical stimulation-assisted leg-cycling wheelchair (FES-LW) in patients with stroke can reduce spasticity of the affected leg and whether FES has additional effects on reducing spasticity.
Design: Within-subject comparison.
Subjects: A total of 17 patients after stroke were recruited from the university hospital.
Methods: Subjects propelled 2 leg-cycling wheelchairs (the FES-LW and the LW) and a manual wheelchair along an oval pathway. The Modified Ashworth Scale (MAS), H reflex/maximal M response (H/M ratio) and relaxation index were used to evaluate the immediate effects on leg spasticity. The changes in MAS, H/M and relaxation index were used to evaluate the effect of FES in comparing 2 leg-cycling wheelchairs.
Results: The MAS and H/M ratio were significantly decreased and the relaxation index significantly increased by FES-LW and LW usage. For subjects with higher muscle tone, significant lowering of the changes in MAS, H/M ratio and higher relaxation index were found for FES-LW usage compared with LW usage.
Conclusion: Leg spasticity is reduced after short-term propulsion of the FES-LW and LW. The application of FES has an additional effect on reducing spasticity in subjects with higher muscle tone.

Cycling exercise with functional electrical stimulation improves postural control in stroke patients.

Lo H.C.; Tsai K.H.; Su F.C.; Chang G.L.Yeh C.Y. (2012).

Gait & Posture, 35(3): 506-510.

Abstract

The aim of this study is to determine whether short term functional electrical stimulation (FES)-assisted cycling training can affect the postural control of stroke patients, and whether the application of FES can enhance the effect of cycling training. 20 stroke patients were randomly assigned to the FES-cycling group (FES-CG) or the cycling group (CG). Measurements were completed before and immediately after each 20 min training sessions. The measurements included a balance test (to quantify the postural control ability), a Hoffmann's reflex/motor response ratio (H/M ratio) test and a pendulum test (to quantify the muscle tone). In the balance test, some parameters in all directions exhibited significant intervention effects between the FES-CG group and the CG group. The H/M ratios (p = .014; .005, FES-CG and CG respectively) and relaxation index (p = .005; .047, FES-CG and CG respectively) revealed significant difference between FES-CG and CG group. The change ratios of directional control in the forward direction and H/M ratio revealed significant difference (p = .022; .015) between FES-CG and CG among subjects with higher muscle tone. The stroke subjects' postural control was improved while their muscle tone was reduced after the 20 min cycling training program both with and without FES. We conclude that cycling training, with or without FES may reduce spasticity in stroke patients. The application of FES in cycling exercise was shown to be more effective in stroke patients with higher muscle tone.

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.

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.

Functional Electrical Stimulation Cycling Pre- and Post-Bilateral Orthotopic Lung Transplantation: A Case Report.

Pastva, A., Kirk, T. & Parry, S.M. (2015).
American Journal of Respiratory and Critical Care Medicine, 191: A1643.

ABSTRACT TO ADD

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.

Rationale and design of a randomized controlled clinical trial of functional electrical stimulation cycling in persons with severe multiple sclerosis.

Pilutti, L.A., Motl, R.W., Edwards, T.A. & Wilund, K.R. (2016).
Contemporary Clinical Trials Communications, 3: 147-152

Abstract

Background - This randomized controlled trial (RCT) will examine the efficacy of supervised functional electrical stimulation (FES) cycling on walking performance and physiological function among persons with multiple sclerosis (MS) with severe mobility disability. Methods/design - This RCT will recruit 16 persons with MS that require unilateral or bilateral assistance for ambulation (i.e., Expanded Disability Status Scale (EDSS) score = 6.0–6.5). Participants will be randomized to one of two conditions: supervised FES cycling or passive cycling. The FES cycling condition will involve mild electrical stimulation that will generate an activation pattern that results in cycling the leg ergometer. The passive cycling condition will not provide any electrical stimulation, rather the movement of the pedals will be controlled by the electrical motor. Both conditions will be delivered 3 days/week for the same duration, over 6 months. Primary outcomes will include walking performance assessed as walking speed, endurance, and agility. Secondary outcomes will include physiological function assessed as cardiorespiratory fitness, muscular strength, and balance. Assessments will take place at baseline, mid-point (3-

months), and immediately following the intervention (6-months).
Discussion - This study will lay the foundation for the design of a future RCT by: (1) providing effect sizes that can be included in a power analysis for optimal sample size estimation; and (2) identifying cardiorespiratory fitness, muscular strength, and balance (i.e., physiological function) as mechanisms for the beneficial effects of FES cycling on walking performance. This trial will provide important information on a novel exercise rehabilitation therapy for managing walking impairment in persons with severe MS.

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.

A pilot study of functional electrical stimulation cycling in progressive multiple sclerosis.

Ratchford J.N.; Shore W.; Hammond E.R.; Rose J.G.; Rifkin R.; Nie P.; Tan K.; Quigg M.E.; de Lateur B.J.; Kerr D.A. (2010).

NeuroRehabilitation, 27(2): 121-128.

Abstract

Background: Functional electrical stimulation (FES) cycling is used by spinal cord injury patients to facilitate neurologic recovery and may also be useful for progressive MS patients. Objective: To evaluate the safety and preliminary efficacy of home FES cycling in progressive MS and to explore how it changes cerebrospinal fluid (CSF) cytokine levels. Methods: Five patients with primary or secondary progressive MS were given an FES cycle for six months. Main outcome measures were: Two Minute Walk Test, Timed 25-foot Walk, Timed Up and Go Test, leg strength, Expanded Disability Status Scale (EDSS) score, and Multiple Sclerosis Functional Composite (MSFC) score. Quality-of-life was measured using the Short-Form 36 (SF-36). Cytokines and growth factors were measured in the CSF before and after FES cycling. Results: Improvements were seen in the Two Minute Walk Test, Timed 25-foot Walk, and Timed Up and Go tests. Strength improved in muscles stimulated by the FES cycle, but not in other muscles. No change was seen in the EDSS score, but the MSFC score improved. The physical and mental health subscores and the total SF-36 score improved. Conclusions: FES cycling was reasonably well tolerated by progressive MS patients and encouraging improvements were seen in walking and quality-of-life. Larger studies of FES cycling in progressive MS are indicated.

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.

Pilot Study: Evaluation of Functional Electrical Stimulation Cycling on Muscle Metabolism in Nonambuatory People With Multiple Sclerosis.

Reynolds, M.A.; McCully, K.; Burdett, B.; Manella, C.; Hawkins, L.; Backus, D. (2015).

Archives of Physical Medicine and Rehabilitation, 96(4): 627-632.

Abstract

Objective: To investigate the changes in muscle oxygen consumption (mMath EqO2) using near-infrared spectroscopy (NIRS) after 4 weeks of training with functional electrical stimulation (FES) cycling in nonambulatory people with multiple sclerosis (MS).
Design: Four-week before-after trial to assess changes in mMath EqO2 after an FES cycling intervention.
Setting: Rehabilitation hospital.
Participants: People (N=8; 7 men, 1 women) from a volunteer/referred sample with moderate to severe MS (Expanded Disability Status Scale score>6.0).
Intervention: Participants cycled 30 minutes per session, 3d/wk for 4 weeks or a total of 12 sessions.
Main Outcome Measures: mMath EqO2 of the right vastus lateralis muscle was measured with NIRS before and within 1 week after the intervention. Six bouts of 15-second electrical stimulation increasing from 2 to 7Hz were used to activate the muscle. mMath EqO2 was assessed by analyzing the slope of the NIRS oxygen signal during a 10-second arterial occlusion after each electrical stimulation bout.
Results: Significant FES training by electrical stimulation frequency level interaction was observed (P=.031), with an average increase in mMath EqO2 of 47% across frequencies with a main effect of training (P=.047).
Conclusions: FES cycling for 4 weeks improved mMath EqO2, suggesting that FES cycling is a potential therapy for improving muscle health in people with MS who are nonambulatory.

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.

Functional electrical stimulation in neurological disorders.

Sujith O.K. (2008).
European Journal of Neurology, 15(5): 437-444.

Abstract

Functional electrical stimulation (FES) refers to electrical stimulation of muscles in order to improve the impaired motor function. This is achieved by activating skeletal muscles with constant frequency trains of stimulations. This method has been found useful in various neurological disorders like hemiplegia, foot drop and paraplegia including spinal cord injuries. The first half of this review focuses on the broad clinical applications of functional electrical stimulation, its mechanism of action and the complications of this mode of therapy. Advanced Parkinson's disease (PD) is characterized by marked slowing of gait and frequent freezing episodes. Medical and surgical treatments are often ineffective in managing freezing episodes. The second half of this review discusses briefly the gait abnormalities in PD and the available treatment options. The possible role of FES in improving gait in parkinsonism and the importance of future research in this direction are highlighted.

Functional electrical stimulation assisted cycling of patients with sub acute stroke: kinetic and kinematic analysis.

Szecsi J.; Krewer C.; Muller F.Straube A. (2008).
Clinical Biomechanics, 23(8): 1086-1094.

Abstract

Background: Cycling is a safe and functionally effective exercise for patients with early post-stroke and poor balance. Such exercise is considered even more effective when functional electrical stimulation is added.
Aims: Our principal aim was to determine the biomechanically quantifiable parameters of cycling that can be improved in patients with subacute hemiparesis by incorporating functional electrical stimulation. These parameters were defined as objective goals that can be achieved in clinical applications. A secondary aim was to determine whether they could be used to identify subjects who would benefit from such therapy.
Methods: Using a tricycle testbed, we tested 39 subacute (mean 10.9 weeks post-stroke (SD 5.9)), hemiplegic subjects. During isometric measurements we recorded volitional and electrically evoked crank torques, the latter at maximal tolerable intensity. During ergometric measurements, volitional pedaling was alternated with combined pedaling (volitional supported by stimulation), performed at 30-s intervals. Power, smoothness, and symmetry of cycling were evaluated.
Findings: Twenty-six percent of the subjects significantly improved the smoothness of their cycling with functional electrical stimulation. Only 8% and 10% significantly increased their power and symmetry, respectively. The improvement in smoothness significantly correlated with the capability of the individual to generate electrical torque (Spearman's rank correlation coefficient = 0.66 at P = 0.001).
Interpretation: The smoothness of cycling was the most sensitive parameter improved by functional electrical stimulation. This improvement depended on the amount of torque evoked, and the torque achieved, in turn, correlated with the tolerated intensity of stimulation.

Functional electrical Stimulation-assisted cycling of patient with multiple sclerosis: biomechanical and functional outcome - a pilot study.

Szecsi J.; Schlick C.; Schiller M.; Pollmann W.; Koenig N.; Straube A. (2009).
Journal of Rehabilitation Medicine, 41(8): 675-680.

Abstract

Objective: To determine whether functional electrical stimulation-supported ergometric training of patients with multiple sclerosis has a prosthetic or therapeutic effect on biomechanical (power, smoothness of cycling) and functional outcomes (walking capability, strength of muscle, spasticity).
Design: Twelve subjects with multiple sclerosis participated in an electrical stimulation-supported ergometric training (3 sessions/week for 2 weeks). Measurements were made in a cross-over design to study prosthetic (with and without stimulation) and therapeutic effects (before and after training).
Methods: Power and smoothness were calculated by cadence and torque recordings of cycling and spasticity; strength and walking capability were measured by the Modified Ashworth Scale, Manual Muscle Test, and 10-Metre Walk Test.
Results: The power and smoothness of pedalling significantly improved prosthetically with electrical stimulation ($p=0.02$), but did not show significant improvement over the 2 weeks of training. Significant short-term reductions in spasticity (before vs after training session; $p<0.05$) were found. Isometric strength did not increase significantly during the 2-week training period and there was no improvement in walking ability.
Conclusion: Patients with multiple sclerosis are able to improve their cycling power and smoothness by pedalling with stimulation. We suggest that severely affected patients benefit more from functional electric stimulation-cycling therapy than do slightly affected patients.

Cycling induced by FES in children affected by Cerebral Palsy case report.

Trevisi. (2011).

European Journal of Physical and Rehabilitation Medicine, 48(1): 135-145.

Abstract

BACKGROUND: Recently, the efficacy of functional electrical stimulation (FES) cycling have been demonstrated on the improvement of strength and motor control in adults with stroke. FES-cycling, providing a repetitive goal-oriented task, could facilitate cortical reorganization and utilization of residual cortico-spinal pathways. These benefits could be more enhanced in children because of the greater plasticity and flexibility of their central nervous system. AIM: The aim of the present case report study was to explore the feasibility of FES-cycling in children with cerebral palsy (CP) and to provide a set of instrumental measures able to evaluate the effects of this novel treatment on cycling and walking ability.
DESIGN: Interventional study.
SETTING AND POPULATION: Two ambulant outpatient children with diplegic CP were recruited by the "E. Medea" Scientific Institute.
METHODS: Patients followed a FES-cycling treatment for 30 minutes a day, 3 days a week for 7 weeks. Pre and post treatment tests were performed, namely clinical measures and electromyographic, kinematic and oxygen expenditure analysis during gait and cycling.
RESULTS: The treatment was safe, feasible and well accepted by the 2 children. After treatment both patients achieved a more symmetrical muscular strategy during voluntary cycling and gait and a significant reduction of muscle co-contractions during cycling. These improvements were corroborated by a decrease in oxygen expenditure during the post test for one of the two children, the less impaired, implying a better exploiting of bi-articular muscles.
CONCLUSION AND CLINICAL REHABILITATION IMPACT: FES-cycling is feasible and safe and it may be an alternative rehabilitation method for diplegic CP patients. The set of instrumental measurements proposed seems to be a valuable tool for functional assessment to identify subclinical anomalies and improvements on cycling and gait in CP patients.

Effect of a bout of leg cycling with electrical stimulation on reduction of hypertonia in patients with stroke.

Yeh C.Y.; Tsai K.H.; Su F.C.; Lo H.C. (2010).

Archives of Physical Medicine and Rehabilitation, 91(11): 1731-1736.

Abstract

Objectives: To evaluate whether a bout of leg cycling in patients with stroke reduces muscle tone and to determine whether neuromuscular functional electrical stimulation (FES) to the affected leg during cycling is more effective than cycling without FES.
Design: Within-subject comparison.
Setting: University hospital.
Participants: Patients with stroke (N=16; age range, 42-72y; <8wk poststroke) with hypertonia in the affected leg.
Interventions: Subjects' affected leg (1) performed cycling exercise with the assistance of FES (assisted-cycling session) and (2) performed cycling exercise without the assistance of FES (nonassisted-cycling session). Subjects sat in a specially designed wheelchair positioned on a resistance-free roller for each 20-minute session.
Main Outcome Measures: Changes in muscle tone pre- and posttest session were compared by using the Modified Ashworth Scale and the pendulum test (relaxation index and peak velocity).
Results: Modified Ashworth Scale scores were significantly lower (P<.05) and relaxation index and peak velocity values were significantly higher (P<.05) after both sessions. Changes in Modified Ashworth Scale scores, relaxation index, and peak velocity values showed a significant (P<.05) difference between the 2 sessions, and assisted cycling reduced hypertonia more than nonassisted cycling.
Conclusions: The hypertonia of patients with stroke showed a significant decrease immediately after a bout of leg-cycling exercise. FES-assisted leg cycling was better than nonassisted cycling for reducing hypertonia.

The effect of functional electrical stimulation cycling on late functional improvement in patients with chronic incomplete spinal cord injury.

Yasar, E., Yilmaz, B., Goktepe, S. & Kesikburun, S. (2015).
Spinal Cord, 53: 866–869.

Abstract

Study design: Prospective single-arm study.

Objectives: To investigate the effect of functional electrical stimulation (FES) cycling on late functional recovery, spasticity, gait parameters and oxygen consumption during walking in patients with chronic incomplete spinal cord injury (SCI).

Setting: Turkish Armed Forces Rehabilitation Center, Ankara, Turkey.

Methods: Ten patients with chronic (duration of more than 2 years) incomplete SCI who could ambulate at least 10 m independently or with the assistance of a cane or walker, but no hip-knee-ankle-foot orthosis. The subjects underwent 1-h FES cycling sessions three times a week for 16 weeks. Outcome measures including the total motor score, the Functional Independence Measure (FIM) score, the Modified Ashworth Scale for knee spasticity, temporal spatial gait parameters and oxygen consumption rate during walking were assessed at baseline, 3 and 6 months after the baseline.

Results: There were statistically significant improvements in total motor scores, the FIM scores and spasticity level at the 6-month follow-up (P<0.01). The changes in gait parameters reached no significant level (P>0.05). Oxygen consumption rate of the patients showed significant reduction at only 6 months compared with baseline (P<0.01).

Conclusion: The results suggest that FES cycling may provide some functional improvements in the late period of SCI.

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