

Electrical Stimulation In Spinal Cord Injury

Allison G.T., Singer K.P., and Marshall R.N. (1996) Transfer movement strategies of individuals with spinal cord injuries. *Disabil. Rehabil.* 18, 35-41.

Abstract: The ability to transfer in tetraplegia is a focal point of rehabilitation. Many factors have been associated with independence in transferring, yet the majority of these are anecdotal reports. The purpose of this paper is to report preliminary findings of the study of movement strategies of individuals with spinal cord injury attempting a long sitting transfer. Analyses were made from the lateral and posterior views. Pattern recognition techniques show two distinct movement strategies in both views. These were a lift and forward flexion technique from the lateral perspective and a translatory and rotatory technique when viewed from behind. It would seem that the posterior view provides more discriminative information. It is recommended that intervention techniques, such as Functional Electrical Stimulation or orthotic devices be developed within fundamental motion analysis constructs to optimize functional outcome

Ashley E.A., Laskin J.J., Olenik L.M., Burnham R., Steadward R.D., Cumming D.C., Wheeler G.D. (1993) Evidence of autonomic dysreflexia during functional electrical stimulation in individuals with spinal cord injuries. *Paraplegia* 31, 593-605.

Ayas N.T., McCool F.D., Gore R., Lieberman S.L., and Brown R. (1999) Prevention of human diaphragm atrophy with short periods of electrical stimulation. *Am. J. Respir. Crit Care Med.* 159, 2018-2020.

Abstract: We determined whether prolonged complete inactivation of the human diaphragm results in atrophy and whether this could be prevented by brief periods of electrical phrenic nerve stimulation. We studied a subject with high spinal cord injury who required removal of his left phrenic nerve pacemaker (PNP) and the reinstatement of positive- pressure ventilation for 8 mo. During this time, the right phrenic nerve was stimulated 30 min per day. Thickness of each diaphragm (tdi) was determined by ultrasonography. Maximal tidal volume (VT) was measured during stimulation of each diaphragm separately. After left PNP reimplantation, VT and tdi were measured just before the resumption of electrical stimulation and serially for 33 wk. On the previously nonfunctioning side, there were substantial changes in VT (from 220 to 600 ml) and tdi (from 0.18 to 0.34 cm). On the side that had been stimulated, neither VT nor tdi changed appreciably (VT from 770 to 900 ml; tdi from 0.25 to 0.28 cm). We conclude that prolonged inactivation of the diaphragm causes atrophy which may be prevented by brief periods of daily phrenic nerve stimulation

Bajd T., Gregoric M., Vodovnik L., and Benko H. (1985) Electrical stimulation in treating spasticity resulting from spinal cord injury. *Arch. Phys. Med. Rehabil.* 66, 515-517.

Abstract: To study the efficacy of electrical stimulation in treating spasticity of six spinal cord injured patients, transcutaneous electrical nerve stimulation (TENS) was applied to the dermatomes belonging to the same spinal cord level as the selected spastic muscle group. Spasticity was assessed in knee extensors by a pendulum test in which the knee joint angle of a swinging lower leg was recorded with an electrogoniometer. TENS was found to produce a noticeable decrease of spasticity in three of the patients, but had little effect on the others

Bajd T., Kralj A., Turk R., Benko H., Segal J. (1989) Use of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injuries. *J Biomed Eng* 11, 96-102.

Bajd T., Kralj A., and Zefran M. (1993) Unstable states in four-point walking. *J. Biomed. Eng* 15, 159-162.

Abstract: The presently utilized walking patterns in paraplegic subjects with complete spinal cord injury (SCI) are compared by the help of graphic representations. Improved four-point gait assisted by functional electrical stimulation (FES) and crutches is proposed by introducing unstable states into the walking sequence. The unstable states are defined as passive phases of walking where the centre of mass (COM) is gravity driven in the direction of progression. The unstable state is described by a simple inverted pendulum model. Kinematic measurements of the unstable state were performed in normal and paraplegic subjects

Bajd T., Munih M., and Kralj A. (1999) Problems associated with FES-standing in paraplegia. *Technol. Health Care* 7, 301-308.

Abstract: Prolonged immobilization, such as occurs after the spinal cord injury (SCI), results in several physiological problems. It has been demonstrated that the standing posture can ameliorate many of these problems. Standing exercise can be efficiently performed by the help of functional electrical stimulation (FES). The first application of FES to a paraplegic patient was reported by Kantrowitz in 1963. It was later shown by our group that standing for therapeutic purposes can be achieved by a minimum of two channels of FES delivered to both knee extensors. The properties of the stimulated knee extensors (maximal isometric joint torque, fatiguing, and spasticity) were not found as sufficient conditions for efficient standing exercise. According to our studies, the ankle joint torque during standing is the only parameter which is well correlated to the duration of FES assisted standing. For good standing low values of the ankle joint torque are required. To minimize the ankle joint torque the lever belonging to the vertical reaction force must be decreased. Adequate alignment of the posture appears to be the prerequisite for efficient FES assisted and arm supported standing exercise. Some patients are able to assume such posture by themselves, while many must be aided by additional measures. At present, surface stimulation of knee extensors combined with some appropriately "compliant shoes" looks to be adequate choice

Bajzek T.J. and Jaeger R.J. (1987) Characterization and control of muscle response to electrical stimulation. *Ann. Biomed. Eng* 15, 485-501.

Abstract: The maintenance of upright posture in neurologically intact human subjects is mediated by two major nervous pathways. The first, leading from the cerebral cortex through the spinal cord to motor neurons, activates muscles which produce postural movements. The second, leading from various sensory organs to higher centers, provides sensory feedback regarding the postural state. The path through the spinal cord is no longer intact in victims of spinal cord injury and loss of normal control of muscle activity results. Functional neuromuscular stimulation (FNS) has been shown as a feasible method for obtaining muscle contraction in paraplegics and has been proposed as a means for control of antero-posterior sway to make upright posture possible for these individuals. Before muscle can be controlled through the use of FNS, the response of muscle to electrical stimulation must be understood. In past studies, linear control theory has been applied to the analysis of this response and to the testing of various controllers. The aim of this study was to

demonstrate some control issues in FNS using linear control theory, as it applies to electrical stimulation of muscle for stabilization of posture. The linearity of the muscle response was improved through closed-loop control using pole compensation techniques. The excess phase shift of the system due to the time delay in the muscle response, however, limits the ability to increase the open-loop gain in order to obtain improved performance. A suggestion for further study is the application of this methodology for uses in posture control

Baldi J.C., Jackson R.D., Moraille R., and Mysiw W.J. (1998) Muscle atrophy is prevented in patients with acute spinal cord injury using functional electrical stimulation. *Spinal Cord*. 36, 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 progressively increasing resistance. Subjects were involved in the study for 3 or 6 months. Total body lean body mass (TB-LBM), lower limb lean body mass (LL-LBM), and gluteal lean body mass (G-LBM) were 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

Baratta R.V. and Solomonow M. (1992) The dynamic performance model of skeletal muscle. *Crit Rev. Biomed. Eng* 19, 419-454.

Abstract: Applications of electrical stimulation to the nerve or muscles associated with a defunct limb joint due to stroke or spinal cord injury are a viable means of restoring a certain level of functional movement to the patient. In this article, the currently acceptable physiology of motor control is outlined and used as a criterion for electrophysiological and biomechanical performance evaluation of contemporary electrical stimulation strategies used by various systems attempting to duplicate such motor control in an effort to restore meaningful limb function. Strategies associated

with surface, nerve, intramuscular, and reflex stimulation are critically reviewed with special reference to voluntary sensory motor control of a limb joint rather than an isolated muscle

Barbeau H., Norman K., Fung J., Visintin M., and Ladouceur M. (1998) Does neurorehabilitation play a role in the recovery of walking in neurological populations? *Ann. N. Y. Acad. Sci.* 860, 377-392.

Abstract: This review demonstrates that neurorehabilitation approaches, based on recent neuroscience findings, can enhance locomotor recovery after a spinal cord injury or stroke. Findings are presented from more than 20 clinical studies conducted by numerous research groups on the effect of locomotor training using either body weight support (BWS), functional electrical stimulation (FES), pharmacological approaches or a combination of them. Among the approaches, only BWS-assisted locomotor training has been demonstrated to have a greater effect than conventional or locomotor training alone. However, when study results were combined and weighted for the number of subjects, the results indicated that there is a gradient of effects from small changes with the immediate application of FES or BWS to larger changes when locomotor training is combined with FES or BWS or pharmacological approaches. The findings of these studies suggest that these neurorehabilitation approaches do play a role in the recovery of walking in subjects with spinal cord injury or stroke. Several factors contribute to the potential for recovery including the site, etiology, and chronicity of the injury, as well as the type, duration, and specificity of the intervention and whether interventions are combined. Furthermore, how these neurorehabilitation approaches may take advantage of the plasticity process following neurological lesion is also discussed

Barstow T.J., Scremin A.M., Mutton D.L., Kunkel C.F., Cagle T.G., and Whipp B.J. (1995) Gas exchange kinetics during functional electrical stimulation in subjects with spinal cord injury. *Med. Sci. Sports Exerc.* 27, 1284-1291.

Abstract: We examined the kinetics of VO_2 , VCO_2 , and VE following the onset of unloaded leg cycling, and in recovery, in six patients with spinal cord injury (SCI). Exercise was produced by functional electrical stimulation (FES) of the quadriceps, hamstrings, and gluteal muscles. End-exercise VO_2 ($1.03 \pm 0.16 \text{ l}\cdot\text{min}^{-1}$), VCO_2 ($1.20 \pm 0.22 \text{ l}\cdot\text{min}^{-1}$) and VE ($41 \pm 10 \text{ l}\cdot\text{min}^{-1}$) were elevated compared to values typically seen in healthy ambulatory subjects performing similar unloaded cycling. Mean response times for the on transients (MRT_{on}) were both long and variable across subjects for VO_2 ($165 \pm 62 \text{ s}$), VCO_2 ($173 \pm 58 \text{ s}$), and VE ($202 \pm 61 \text{ s}$). Recovery kinetics showed much less intersubject variability, and for five of six subjects were faster than the equivalent exercise MRT for all three variables (MRT_{off} for VO_2 of $103 \pm 28 \text{ s}$, VCO_2 $136 \pm 20 \text{ s}$, and VE $144 \pm 34 \text{ s}$), but $P > 0.05$ for all three. Size of the O_2 deficit ($1.96 \pm 0.90 \text{ l}$) and end-exercise lactate ($7.05 \pm 1.65 \text{ mmol}\cdot\text{l}^{-1}$) were similar to values reported for healthy sedentary subjects performing maximal voluntary exercise, but the end-exercise heart rate ($102 \pm 16 \text{ bpm}$) was lower than expected for this intensity of exercise. In conclusion, FES-induced unloaded cycling leads to exaggerated responses of pulmonary gas exchange and long time constants in patients with SCI. The delayed kinetics may be due in part to a blunted increase in heart rate in addition to severe deconditioning

Barstow T.J., Scremin A.M., Mutton D.L., Kunkel C.F., Cagle T.G., and Whipp B.J. (1996) Changes in gas exchange kinetics with training in patients with spinal cord injury. *Med. Sci. Sports Exerc.* 28, 1221-1228.

Abstract: We examined the ability of patients with spinal cord injury to undergo adaptations to chronic exercise training (cycle ergometry) invoked by functional electrical stimulation (FES) of the legs. Nine such patients performed incremental and constant work rate exercise before and after exercise training. Exercise sessions averaged 2.1 +/- 0.4/wk, and consisted of 30 min/session of continuous FES recumbent cycling with increasing work rate as tolerated. Peak VO₂ and peak work rate significantly improved with training. Peak VO₂ was significantly correlated with peak heart rate both before and after training ($r = 0.97$ pre and 0.85 post, $P < 0.01$ for both). The time course of the VO₂, VCO₂ and VE responses to constant-load exercise (unloaded cycling) and in recovery (mean response time MRT) were very long prior to training, and became significantly faster following training. However, there was no correlation between percentage improvement in either MRT_{on} or MRT_{off} for VO₂ and the percentage increase in peak VO₂. Exercise tolerance in these patients with spinal cord injury appears to be a direct function of the ability to increase heart rate. Further, exercise training can elicit significant improvements in both exercise tolerance and in gas exchange kinetics, even when performed only twice per week. However, these improvements may be accomplished by different mechanisms

Barstow T.J., Scremin A.M., Mutton D.L., Kunkel C.F., Cagle T.G., and Whipp B.J. (2000) Peak and kinetic cardiorespiratory responses during arm and leg exercise in patients with spinal cord injury. *Spinal Cord*. 38, 340-345.
Abstract: STUDY DESIGN: A paired comparison of the peak and submaximal responses of oxygen uptake and heart rate in patients with spinal cord injury (SCI) performing voluntary arm cycle exercise and functional electrical stimulation (FES) leg cycling exercise. OBJECTIVES: To test if the blunted heart rate response and slower rate of adjustment of oxygen uptake seen in patients with SCI performing FES leg cycle exercise are also characteristic of arm exercise in these patients. METHODS: Eight paraplegics performed incremental and constant work rate (CWR) exercise with the legs and arms. Mean response times (MRT) for Vo₂ during exercise (on) and in recovery (off) were calculated from the breath-by-breath Vo₂ profile. RESULTS: Peak heart rate was higher during incremental arm exercise, and uncorrelated with that observed during incremental FES leg cycling. For the same increase in Vo₂, constant work rate arm exercise was associated with faster (and normal) Vo₂ kinetics, greater increase in heart rate, and lower end-exercise blood lactate, compared to FES leg cycling. CONCLUSIONS: The consistently higher peak heart rate and Vo₂, and faster Vo₂ kinetics, for voluntary arm compared to FES leg cycle exercise suggest no intrinsic dysfunction of heart rate control in these paraplegics. Rather, these data suggest that during FES leg cycling the changes seen are due to some characteristic specific to the injury, such as reduced muscle mass and/or deconditioning of the remaining muscle. SPONSORSHIP: This research was supported by The Department of Veterans Affairs, Rehabilitation Research and Development Project #B603-RA. *Spinal Cord* (2000) 38,

Bauchet L., Segnarbieux F., Martinazzo G., Frerebeau P., and Ohanna F. (2001) [Neurosurgical treatment of hyperactive bladder in spinal cord injury patients]. *Neurochirurgie* 47, 13-24.
Abstract: OBJECTIVES: We report long-term results of posterior sacral root rhizotomies in combination with Finetech-Brindley anterior sacral root stimulators implanted intradurally in 20 spinal cord injury patients. MATERIAL: and methods: The 14 female and 6 male patients included 14 paraplegics and 6 tetraplegics. All of

them initially presented hyperactive bladder, detrusor-sphincter dyssynergia, recurrent urinary tract infection and performed (self) intermittent catheterization. Prior to implantation, an intrathecal test using bupivacaine was performed to confirm the compliances of the bladder. The main indication for implantation was persistent urinary incontinence refractory to medical therapy. RESULTS: After implantation the mean follow-up was 4,5 years. In all, 18 patients used the stimulator alone for bladder emptying and 18 patients were completely continent. The mean bladder capacity increased from 190 ml preoperatively to 460 ml after the operation. The mean residual urinary volume was reduced from 90 ml to 25 ml. No changes were noted by renal isotopic scanning in upper urinary tracts of patients. In 1 patient, a second extradural implant was performed. DISCUSSION: This article also include an overview of a) the different available sites where application of electrical stimulation results in a detrusor contraction, b) the benefits and disadvantages of the sacral posterior rhizotomy, c) selective stimulation techniques that allow selective detrusor activation by sacral root stimulation. CONCLUSION: Sacral anterior root stimulation combined with sacral posterior rhizotomy is a valuable method to restore bladder functions in spinal cord injured patients suffering from hyperactive bladder refractory to medical therapy

Bauman W.A., Spungen A.M., Adkins R.H., and Kemp B.J. (1999) Metabolic and endocrine changes in persons aging with spinal cord injury. *Assist. Technol.* 11, 88-96.

Abstract: Persons with spinal cord injury (SCI) have secondary medical disabilities that impair their ability to function. With paralysis, dramatic deleterious changes in body composition occur acutely with further adverse changes ensuing with increasing duration of injury. Lean mass, composed of skeletal muscle and bone, is lost and adiposity is relatively increased. The body composition changes may be further exacerbated by associated reductions in anabolic hormones, testosterone, and growth hormone. Individuals with SCI also have decreased levels of activity. These body composition and activity changes are associated with insulin resistance, disorders in carbohydrate and lipid metabolism, and may be associated with premature cardiovascular disease. Although limited information is available, upper body exercise and cycle ergometry of the lower extremities by functional electrical stimulation (FES) have been reported to have a salutary effect on these body composition and metabolic sequelae of paralysis. Perhaps other innovative, externally mediated forms of active exercise of the paralyzed extremities will result in an increased functional capacity, metabolic improvement, and reduction of atherosclerotic vascular disease

BeDell K.K., Scremin A.M.E., Perell K.L., Kunkel C.F. (1996) Effects of functional electrical stimulation-induced lower extremity cycling on bone density of spinal-cord injured patients. *Am J Phys Med Rehabil* 75, 29-34.

Belanger M., Stein R.B., Wheeler G.D., Gordon T., and Leduc B. (2000) Electrical stimulation: can it increase muscle strength and reverse osteopenia in spinal cord injured individuals? *Arch. Phys. Med. Rehabil.* 81, 1090-1098.

Abstract: OBJECTIVE: To study the extent to which atrophy of muscle and progressive weakening of the long bones after spinal cord injury (SCI) can be reversed by functional electrical stimulation (FES) and resistance training. DESIGN: A within-subject, contralateral limb, and matching design. SETTING: Research laboratories in university settings. PARTICIPANTS: Fourteen patients with SCI (C5

to T5) and 14 control subjects volunteered for this study. INTERVENTIONS: The left quadriceps were stimulated to contract against an isokinetic load (resisted) while the right quadriceps contracted against gravity (unresisted) for 1 hour a day, 5 days a week, for 24 weeks. MAIN OUTCOME MEASURES: Bone mineral density (BMD) of the distal femur, proximal tibia, and mid-tibia obtained by dual energy x-ray absorptiometry, and torque (strength). RESULTS: Initially, the BMD of SCI subjects was lower than that of controls. After training, the distal femur and proximal tibia had recovered nearly 30% of the bone lost, compared with the controls. There was no difference in the mid-tibia or between the sides at any level. There was a large strength gain, with the rate of increase being substantially greater on the resisted side. CONCLUSION: Osteopenia of the distal femur and proximal tibia and the loss of strength of the quadriceps can be partly reversed by regular FES-assisted training

Benzel E.C., Barolat-Romana G., and Larson S.J. (1988) Femoral obturator and sciatic neurectomy with iliacus and psoas muscle section for spasticity following spinal cord injury. *Spine* 13, 905-908.

Abstract: The treatment of severe refractory spasticity following spinal cord injury may raise challenging therapeutic problems. Classical approaches involve various types of myelotomies, rhizotomies and intrathecal injections of neurolytic substances. Alternative approaches include percutaneous rhizotomies and, more recently, the possible use of electrical stimulation of the spinal cord. Certain cases, however, may not be amenable to commonly accepted techniques. An operative technique is presented which involves a suprapubic incision for an infraperitoneal approach to a femoral and obturator neurectomy and an incision of the iliacus and psoas muscles bilaterally. This may be followed, when indicated, by a bilateral infragluteal section of the sciatic nerves. This technique offers a viable surgical alternative to the treatment of spasticity following spinal cord injury in cases where other traditional methods are contraindicated or have failed

Betz R., Boden B., Triolo R., Mesgarzadeh M., Gardner E., and Fife R. (1996) Effects of functional electrical stimulation on the joints of adolescents with spinal cord injury. *Paraplegia* 34, 127-136.

Abstract: Nineteen adolescent subjects with complete spinal cord injuries resulting in paraplegia or tetraplegia participated in a functional electrical stimulation (FES) program consisting of computerized, controlled exercise and/or weight bearing. The effects of stimulated exercise and standing/walking on the lower extremity joints were prospectively studied. Plain radiographs and MRIs were obtained prior to and following completion of the exercise and standing and walking stages. In addition, the joints of five subjects were studied with synovial biopsies, arthroscopy, and the analysis of serum and synovial fluid for a 550 000 dalton cartilage matrix glycoprotein (CMGP). Pre-exercise joint abnormalities secondary to the spinal cord injury improved following the stimulation program. None of the subjects developed Charcot joint changes. Upon standing with FES, one subject with poor hip coverage prior to participation developed hip subluxation which required surgical repair. No other detrimental clinical effects occurred in the lower extremity joints of subjects participating in an FES program over a 1-year period

Betz R.R., Mulcahey M.J., Smith B.T., Triolo R.J., Weiss A.A., Moynahan M., Keith M.W., and Peckham P.H. (1992) Bipolar latissimus dorsi transposition and functional neuromuscular stimulation to restore elbow flexion in an individual with C4

quadriplegia and C5 denervation. *J. Am. Paraplegia Soc.* 15, 220-228.

Abstract: A bipolar latissimus dorsi transposition was performed on a 17-year-old male patient with a C4 spinal cord injury and complete peripheral denervation at C5. Electrical stimulation of the paralyzed but excitable latissimus dorsi provided elbow flexion that could not be achieved with the paralyzed and denervated elbow flexors. The muscle was attached from the coracoid to the ulna allowing the elbow to be flexed with the forearm and wrist maintained in the neutral position. Following a 6-week immobilization period, the transposed muscle was exercised daily with intramuscular stimulation to increase both strength and endurance. By the fourth month after surgery, the subject could control elbow flexion proportionally with contralateral shoulder elevation using a shoulder position transducer. Functionally, the subject was able to use the neuroprosthetic system to bring his hand to his mouth and feed himself with the aid of a universal cuff and a support to stabilize the shoulder

Bhambhani Y., Tuchak C., Burnham R., Jeon J., and Maikala R. (2000) Quadriceps muscle deoxygenation during functional electrical stimulation in adults with spinal cord injury. *Spinal Cord*. 38, 630-638.

Abstract: STUDY DESIGN: Cross-sectional study comparing healthy subjects with age and gender matched subjects with spinal cord injury (SCI, injury levels from C5 to T12). OBJECTIVES: To compare the acute cardiorespiratory responses and muscle oxygenation trends during functional electrical stimulation (FES) cycle exercise and recovery in the SCI and healthy subjects exercising on a mechanical cycle ergometer. SETTING: Seven volunteers in each group participated in one exercise test at the Rick Hansen Center, University of Alberta, Edmonton, Canada. METHODS: Both groups completed a stagewise incremental test to voluntary fatigue followed by 2 min each of active and passive recovery. Cardiorespiratory responses were continuously monitored using an automated metabolic cart and a wireless heart rate monitor. Tissue absorbency, an index of muscle oxygenation, was monitored non-invasively from the vastus lateralis using near infrared spectroscopy. RESULTS: The healthy subjects showed significant ($P < 0.05$) increases in the oxygen uptake (VO_2), heart rate (HR) and ventilation rate (VE) from rest to maximal exercise. The SCI subjects showed a twofold increase in VO_2 ($P > 0.05$), a threefold increase in VE ($P < 0.05$) and a 5 beats/min increase in HR ($P > 0.05$) from the resting value. The SCI subjects demonstrated a lesser degree ($P < 0.05$) of muscle deoxygenation than the healthy subjects during the transition from rest to exercise. Regression analysis indicated that the rate of decline in muscle deoxygenation with respect to the VO_2 was significantly ($P < 0.05$) faster in the SCI subjects compared to healthy subjects. CONCLUSIONS: FES exercise in SCI subjects elicits: (a) modest increases in the cardiorespiratory responses when compared to resting levels; (b) lower degree of muscle deoxygenation during maximal exercise, and (c) faster changes in muscle deoxygenation with respect to the VO_2 during exercise when compared to healthy subjects

Blight A.R. (1986) Motor evoked potentials in CNS trauma. *Cent. Nerv. Syst. Trauma* 3, 207-214.

Abstract: The evolving techniques of motor evoked potential (MEP) monitoring are reviewed here with reference to their application in clinical and experimental CNS trauma, and with particular relevance to spinal cord injury. Transcutaneous electrical stimulation of the motor cortex for analysis of descending pathways has been developed over the past 6 years in a number of centers. It has now been greatly

augmented by the introduction of magnetic stimulation technology. The MEP offers a valuable insight into the physiological status of motor tracts within the spinal cord and is applicable to conscious patients, intraoperative monitoring, and animal studies. It is seen as complementary to somatosensory evoked potential monitoring rather than an alternative or replacement for it. The chief limitations of the technique, common to all evoked potential methods, are the restricted information content, and the need for rigorous electrophysiological interpretation of the resulting signals, if meaningful diagnostic data are to be extracted

Block J.E., Steinbach L.S., Friedlander A.L., Steiger P., Ellis W., Morris J.M., and Genant H.K. (1989) Electrically-stimulated muscle hypertrophy in paraplegia: assessment by quantitative CT. *J. Comput. Assist. Tomogr.* 13, 852-854.
Abstract: To identify the magnitude of muscle hypertrophy following electrically stimulated exercise in paraplegic subjects, we used quantitative CT (QCT) of the midthigh prior to and following 6 weeks of bicycle ergometry. Three patients who had suffered acute spinal cord injury were examined in this pilot investigation. Average absolute changes in muscle cross-sectional area by QCT were determined to be 10.6 cm² ($p = 0.042$) at a distal site located 100 mm above the tibial plateau and 18.8 cm² ($p = 0.019$) at a more proximal site (175 mm). Expressed as a percentage increase, these changes were likewise found to be significant. When the total thigh musculature was segmented into anterior and posterior regions, significant increases were observed only among the anterior muscle groups at both the distal and the proximal sites. Muscle hypertrophy as determined by standard anthropometric techniques at 200 mm above the patella was not found to be significant. We conclude that QCT is a valuable technique for discerning changes in muscle size during fitness training and that, in our population, it was capable of differentiating specific muscle compartment hypertrophy secondary to electrical stimulation

Bogey R.A., Perry J., Bontrager E.L., Gronley J.K. (2000) Comparison of across-subject EMG profiles using surface and multiple indwelling wire electrodes during gait. *J Electromyogr Kinesiol* 10:255-259.

Bonaroti D., Akers J., Smith B.T., Mulcahey M.J., and Betz R.R. (1999) A comparison of FES with KAFO for providing ambulation and upright mobility in a child with a complete thoracic spinal cord injury. *J. Spinal Cord. Med.* 22, 159-166.
Abstract: This study compared functional and physiologic measures of ambulation and upright mobility with functional electrical stimulation (FES) versus knee-ankle-foot-orthoses (KAFO) in an 11-year-old boy with a T-10 level spinal cord injury. The child was a limited community ambulator with bilateral KAFO and loftstrand crutches. The FES system consisted of percutaneous intramuscular electrodes controlled by a portable stimulator and thumbswitch, an AFO for ankle and foot support, and loftstrand crutches. The subject used a swing-through gait pattern with both modes of mobility. The Functional Independence Measure scoring system and time to completion were used to compare performance in 6 standardized activities: donning, high transfer, inaccessible toilet transfer, ascend/descend stairs, and floor-to-standing transfer. Ten repeated measures were performed for each mode. Physiologic measures included energy expenditure, postural stability using forceplates, and a Functional Standing Test (FST). The subject performed all 6 mobility activities independently with FES and KAFO. In 4 of 6 activities, there was a trend toward faster times with FES, but this was not statistically significant. Toilet transfers and stair descent were performed significantly faster with KAFO. There was

no difference in completion times on the activities of the FST. Measures of postural sway suggested that the subject was more stable with KAFO during quiet standing, while the modes were equal during a dynamic activity (raising arm for functional use). Energy expenditure results revealed no significant difference in oxygen cost per meter but a significantly higher oxygen consumption rate per minute for FES. Ambulation with both modes was performed at levels consistent with strenuous exercise. Maximum ambulation distances were relatively equal while the subject's velocity was significantly faster with FES. Of note, the subject reported ceasing ambulation during maximum distance trials due to general fatigue when using FES and due to shoulder pain with KAFO ambulation. For this subject, FES provided a means of performing upright mobility tasks independently, comparable with that of KAFO, while providing a faster ambulation velocity and a potential means of cardiovascular training

Bradley M.B. (1994) The effect of participating in a functional electrical stimulation exercise program on affect in people with spinal cord injuries. *Arch. Phys. Med. Rehabil.* 75, 676-679.

Abstract: Functional electrical stimulation (FES) is a technology that is increasingly being used in the acute and post rehabilitation of people with spinal cord injuries. Though there has been considerable interest in the potential psychological effects of FES, little research has been done in this area. This study examined the effect of participation in an FES exercise program on affect in 37 persons with spinal cord injury. The effect of the subjects' expectations is also examined. Results indicate significant changes in negative affective status but no significant changes in positive affect. In particular, the results show increases in depression and hostility in subjects in the treatment group who had unrealistic expectations for the FES program. It is important to identify and monitor FES participants who have unrealistic expectations

Brindley G.S. (1994) The first 500 patients with sacral anterior root stimulator implants: General description. *Paraplegia* 32, 795-805.

Brissot R., Gallien P., Le Bot M.P., Beaubras A., Laisne D., Beillot J., and Dassonville J. (2000) Clinical

experience with functional electrical stimulation-assisted gait with Parastep in spinal cord-injured patients. *Spine* 25, 501-508.

Abstract: STUDY DESIGN: Clinical evaluation of the Parastep method, a six-channel transcutaneous functional electrical stimulation device, in spinal cord-injured patients. OBJECTIVES: To investigate the motor performances of this new technique regarding energy expenditure and to evaluate its advantages and limitations, especially in social activities involving ambulation. METHODS: This study was conducted in 15 thoracic spine-injured patients. The lesion was complete except in two patients. The gait ability and the functional use were judged clinically. Energy cost was evaluated from heart rate, peak oxygen uptake, and lactatemia. RESULTS: Thirteen patients completed the training (mean: 20 sessions) and achieved independent ambulation with a walker. The mean walking distance, without rest, was 52.8 +/- 69 m, and the mean speed was 0.15 +/- 0.14 m/sec. One patient with incomplete lesion, who had been nonambulatory for 8 months after the injury, became able to walk without functional electrical stimulation after five sessions. The follow-up was 40 +/- 11 months. Five patients pursued using functional electrical stimulation-assisted gait as a means of physical exercise but not for ambulation in social activities. The patients experienced marked psychological benefits, with

positive changes in their way of life. In three subjects, a comparison of physiologic responses to exercise between a progressive arm ergometer test and a walking test with the Parastep (Sigmedics, Inc., Northfield, IL) at a speed of 0.1 m/sec was performed, showing that the heart rate, the peak oxygen uptake, and lactatemia during gait were close to those obtained at the end of the maximal test on the ergometer. CONCLUSIONS: In spite of its ease of operation and good cosmetic acceptance, the Parastep approach has very limited applications for mobility in daily life, because of its modest performance associated with high metabolic cost and cardiovascular strain. However, it can be proposed as a resource to keep physical and psychological fitness in patients with spinal cord injury

Bruninga K., Riedy L., Keshavarzian A., and Walter J. (1998) The effect of electrical stimulation on colonic transit following spinal cord injury in cats. *Spinal Cord*. 36, 847-853.

Abstract: The effect of direct electrical stimulation on colonic transit and manometric recordings following spinal cord injury were assessed in five adult male cats. Intra-colonic catheters were surgically placed, stimulating electrodes were sutured to the colonic serosa and a laminectomy with spinal cord clamping at a T4 level was done to induce spinal cord injury (SCI). Twenty radiopaque markers were inserted through an intra-colonic catheter located 1 cm distal to the cecum and were monitored with daily fluoroscopy as a measure of colonic transit. Transit measurements were compared before SCI, after SCI and after SCI with electrical stimulation of 40 pps, 1 ms, and 0-50 mA. Colonic transit following SCI was significantly prolonged ($P < 0.05$) when compared to the transit before SCI. Electrical stimulation following SCI improved colonic transit to values not significantly different from those before SCI. Spontaneous colonic phasic motor activity was similar both before and after SCI. Manometric defecation patterns were also observed to be similar before SCI and after SCI with electrical stimulation. Based on our scoring criteria, the most frequent response to electrical stimulation was an abdominal contraction. These findings demonstrate that colonic transit is prolonged following SCI and that direct electrical stimulation of the colon following SCI improves colonic transit in an animal model

Buchanan L.E., Ditunno J.F., Jr., Osterholm J.L., Cotler J.M., and Staas W.E., Jr. (1990) Spinal cord injury: a ten-year report. *Pa Med*. 93, 36-39.

Abstract: In the past 10 years, the RSCICDV has had a unique opportunity to serve and expand the bounds of knowledge regarding this most devastating injury. The RSCICDV has collaborated with other model SCI systems in research regarding the incidence of respiratory complications, the value of removing bullet fragments lodged within the spinal canal, the survival/cause of death following spinal cord injury, the cost of spinal cord injury care, and the recovery of motor strength after quadriplegia. Key on-site research efforts have focused on preventing deep vein thrombosis and in documenting the course of motor recovery after spinal cord injury. The identification of electrical stimulation plus low dose heparin as a prophylaxis has been a major breakthrough in the prevention of deep vein thrombosis. The documentation of motor recovery after injury has led to the designation of Thomas Jefferson University as a federally-funded National Rehabilitation Research and Training Center in Neural Recovery and Functional Enhancement (1988- 1993). It cannot be stressed enough, however, that the accomplishments of the Regional Spinal Cord Injury Center of Delaware Valley would have been quite impossible without the cooperation and support of the many physicians who have referred their patients to this regional

center program. Continuing and expanding this cooperative effort should result in even greater achievements for persons with spinal cord injury in the years to come

- BurrIDGE J., Taylor P., Hagan S., and Swain I. (1997) Experience of clinical use of the Odstock dropped foot stimulator. *Artif. Organs* 21, 254-260.
Abstract: The Odstock dropped foot stimulator (ODFS) is a simple functional electrical stimulation (FES) device for the correction of dropped foot. Improved reliability, fine control of stimulation parameters, and careful application and follow-up have led to 86% compliance. Data on 56 patients (50 patients with hemiplegia, 5 patients with multiple sclerosis, and 1 patient with spinal cord injury) who have used the system for between 6 and 18 months are presented and show a statistically significant increase in walking speed with the stimulator at 3 months of 14% ($p < 0.001$); decreased effort of walking, measured as physiological cost index (PCI), of 37% ($p < 0.001$); and statistically significant improvement in functional mobility tests and questionnaires. No statistically significant carryover was seen although 3 patients had sufficient improvement in active ankle control and gait parameters to no longer need the stimulator. Six patients who used the stimulator all day every day had a problem with skin irritation, which we have not yet been able to solve. Two patients discontinued use after experiencing increased spasticity in the calf
- Campbell J.M., Gerber N., Mathe C. (1988) Innervation status of muscles paralyzed by SCI. *Phys Ther* 68, 864.
- Campbell J.M., Meadows P.M., Waters R.L. (1991) Spasticity in SCI: day to day variability in response to joint movement and electrical stimulation. *Proc 14 Annual RESNA Conf*, Kansas City, MO, pp 274-276.
- Campbell J.M., Meadows P.M., Wederich C., Waters R.L. (1992) FNS Knee Extension in paraplegia: factors associated with gains in muscle performance. *Proc 15 Annual RESNA Conf*, Toronto, Canada, pp 225-227.
- Campbell J.M., Meadows P.M. (1992) Therapeutic FES: From Rehabilitation to Neural Prosthetics. *Assistive Technology* 4, 4-18.
- Campbell J.M., Meadows P.M., Monlux J., Waters R.L., Wederich C. (1994) FES in SCI: Comprehensive Management of Muscle Performance in Complete and Incomplete Paralysis. *Basic and Applied Myology* 4, 187-194.
- Campos R.J., Dimitrijevic M.M., Faganel J., and Sharkey P.C. (1981) Clinical evaluation of the effect of spinal cord stimulation on motor performance in patients with upper motor neuron lesions. *Appl. Neurophysiol.* 44, 141-151.
Abstract: The effect of chronic electrical stimulation of the spinal cord was evaluated in a group of 24 patients with multiple sclerosis, spinal cord injury, and degenerative disorders of the central nervous system. The systems for stimulation had been implanted from 12 to 30 months prior to completion of evaluation. At the time of completion of evaluation, 23 of the 24 patients still had implanted systems, although 6 of them had not used spinal cord stimulation because of no noticeable effect. In 3 patients stimulation had been disconnected because of technical failure of the system. In 1 patient the system had been removed 8 weeks after implantation because of inflammation in the under-skin receiver pocket. The effects on motor performance of the remaining 14 patients who had continuously active systems were

improved bladder control, diminished spasticity, improved movement coordination, and increased endurance

- Castro M.J., Apple D.F., Jr., Staron R.S., Campos G.E., and Dudley G.A. (1999) Influence of complete spinal cord injury on skeletal muscle within 6 mo of injury. *J. Appl. Physiol* 86, 350-358.
Abstract: This study examined the influence of spinal cord injury (SCI) on affected skeletal muscle. The right vastus lateralis muscle was biopsied in 12 patients as soon as they were clinically stable (average 6 wk after SCI), and 11 and 24 wk after injury. Samples were also taken from nine able-bodied controls at two time points 18 wk apart. Surface electrical stimulation (ES) was applied to the left quadriceps femoris muscle to assess fatigue at these same time intervals. Biopsies were analyzed for fiber type percent and cross-sectional area (CSA), fiber type-specific succinic dehydrogenase (SDH) and alpha-glycerophosphate dehydrogenase (GPDH) activities, and myosin heavy chain percent. Controls showed no change in any variable over time. Patients showed 27- 56% atrophy ($P = 0.000$) of type I, IIa, and IIax+IIx fibers from 6 to 24 wk after injury, resulting in fiber CSA approximately one-third that of controls. Their fiber type specific SDH and GPDH activities increased ($P \leq 0.001$) from 32 to 90% over the 18 wk, thereby approaching or surpassing control values. The relative CSA of type I fibers and percentage of myosin heavy chain type I did not change. There was apparent conversion among type II fiber subtypes; type IIa decreased and type IIax+IIx increased ($P \leq 0.012$). Force loss during ES did not change over time for either group but was greater ($P = 0.000$) for SCI patients than for controls overall (27 vs. 9%). The results indicate that vastus lateralis muscle shows marked fiber atrophy, no change in the proportion of type I fibers, and a relative independence of metabolic enzyme levels from activation during the first 24 wk after clinically complete SCI. Over this time, quadriceps femoris muscle showed moderately greater force loss during ES in patients than in controls. It is suggested that the predominant response of mixed human skeletal muscle within 6 mo of SCI is loss of contractile protein. Therapeutic interventions could take advantage of this to increase muscle mass
- Chaplin E.R. (1996) Functional Neuromuscular Stimulation for Mobility in People with Spinal Cord Injuries - The Parastep System. *J Spinal Cord Med* 19, 100-105.
- Chen D., Jaeger R.J. (1977) Functional Electrical Stimulation: Technical Advances and Clinical Applications. *Phys Med & Rehabil: State of the Art Reviews* 11, 39-53.
- Closson J.B., Toerge J.E., Ragnarsson K.T., Parsons K.C., and Lammertse D.P. (1991) Rehabilitation in spinal cord disorders. 3. Comprehensive management of spinal cord injury. *Arch. Phys. Med. Rehabil.* 72, S298-S308.
Abstract: This self-directed learning module highlights advances in the management of the person with a spinal cord deficit. Traumatic spinal cord injury is being used as the model, but the principles apply to all patients with spinal cord deficits. This article is part of the chapter on rehabilitation of spinal cord disorders for the Self-Directed Medical Knowledge Program Study Guide for practitioners and trainees in physical medicine and rehabilitation. Specifically, this section contains information regarding prehospital care, acute assessment and management, primary rehabilitation by systems, sexuality and psychosocial issues, management of pain and spasticity, functional goals, the role of functional electrical stimulation, and long-term follow-up

Crago P.E., Memberg W.D., Usey M.K., Keith M.W., Kirsch R.F., Chapman G.J., Katorgi M.A., and Perreault E.J. (1998) An elbow extension neuroprosthesis for individuals with tetraplegia. *IEEE Trans. Rehabil. Eng* 6, 1-6.

Abstract: Functional electrical stimulation (FES) of the triceps to restore control of elbow extension was integrated into a portable hand grasp neuroprosthesis for use by people with cervical level spinal cord injury. An accelerometer mounted on the upper arm activated triceps stimulation when the arm was raised above a predetermined threshold angle. Elbow posture was controlled by the subjects voluntarily flexing to counteract the stimulated elbow extension. The elbow moments created by the stimulated triceps were at least 4 N.m, which was sufficient to extend the arm against gravity. Electrical stimulation of the triceps increased the range of locations and orientations in the workspace over which subjects could grasp and move objects. In addition, object acquisition speed was increased. Thus elbow extension enhances a person's ability to grasp and manipulate objects in an unstructured environment

Cramer R.M., Weston A.R., Rutkowski S., Middleton J.W., Davis G.M., and Sutton J.R. (2000) Effects of electrical stimulation leg training during the acute phase of spinal cord injury: a pilot study. *Eur. J. Appl. Physiol* 83, 409-415.

Abstract: Four individuals with a spinal cord injury underwent 16 weeks of isometric electrical stimulation training to both legs for 60 min, five times per week during the first 5 months after injury, while two SCI individuals remained untrained. A baseline biopsy sample of the vastus lateralis muscle was obtained within 1 month of injury, and another biopsy sample was taken after a further 16 weeks. The untrained, paralyzed skeletal muscle displayed a reduction in (1) type I fibers (from 50% to 9%), (2) myosin heavy chain (MHC) I (from 27% to 6%), and (3) fiber cross-sectional area of type I, type IIA and type IIX fibers (-62%, -68%, and -55%, respectively) when compared to the baseline sample of muscle taken within 1 month of injury. In contrast, the trained group showed smaller alterations in type I fibers (from 49% to 40%) and MHC I composition (from 39% to 25%), while fiber cross-sectional area was similar to baseline levels for type I, type IIA and type IIX fibers (-3%, -8%, and -4%, respectively). In conclusion, electrical stimulation training can largely prevent the adverse effects of a spinal cord injury upon paralyzed human skeletal muscle if applied soon after the injury

Creasey G.H. (1993) Electrical stimulation of sacral roots for micturition after spinal cord injury. *Urol. Clin. North Am.* 20, 505-515.

Abstract: In patients with suprasacral spinal cord injury, electrical stimulation of the sacral anterior nerve roots can produce micturition with low residual volumes of urine and reduced urinary tract infection. Voiding pressures can be maintained at acceptable levels by selective peripheral neurotomy and myotomy or, more commonly, by an intermittent pattern of stimulation. Occasionally, external sphincterotomy is required. The procedure is usually combined with division of the sacral posterior roots, which increases bladder capacity and continence; this also increases bladder compliance, which may be protective for the upper urinary tracts. A reduction in constipation usually is observed, and some patients are able to defecate with the aid of electrical stimulation. Penile erection is produced in a substantial proportion of male patients. The procedure has now been applied in about 700 patients with spinal cord injury, some of whom have been followed for nearly 15 years. The nerves do not appear to be damaged by long-term stimulation, and technical faults with the equipment are now uncommon

Creasey G.H. (1994) Managing bladder, bowel and sexual function after spinal cord injury. In: Rushton D.N. [Ed]: *Neuro-urology*. New York, Marcel Dekker, pp 233-251.

Creasey G.H., Elefteriades J., DeMarco A., Talonen P., Bijak M., Girsch W., Kantor C. (1996) Electrical stimulation to restore respiration. *J Rehab Res & Dev* 33, 123-132.

Creasey G.H. (2000) Lecture 6: restoration of male sexual function following spinal cord injury. *Int. J. Impot. Res.* 12 Suppl 3, S54-S55.

Creasey G.H., Kilgore K.L., Brown-Triolo D.L., Dahlberg J.E., Peckham P.H., and Keith M.W. (2000) Reduction of costs of disability using neuroprostheses. *Assist. Technol.* 12, 67-75.

Abstract: The lifetime costs associated with spinal cord injury are substantial. Assistive technology that reduces complications, increases independence, or decreases the need for attendant services can provide economic as well as medical or functional benefit. This study describes two approaches for estimating the economic consequences of implanted neuroprostheses utilizing functional electrical stimulation. Life care plan analysis was used to estimate the costs of bladder and bowel care with and without a device restoring bladder and bowel function and to compare these with the costs of implementing the device. For a neuroprosthesis restoring hand grasp, the costs of implementation were compared to the potential savings in attendant care costs that could be achieved by the use of the device. The results indicate that the costs of implementing the bladder and bowel system would be recovered in 5 years, primarily from reduced costs of supplies, medications, and procedures. The costs of the hand grasp neuroprosthesis would be recovered over the lifetime of the user if attendant time was reduced only 2 hours per day and in a shorter time if attendant care was further reduced. Neither analysis includes valuation of the quality of life, which is further enhanced by the neuroprostheses through restoration of greater independence and dignity. Our results demonstrate that implantable neuroprosthetic systems provide good health care value in addition to improved independence for the disabled individual

Dai R., Stein R.B., Andrews B.J., James K.B., and Wieler M. (1996) Application of tilt sensors in functional electrical stimulation. *IEEE Trans. Rehabil. Eng* 4, 63-72.

Abstract: Tilt sensors, or inclinometers have been investigated for the control of Functional Electrical Stimulation (FES) to improve the gait of persons who had a stroke or incomplete spinal cord injury (SCI). Different types of tilt sensors were studied for their characteristics and their performance in measuring the angular displacement of leg segments during gait. Signal patterns of the lower leg with inertial tilt sensors were identified with control subjects and subjects with footdrop who are being stimulated during level walking. To minimize acceleration responses when the foot swings or hits the ground, we use low-pass filtering (1.5-2 Hz). A finite state approach allows the sensor fixed on the shank to effectively detect the step intention in a population of stroke and incomplete SCI subjects and to control the FES. When the lower leg tilts backward, the common peroneal nerve is stimulated to bring the foot up and forward. We have designed a miniature footdrop stimulator with a magnetoresistive tilt sensor built in, so no external sensor cables are required. The thresholds to turn the stimulator on and off can be adjusted, as well as the maximum period of stimulation and the minimum interval between periods of stimulation. This device features several important advantages over traditional AFO's or stimulators controlled by foot switches. Initial trials with stroke and SCI subjects have

demonstrated substantial gait improvement for some subjects, while most liked the good cosmesis and ease of using the device with a tilt sensor

Daly J.J., Marsolais E.B., Mendell L.M., Rymer W.Z., Stefanovska A., Wolpaw J.R., and Kantor C. (1996) Therapeutic neural effects of electrical stimulation. *IEEE Trans. Rehabil. Eng* 4, 218-230.

Abstract: The use of a functional neuromuscular stimulation (FNS) device can have therapeutic effects that persist when the device is not in use. Clinicians have reported changes in both voluntary and electrically assisted neuromuscular function and improvements in the condition of soft tissue. Motor recovery has been observed in people with incomplete spinal cord injury, stroke, or traumatic brain injury after the use of motor prostheses. Improvement in voluntary dorsiflexion and overall gait pattern has been reported both in the short term (several hours) and permanently. Electrical stimulation of skin over flexor muscles in the upper limb produced substantial reductions for up to 1 h in the severity of spasticity in brain-injured subjects, as measured by the change in torque generation during ramp-and-hold muscle stretch. There was typically an aggravation of the severity of spasticity when surface stimulation reached intensities sufficient to also excite muscle. Animals were trained to alter the size of the H-reflex to obtain a reward. The plasticity that underlies this operantly conditioned H-reflex change includes changes in the spinal cord itself. Comparable changes appear to occur with acquisition of certain motor skills. Current studies are exploring such changes in humans and animals with spinal cord injuries with the goal of using conditioning methods to assess function after injury and to promote and guide recovery of function. A better understanding of the mechanisms of neural plasticity, achieved through human and animal studies, may help us to design and implement FNS systems that have the potential to produce beneficial changes in the subject's central nervous systems

Dewald J.P.A., Given J.D., Rymer W.Z. (1996) Long-Lasting Reductions of Spasticity Induced by Skin Electrical Stimulation. *IEEE Trans Rehab Eng* 4, 231-242.

DiMarco A.F., Romaniuk J.R., and Supinski G.S. (1995) Electrical activation of the expiratory muscles to restore cough. *Am. J. Respir. Crit Care Med.* 151, 1466-1471. Abstract: Many patients with spinal cord injury have paralysis of their expiratory muscles and, consequently, lack an effective cough. The purpose of the present study was to evaluate the utility of lower thoracic spinal cord stimulation (SCS) to activate the expiratory muscles. Studies were performed on 15 anesthetized dogs. A quadripolar stimulating electrode (Medtronic Model 3586) was inserted epidurally and on the ventral surface of the lower thoracic spinal cord. Changes in airway pressure, airflow, and internal intercostal and abdominal muscle length were monitored to assess the effects of electrical stimulation. Spinal stimulation applied at the T9-T10 spinal level provided maximal changes in airway pressure generation in preliminary experiments. All subsequent studies were therefore performed with the electrode positioned at this level. The expiratory muscles were stimulated supramaximally over a wide range of lung volumes which were expressed as the corresponding change in airway pressure. The pressure-generating capacity of the expiratory muscles was evaluated by the change in airway pressure produced by SCS during airway occlusion. Peak expiratory airflow was also monitored following release of occlusion. At FRC, deflation (-10 cm H₂O) and inflation (+ 30 cm H₂O), SCS resulted in positive airway pressures of 44 cm H₂O +/- 4 SE, 28 cm H₂O +/- 3 SE, and 82 cm H₂O +/- 7 SE. The relationship between airway pressure expiratory

airflow generation and lung volume was linear (slope = 1.34 +/- 0.04) over the entire vital capacity range. Our results indicate that: (1) a major portion of the expiratory muscles can be activated reproducibly and in concert by electrical stimulation, and (2) this technique may be a clinically useful method of restoring cough in spinal cord injured patients

Donaldson N., Perkins T.A., Fitzwater R., Wood D.E., and Middleton F. (2000) FES cycling may promote recovery of leg function after incomplete spinal cord injury. *Spinal Cord*. 38, 680-682.

Abstract: STUDY DESIGN: Single subject pilot. OBJECTIVES: (i) To see whether strength and endurance for recreational cycling by functional electrical stimulation (FES) are possible following spinal cord injury (SCI). (ii) To develop the equipment for FES-cycling. SETTING: England. METHODS: Near-isometric or cycling exercise was performed by the incomplete SCI subject at home. RESULTS: After training for an average of 21 min per day for 16 months, the stimulated muscles increased in size and the subject was able to cycle for 12 km on the level. Surprisingly, there was a substantial increase in the measured voluntary strength of the knee extensors and the subject reports improved leg function. CONCLUSION: FES-cycling may promote recovery after incomplete spinal cord injury. If so, it offers the possibility of being a convenient method for widespread use

Dudley G.A., Castro M.J., Rogers S., and Apple D.F., Jr. (1999) A simple means of increasing muscle size after spinal cord injury: a pilot study. *Eur. J. Appl. Physiol Occup. Physiol* 80, 394-396.

Abstract: This study tested that hypothesis that skeletal muscle within a year of spinal cord injury (SCI) would respond to intermittent high force loading by showing an increase in size. Three males about 46 weeks post clinically complete SCI underwent surface electrical stimulation of their left or right m. quadriceps femoris 2 days per week for 8 weeks to evoke 4 sets of ten isometric or dynamic actions each session. Conditioning increased average cross-sectional area of m. quadriceps femoris, assessed by magnetic resonance imaging, by 20+/-1% (p = 0.0103). This reversed 48 weeks of atrophy such that m. quadriceps femoris 54 weeks after SCI was the same size as when the patients were first studied 6 weeks after injury. The results suggest that skeletal muscle is remarkably responsive to intermittent, high force loading after almost one year of little if any contractile activity

Egon G., Barat M., Colombel P., Visentin C., Isambert J.L., and Guerin J. (1998) Implantation of anterior sacral root stimulators combined with posterior sacral rhizotomy in spinal injury patients. *World J. Urol.* 16, 342-349.

Abstract: Brindley-Finotech sacral anterior root stimulators combined with posterior sacral rhizotomy were implanted in 68 males and 28 females with spinal cord lesions. In 9 patients the electrodes were implanted extradurally in the sacrum, and in 90 patients they were implanted intradurally (3 patients had a second extradural implant after a first intradural implant). Three patients died from causes unrelated to the implant. Of the 93 surviving patients, 83 used their implants for micturition and 82 were fully continent. The mean bladder capacity increased from 206 ml preoperatively to 564 ml after the operation. Three patients had a preoperative vesicorenal reflux that disappeared after surgery. In all, 51 patients used the stimulator for defecation. Erection was possible with electrical stimulation in 46 males and was used for coitus by 17 couples. Secondary deafferentation at the level of the conus was performed four times. Three patients who had a cerebrospinal fluid

leak were operated on again. Two implants had to be removed because of infection. Sacral anterior root stimulation combined with sacral deafferentation is a welcome addition to the treatment of neurogenic bladder in spinal cord injury patients

Ferguson A.C., Keating J.F., Delargy M.A., and Andrews B.J. (1992) Reduction of seating pressure using FES in patients with spinal cord injury. A preliminary report. *Paraplegia* 30, 474-478.

Abstract: The aim of this study was to investigate the use of functional electrical stimulation (FES) as a means of pressure sore prevention in seated spinal cord injured (SCI) subjects. Nine SCI subjects took part in tests in which electrical stimulation was applied to the quadriceps with the lower legs restrained. Ischial pressures were measured during periods of quiet sitting and FES application. A strain gauged lever arm was used to measure the knee moment during quadriceps stimulation. The average pressure drop at the right and left buttocks was 44 mmHg and 27 mmHg respectively. In general the greatest reductions occurred in subjects with larger knee moments; however, there was no direct relationship between the pressure reduction obtained and the quadriceps strength. This form of FES may be useful as a prophylactic aid in the management of pressure sores in SCI subjects

Field-Fote E.C. (2000) Spinal cord control of movement: implications for locomotor rehabilitation following spinal cord injury. *Phys. Ther.* 80, 477-484.

Abstract: In recent years, our understanding of the spinal cord's role in movement control has been greatly advanced. Research suggests that body weight support (BWS) walking and functional electrical stimulation (FES), techniques that are used by physical therapists, have potential to improve walking function in individuals with spinal cord injury (SCI), perhaps long after the stage of spontaneous recovery. Walking is one of the most desired goals of people with SCI; however, we are obligated to be judicious in our claims of locomotor recovery. There are few controlled studies that compare outcomes of BWS training or FES with those of conventional interventions, and access to services using BWS training or FES may be restricted under managed care

Figoni S.F. (1990) Perspectives on cardiovascular fitness and SCI. *J. Am. Paraplegia Soc.* 13, 63-71.

Abstract: The purpose of these papers is to review and discuss the fundamental concepts and problems underlying cardiovascular fitness and spinal cord injury. Particular attention is paid to several modes of exercise available to individuals with spinal cord injury (SCI)--voluntary arm- crank and wheelchair ergometry, electrical stimulation leg cycle ergometry, and combined voluntary arm-cranking and electrical stimulation leg (hybrid) exercise. The effects of level of injury, active muscle mass, and sympathetic dysfunction upon acute central hemodynamic adjustments during exercise testing and chronic training adaptations are discussed for both quadriplegics and paraplegics. Several topics for future research are suggested

Formal C.S., Cawley M.F., and Stiens S.A. (1997) Spinal cord injury rehabilitation. 3. Functional outcomes. *Arch. Phys. Med. Rehabil.* 78, S59-S64.

Abstract: This self-directed learning module highlights new advances in this topic area. It is part of the chapter on spinal cord injury rehabilitation in the Self-Directed Physiatric Education Program for practitioners and trainees in physical medicine and rehabilitation. This article contains information about mobility, ambulation, upper extremity function, bowel management, and technology to enhance function in the

community. New advances covered in this section include functional electrical stimulation for enhancing mobility and upper extremity function

Franco J.C., Perell K.L., Gregor R.J., and Scremin A.M. (1999) Knee kinetics during functional electrical stimulation induced cycling in subjects with spinal cord injury: a preliminary study. *J. Rehabil. Res. Dev.* 36, 207-216.

Abstract: The purpose of this preliminary study was to describe pedal effectiveness parameters and knee-joint reaction forces generated by subjects with chronic spinal cord injury (SCI) during functional electrical stimulation (FES)-induced bicycling. Three male subjects (age 33-36 years old), who were post-traumatic SCI (ASIA-modified level A, level T4-C5) and enrolled in an FES rehabilitation program, signed informed consent forms and participated in this study. Kinematic data and pedal forces during bicycling were collected and effective force, knee-joint reaction forces, knee generalized muscle moments, and knee-joint power and work were calculated. There were three critical findings of this study: 1) pedaling effectiveness was severely compromised in this subject population as indicated by a lack of overall positive crank work; 2) knee-joint kinetics were similar in magnitude to data reported for unimpaired individuals pedaling at higher rates and workloads, suggesting excessive knee-joint loading for subjects with SCI; and 3) shear reaction forces and muscle moments were opposite in direction to data reported for unimpaired individuals, revealing an energetically unfavorable knee stabilizing mechanism. The critical findings of this study suggest that knee-joint kinetics may be large enough to produce a fracture in the compromised lower limbs of individuals with SCI

Freehafer A.A., Hazel C.M., Becker C.L. (1981) Lower extremity fractures in patients with spinal cord injury. *Paraplegia* 19, 367-372.

Frost F., Hartwig D., Jaeger R., Leffler E., and Wu Y. (1993) Electrical stimulation of the sacral dermatomes in spinal cord injury: effect on rectal manometry and bowel emptying. *Arch. Phys. Med. Rehabil.* 74, 696-701.

Abstract: The impairment in defecation function that comes as a result of spinal cord injury may have a significant negative impact upon quality of life. Electrical stimulation (ES) of the somatic nervous system has been used to elicit autonomic reflexes in animals, before and after spinal cord transection. To determine whether ES might be used to promote bowel emptying, seven persons with recent spinal cord injury (SCI) and seven control subjects were studied. Electrical stimulation of the second sacral dermatome was applied during rectal manometry in both groups, and ES was added to the bowel programs of SCI patients. A significant rise in the number of rectal pressure spikes was noted in both groups after application of ES ($p < .002$, $f = 6.34$). There was no significant differences between the SCI and control groups when measuring the amplitude of spike waves in the colon. No significant change was noted in the time required for SCI patients to initiate a bowel movement, or in the time required to complete bowel emptying. Electrical stimulation of the sacral dermatomes can result in a change in the bowel activity of the recto-sigmoid colon. To date, no clinical effect on bowel emptying has been demonstrated

Gallien P., Brissot R., Eyssette M., Tell L., Barat M., Wiart L., and Petit H. (1995) Restoration of gait by functional electrical stimulation for spinal cord injured patients. *Paraplegia* 33, 660-664.

Abstract: In this clinical study, we report the results of functional electrical stimulation for the ambulation of paraplegic patients without long leg braces (LLB), according to

the Parastep approach. Of 13 SCI patients with complete neurological lesions included in this trial, 12 progressed to independent ambulation with the aid of the Parastep. The average walking distance was 76 m, with a maximum of 350 m, and the mean speed 0.2 m s⁻¹. Compared to the situation with long leg braces, which in fact are given up by most paraplegic patients, long term home use seems to be much more important. Tolerance of this method is satisfactory. The psychological benefits of the device are remarkable. From this experience, it is concluded that this method is valuable for the restoration of standing and walking in the long term management of spinal cord injury patients

Garland D.E. (1988) Clinical observations on fractures and heterotopic ossification in the spinal cord and traumatic brain injured populations. *Clin Orthop* 86-101.

Garland D.E., Stewart C.A., Adkins R.H., Hu S.S., Rosen C., Liotta F.J. and Weinstein D.A. (1992) Osteoporosis after spinal cord injury. *J Orthop Res* 10, 371-378.

Garland D.E., Adkins R.H., Matsuno N.N., and Stewart C.A. (1999) The effect of pulsed electromagnetic fields on osteoporosis at the knee in individuals with spinal cord injury. *J. Spinal Cord. Med.* 22, 239-245.

Abstract: The purpose of this study was to determine the effects of pulsed electromagnetic fields on osteoporotic bone at the knee in individuals with chronic spinal injury. The study consisted of 6 males with complete spinal cord injury at a minimum of 2 years duration. Bone mineral density (BMD) was obtained at both knees at initiation, 3 months, 6 months, and 12 months using dual energy X-ray absorptiometry. In each case, 1 knee was stimulated using The Bone Growth Stimulator Model 3005 from American Medical Electronics, Incorporated and the opposite knee served as the control. Stimulation ceased at 6 months. At 3 months BMD increased in the stimulated knees 5.1% and declined in the control knees 6.6% ($p < .05$ and $p < .02$, respectively). By 6 months the BMD returned to near baseline values and at 12 months both knees had lost bone at a similar rate to 2.4% below baseline for the stimulated knee and 3.6% below baseline for the control. There were larger effects closer to the site of stimulation. While the stimulation appeared useful in retarding osteoporosis, the unexpected exaggerated decline in the control knees and reversal at 6 months suggests underlying mechanisms are more complex than originally anticipated. The authors believe a local as well as a systemic response was created

Garland D. and Wharton G. (1994) Spinal cord injury care: funding for the future. *Orthopedics* 17, 675-678.

Rubayi S., Ambe M.K., Garland D.E., and Capen D. (1992) Heterotopic ossification as a complication of the staged total thigh muscles flap in spinal cord injury patients. *Ann. Plast. Surg.* 29, 41-46.

Abstract: Between 1980 and 1990, 24 total thigh flap procedures were performed at Rancho Los Amigos Medical Center (Downey, CA) by the Pressure Ulcer Management Service. An unexpected occurrence was identified, that is, the rapid development of heterotopic ossification (HO) occurring in the exposed muscle flap between the first and second stages. There were 15 two-stage total thigh flap procedures on 14 patients performed between 1980 and 1990. Of these 15 flap procedures, 11 in 10 patients were found to have HO evident at the second-stage debridement/closure. In comparing our findings with those in other studies (earliest

evidence of HO at 19 days), the initial presentation of HO in affected tissues might be even earlier than previously detected. The risks and technical difficulties due to development of HO associated with the two-stage total thigh flap procedure point toward future modifications in preoperative planning that may prove beneficial. Therefore, if the two-stage total thigh flap procedure is necessary, the interval between initial debridement/disarticulation (stage 1) and definitive flap closure (stage 2) should be kept to an absolute minimum. Additionally, HO medicinal prophylaxis (that is, indomethacin or diphosphonates) or radiation after the first stage of the total thigh flap procedure should be considered. Our final conclusion is that the total thigh flap procedure should be done as a one-stage procedure if possible

Garland D.E., Stewart C.A., Adkins R.H., Hu S.S., Rosen C., Liotta F.J., and Weinstein D.A. (1992) Osteoporosis after spinal cord injury. *J. Orthop. Res.* 10, 371-378.
Abstract: Dual-photon absorptiometry characterized bone loss in males aged less than 40 years after complete traumatic paraplegic and quadriplegic spinal cord injury. Total bone mass of various regions and bone mineral density (BMD) of the knee were measured in 55 subjects. Three different populations were partitioned into four groups: 10 controls (healthy, age matched); 25 acutely injured (114 days after injury), with 12 reexamined 16 months after injury; and 20 chronic (greater than 5 years after injury). Significant differences (p less than 0.0001) in bone mass mineral between groups at the arms, pelvis, legs, distal femur, and proximal tibia were found, with no differences for the head or trunk. Post hoc analyses indicated no differences between the acutely injured at 16 months and the chronically injured. Paraplegic and quadriplegic subjects were significantly different only at the arms and trunk, but were highly similar at the pelvis and below. In the acutely injured, a slight but statistically insignificant rebound was noted above the pelvis. Regression techniques demonstrated early, rapid, linear (p less than 0.0001) decline of bone below the pelvis. Bone mineral loss occurs throughout the entire skeleton, except the skull. Most bone loss occurs rapidly and below the pelvis. Homeostasis is reached by 16 months at two thirds of original bone mass, near fracture threshold

Garland D.E. (1991) A clinical perspective on common forms of acquired heterotopic ossification. *Clin. Orthop.* 13-29.
Abstract: The clinical courses of heterotopic ossification (HO) as a consequence of trauma and central nervous system insults have many similarities as well as dissimilarities. Detection is commonly noted at two months. The incidence of clinically significant HO is 10%-20%. Approximately 10% of the HO is massive and causes severe restriction in joint motion or ankylosis. The most common sign and symptom are decreased range of motion and pain. The locations are the proximal limbs and joints. Sites of HO about a joint may vary according to the etiology of the HO. Roentgenographic evolution of HO occurs during a six-month period in the majority of patients. Treatment modalities include diphosphonates, indomethacin, radiation, range of motion exercises, and surgical excision. Surgical timing differs according to etiology: traumatic HO may be resected at six months; spinal cord injury HO is excised at one year; and traumatic brain injury HO is removed at 1.5 years. A small number of patients have progression of HO with medicinal treatment and recurrence after resection. The patients seem recalcitrant to present treatment methods regardless of the HO etiology

Garland D.E., Shimoyama S.T., Lugo C., Barras D., and Gilgoff I. (1989) Spinal cord insults and heterotopic ossification in the pediatric population. *Clin. Orthop.* 303-310.

Abstract: Fifteen of 152 pediatric patients with spinal cord insults (10%) developed heterotopic ossification (HO) at 19 locations. The average age of the patient was eight and one-half years. The spinal cord levels were 13 thoracic and two cervical. The average time to detection of the HO from spinal insult was six and one-half years. The hip was involved in 15 of 19 HO lesions. Decreased range of motion of the affected extremity was the most common sign of occurrence. Alkaline phosphatase was elevated in five of eight patients at the time of detection. Three patients had some resorption of the HO, and one had nearly complete resorption. Five patients (3.3%) with HO had no other etiologic agent other than the neurologic insult, and their average age at time of injury was 13 and one-half years. The hip was involved in six of seven instances. The average time to diagnose this HO was 14 months after injury. Ten patients had late concurrent etiologic factors such as surgery, decubitus ulcers, late neurogenic hip dislocation, and late acute local trauma influencing HO formation. Pediatric patients who developed HO appeared to have a lower incidence, delayed onset, and fewer associated signs and symptoms compared with their adult counterparts with spinal cord injury. Patterns of ossification about the hip differ from adults. The HO lesion has the potential to resorb. HO may be initiated years after the spinal injury by an incidental insult

Garland D.E. and Orwin J.F. (1989) Resection of heterotopic ossification in patients with spinal cord injuries. *Clin. Orthop.* 169-176.

Abstract: Nineteen spinal cord injury (SCI) patients were treated with resection of heterotopic ossification (HO) in 24 hips. The average follow-up period after surgery was 6.1 years. The mean time to surgery after injury was 50.6 months. The indication for surgery in all patients was improvement in hip motion to allow sitting. The average preoperative motion in flexion and extension was 11.5 degrees. The average intraoperative motion was 82.7 degrees. The average postoperative motion at the follow-up evaluation was 35.2 degrees. Fourteen of 19 patients (74%) had sufficient motion at the follow-up evaluation for sitting. Unlimited sitting tolerance was achieved in seven patients (37%), and seven patients (37%) had improved sitting posture with some time limitations. The average arc of motion in those patients able to sit at the follow-up evaluation was 41.5 degrees. Normal bone scans, alkaline phosphatase levels, and the mature roentgenographic appearance of HO were unreliable predictors of recurrence. The preoperative range of motion was the best predictor of improved postoperative range of motion since patients with retained motion did better than those with severe ankylosis. All six hips with severe recurrence had 0 degree of preoperative motion. The average degree of preoperative motion for all remaining hips was 15.3 degrees. The best predictor of recurrence was the roentgenographic grade of HO. Nineteen of 22 hips (86%) with a mild to severe recurrence had large amounts of bone preoperatively (Grades 3- 5). Complications excluding recurrence occurred in 19 of 24 hips (79%) and included superficial wound infections in nine of 24 hips (38%) and deep persistent infections (osteomyelitis) in eight of 24 hips (33%).(ABSTRACT TRUNCATED AT 250 WORDS)

Garland D.E., Jones R.C., and Kunkle R.W. (1988) Upper extremity fractures in the acute spinal cord injured patient. *Clin. Orthop.* 110-115.

Abstract: Fifty-three long bone upper extremity fractures in 46 patients with recent spinal cord injuries were reviewed with reference to the outcome of operative versus nonoperative treatment. Twenty-four fractures had surgery and 29 fractures were treated nonoperatively. Criteria used in assessing outcome included range of motion,

time to union, total rehabilitation time, and orthopedic and medical complications. Humeral fractures had similar outcomes with either operative or nonoperative treatment. Radial nerve injury occurring with humeral fractures prolonged the rehabilitation time. All three combined radial and ulnar fracture treated surgically developed synostosis whereas two of the three nonoperatively treated fractures had other orthopedic complications. Nondisplaced radial fractures responded appropriately to closed treatment. Displaced radial fractures treated nonoperatively had a high incidence of malunion. All ulnar fractures were treated operatively, and all achieved acceptable range of motion and fracture healing at the time of discharge. Medical complications such as deep venous thromboses and decubitus ulcers occurred more frequently in the nonoperatively treated group (28%) than in the operatively treated group (4%). Standard guidelines for upper extremity fracture care apply to the patient with a spinal cord injury. However, operative stabilization may be associated with a decreased risk of medical complications in these patients

Garland D.E. (1988) Clinical observations on fractures and heterotopic ossification in the spinal cord and traumatic brain injured populations. *Clin. Orthop.* 86-101.

Abstract: Fracture care and osteogenic response deviate significantly from normal in patients with traumatic brain injury (TBI) or spinal cord injury (SCI). In TBI open reduction and internal fixation (ORIF) are recommended whenever possible to improve mobilization in the face of spasticity and the formation of heterotopic ossification (HO). In the patient with SCI, immobility and paralysis negatively alter healing. A fracture above the level of SCI, although not altered in healing, when treated by ORIF will facilitate transfer training and self care. Lower extremity fractures in SCI have a high incidence malunion, delayed union, or nonunion and are best treated by internal fixation. HO occurs in 11% of TBI patients, with the hip, shoulder, and elbow being common sites. Trauma dramatically increases the incidence of HO. In SCI, the incidence of HO is 20%, with most occurring in the hip region. A genetic predisposition to form HO is suspected but not proven

Garland D.E., Saucedo T., and Reiser T.V. (1986) The management of tibial fractures in acute spinal cord injury patients. *Clin. Orthop.* 237-240.

Abstract: Of 34 tibia fractures in 28 acute spinal cord injuries, 13 patients had complete and 15 had incomplete neurologic lesions. Tibia fractures were divided into three groups: Group I, nonoperative treatment; Group II, early open reduction and internal fixation; and Group III, Type III open injuries. Group I included 17 fractures, of which nine (53%) had delayed union, malunion, or nonunion. The average time to union was 6.5 months. Seven patients had pressure sores and pulmonary emboli. Eleven fractures were noted in Group II. One delayed union (9%), one superficial wound infection that healed uneventfully, and one deep vein thrombosis were noted. The average time to union was 12 weeks. All six Group III tibias had delayed and nonunions, regardless of treatment. Nonoperative fractures healed at a prolonged rate, while open reduction and internal fixation enhanced the rate and time to union. Fractures treated with early open reduction and internal fixation, excluding Group III patients, had the least orthopedic and medical complications. Open reduction and internal fixation is a justifiable alternative to nonoperative treatment in the uncomplicated tibia fracture regardless of neurologic lesion for improved medical and fracture care

Garland D.E., Alday B., and Venos K.G. (1984) Heterotopic ossification and HLA antigens. *Arch. Phys. Med. Rehabil.* 65, 531-532.

Abstract: Thirty patients with neurogenic (nontraumatic) heterotopic ossification following spinal cord injury in 20 and head injury in 10, were comprehensively screened for HLA antigens. The frequencies of 68 HLA-A, -B and -C antigens were examined. The HLA-A2 locus was present in 18 patients (60%) as compared to the phenotypically adjusted normal of 48.4% and was not statistically significant at the 0.05 level. No statistically significant increased frequency of the HLA-B18 or HLA-B27 antigens was detected. A positive correlation does not exist between the HLA antigen system and patient susceptibility to heterotopic ossification following head injury or spinal cord injury

Garland D.E., Alday B., Venos K.G., and Vogt J.C. (1983) Diphosphonate treatment for heterotopic ossification in spinal cord injury patients. *Clin. Orthop.* 197-200.
Abstract: Nine patients who had spinal cord injury and were receiving diphosphonate therapy for established neurogenic heterotopic ossification in 14 hips were followed up for an average of 14 months. Diphosphonate therapy at a dosage of 10 mg/kg/day when prescribed an average of 26 days after diagnosis did not prevent radiographically evident progression of heterotopic ossification. The interval of one to 30 days between clinical diagnosis and institution of diphosphonate treatment did not appear to affect the duration of radiographic progression or the final radiographic grade at maturity. Disodium etidronate therapy did not prevent the appearance of heterotopic ossification in three previously unaffected hips, although the final radiographic grade was mild. The radiographic progression of heterotopic ossification averaged 5.3 months. No clinically detectable side effects were attributable to the medication at the dosage prescribed after an average of 14 months of therapy. Due to the radiographic progression noted in patients who received 10 mg/kg/day, diphosphonate has been increased to dosages of 20 mg/kg for six months after early diagnosis

Gaviria M. and Ohanna F. (1999) Variability of the fatigue response of paralyzed skeletal muscle in relation to the time after spinal cord injury: mechanical and electrophysiological characteristics. *Eur. J. Appl. Physiol Occup. Physiol* 80, 145-153.

Abstract: The aim of this study was to determine the effect of the time after spinal cord injury (less than and greater than 10 months) on the mechanical and electrophysiological characteristics of muscle fatigue of the paralyzed electrically stimulated quadriceps muscle. Morphologically and histochemically, a relationship was observed between muscle fatigue and the delay from injury, revealing a critical period of enzymatic turning and a maximum peak of atrophy around the 10th month after the injury, followed by a long-term stabilization. Knee-torque output and M-wave variables (amplitude, latency, duration, and root mean square, RMS) of two muscular heads of the quadriceps were recorded in 19 paraplegic patients during a 120-s isometric contraction. The fatiguing muscle contraction was elicited by supramaximal continuous 20-Hz electrical stimulation. Compared to the chronic group, the acutely paralyzed group showed a greater resistance to fatigue (amount and rate of force decline, $P < \text{or} = 0.01$), smaller alterations of the M-wave amplitude and RMS, and a limited decrease of the muscle fiber conduction velocity ($P < 0.05$). Mechanical and electrophysiological changes during fatigue provided a clear functional support of the transformation of skeletal muscle under the lesion and of the existence of a critical period of muscular turn. In conclusion, when considering the artificial restoration of

motor function, the evolution of the endurance and force-generating capabilities of the muscle actuator must be taken into account, particularly when tasks require important safety conditions (e.g., standing and walking)

Gerrits H.L., de Haan A., Sargeant A.J., Dallmeijer A., and Hopman M.T. (2000) Altered contractile properties of the quadriceps muscle in people with spinal cord injury following functional electrical stimulated cycle training. *Spinal Cord*. 38, 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

Godec C. and Cass A.S. (1979) Electrical stimulation for voiding dysfunction after spinal cord injury. *J. Urol.* 121, 73-75. Abstract: Incontinence and frequency of voiding were present after spinal cord injuries in 18 patients. A hyperreflexic bladder and/or pelvic floor weakness was found in these patients. Functional electrical stimulation resulted in relief or improvement of symptoms in 9 of the 11 patients in whom this procedure was used. An increase in anal sphincter pressure with functional electrical stimulation was a more reliable criterion than an increase in maximum urethral pressure in the selection of patients for the procedure

Goldfarb M. and Durfee W.K. (1996) Design of a controlled-brake orthosis for FES-aided gait. *IEEE Trans. Rehabil. Eng* 4, 13-24. Abstract: Functional electrical stimulation (FES) is a means of restoring gait to individuals with spinal cord injury, but the performance of most FES-aided gait systems is hampered by the rapid muscle fatigue which results from stimulated muscle contraction and the inadequate control of joint torques necessary to produce desired limb trajectories. The controlled-brake orthosis (CBO) addresses these limitations by utilizing FES in combination with a long-leg brace that contains controllable friction brakes at the knees and hips. A laboratory version of the CBO utilizing computer-controlled magnetic particle brakes at the joints was designed and constructed, and preliminary results with a single spinal cord injury (SCI) subject

have demonstrated reduced fatigue and more repeatable gait trajectories when compared to FES-aided gait without the brace. Significant work remains to demonstrate the efficacy of the concept across a wide range of SCI subjects and to design a system which meets appropriate user requirements of size, weight, cosmesis, ease of use and cost. The primary purpose of the paper is to detail the design of the CBO

Gordon T. and Mao J. (1994) Muscle atrophy and procedures for training after spinal cord injury. *Phys. Ther.* 74, 50-60.

Abstract: Functional electrical stimulation (FES) of paralyzed muscles holds promise as a strategy to assist patients in executing functional movements after spinal cord injuries. Muscle atrophy is one of the major problems that must be addressed for this approach to be successful. Loss of muscle mass may occur as a result of lesions to motoneurons in either the spinal cord or the central command pathway, or a combination of the two. For injuries to spinal motoneurons, muscle fibers undergo denervation atrophy. Damage to the central command pathway, on the other hand, results in disuse atrophy. In association with atrophy, the low contractile forces and inability of the muscles to sustain contractions are of direct therapeutic concern. In this review, methods aimed at recovery of function of paralyzed limbs by reducing susceptibility to fatigue and atrophy of paralyzed muscles are discussed. One is related to promoting nerve sprouting in partially denervated muscles to reinnervate muscle fibers and reverse denervation atrophy. The other regards training of paralyzed muscles to increase strength (muscle force) and endurance (fatigue resistance) by means of FES. Most training regimens with low-frequency FES increase muscle endurance. Efforts to design optimal regimens for increasing both muscle strength and endurance must involve consideration of several factors that are still controversial. These factors, which include muscle properties (such as fiber type composition and physiological type) and conditions imposed on the muscle (such as loading) during contractions elicited by FES, are discussed in detail

Gordon T. (1995) Fatigue in adapted systems. Overuse and underuse paradigms. *Adv. Exp. Med. Biol.* 384, 429-456.

Abstract: Alterations in structural and biochemical properties of muscles that underlie physiological parameters of contractile force, speed and fatigability are described under conditions of 1) overuse: imposed electrical stimulation, natural exercise and functional overload; 2) reinnervation of denervated muscles; and 3) underusage: conditions of restricted use after spinal cord injury, weightlessness, immobilization and drug-induced neuromuscular blockade. These conditions demonstrate the remarkable plasticity of muscle fibers with obvious implications in health and disease. They also identify that the amount of neuromuscular activity and loading of muscle contractions are major factors determining susceptibility to fatigue and muscle strength, respectively

Granat M., Keating J.F., Smith A.C., Delargy M., and Andrews B.J. (1992) The use of functional electrical stimulation to assist gait in patients with incomplete spinal cord injury. *Disabil. Rehabil.* 14, 93-97.

Abstract: The use of FES (functional electrical stimulation) for gait reproduction in six patients with spinal cord injury is described. Following a detailed neuromuscular assessment the patients commenced a muscle conditioning programme using electrical stimulation applied via surface electrodes. Once patients were strong enough to stand, gait synthesis was initiated in the laboratory utilizing a

programmable electrical stimulator. When a satisfactory gait pattern had been achieved, patients used their portable stimulator at home. All six patients became able to stand and walk using the FES system and completed the home phase of the programme. Three patients continue to use the system at home for exercise and walking; the other patients have discontinued using the system, preferring a wheelchair or their original orthoses. We conclude that FES-assisted walking is feasible in patients with incomplete spinal cord injury, even with severe motor loss. Further advances in technology are needed for the system to become applicable to a larger number of patients

Granat M.H., Ferguson A.C., Andrews B.J., and Delargy M. (1993) The role of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injury--observed benefits during gait studies. *Paraplegia* 31, 207-215.

Abstract: The benefits of a functional electrical stimulation (FES) gait programme were assessed in a group of 6 incomplete spinal cord injured subjects.

Measurements were made of quadriceps spasticity, lower limb muscle strength, postural stability in standing, spatial and temporal values of gait, physiological cost of gait and independence in activities of daily living. The subjects were assessed before commencement of the programme and after a period of gait training using FES. The benefits derived as a result of the FES gait programme included a reduction in quadriceps tone, an increase in voluntary muscle strength, a decrease in the physiological cost of gait and an increase in stride length

Grill J.H. and Peckham P.H. (1998) Functional neuromuscular stimulation for combined control of elbow extension and hand grasp in C5 and C6 quadriplegics. *IEEE Trans. Rehabil. Eng* 6, 190-199.

Abstract: Spinal cord injury sustained at the C5/C6 level leaves an individual without voluntary control of the muscles of the forearm, hand, or of the elbow extensors. The objective of this research project was to integrate functional neuromuscular stimulation (FNS) control of elbow extension with a previously developed system that provides hand grasp in order to increase the working volume in space in which users can perform functional tasks. Elbow extension control was achieved by detecting the position of the arm in space and determining the magnitude of the gravitational moment acting to oppose extension. An accelerometer was used as the command control source, and this sensor was placed over the ulna near the elbow joint to detect static (gravitational) acceleration, and therefore the gravitational moment acting about the elbow joint. This value determined the level of electrical stimulation required to activate the triceps muscles to full extension against these forces. Combined FNS control of elbow extension and hand grasp was implemented in two quadriplegic subjects. Both subjects were able to reach and grasp objects at locations in space which were unattainable without triceps activation

Grill W.M. and Kirsch R.F. (2000) Neuroprosthetic applications of electrical stimulation. *Assist. Technol.* 12, 6-20.

Abstract: Neural prostheses are a developing technology that use electrical activation of the nervous system to restore function to individuals with neurological impairment. Neural prostheses function by electrical initiation of action potentials in nerve fibers that carry the signal to an endpoint where chemical neurotransmitters are released, either to affect an end organ or another neuron. Thus, in principle, any end organ under neural control is a candidate for neural prosthetic control. Applications have included stimulation in both the sensory and motor systems and

range in scope from experimental trials with single individuals to commercially available devices. Outcomes of motor system neural prostheses include restoration of hand grasp and release in quadriplegia, restoration of standing and stepping in paraplegia, restoration of bladder function (continence, micturition) following spinal cord injury, and electrophrenic respiration in high-level quadriplegia. Neural prostheses restore function and provide greater independence to individuals with disability

Guest R.S., Klose K.J., Needham-Shropshire B.M., and Jacobs P.L. (1997) Evaluation of a training program for persons with SCI paraplegia using the Parastep 1 ambulation system: part 4. Effect on physical self- concept and depression. *Arch. Phys. Med. Rehabil.* 78, 804-807.

Abstract: OBJECTIVE: To determine whether persons with spinal cord injury (SCI) paraplegia who participated in an electrical stimulation walking program experienced changes in measures of physical self-concept and depression. DESIGN: Before-after trial. SETTING: Human SCI applied research laboratory. PARTICIPANTS: Volunteer sample of 12 men and 3 women with SCI paraplegia, mean age 28.75 +/- 6.6yrs and mean duration of injury 3.8 +/- 3.2yrs. INTERVENTION: Thirty-two FNS ambulation training sessions using a commercially available system (Parastep 1). The hybrid system consists of a microprocessor-controlled stimulator and a modified walking frame with finger-operated switches that permit the user to control the stimulation parameters and activate the stepping. OUTCOME MEASURES: The Tennessee Self-Concept Scale (TSCS) and the Beck Depression Inventory (BDI) were administered before and after training. Only the Physical Self subscale of the TSCS was analyzed. After training, individual interviews were performed to assess participants' subjective reactions to the training program. RESULTS: A repeated measures analysis of variance indicated that desired directional and statistically significant changes occurred on the Physical Self subscale of the TSCS ($F(1,14) = 8.54, p < .011$) and on the BDI ($F(1,14) = 5.42, p < .035$). CONCLUSIONS: Subsequent to the ambulation training program there were statistically significant increases in physical self-concept scores and decreases in depression scores

Gurney A.B., Robergs R.A., Aisenbrey J., Cordova J.C., and McClanahan L. (1998) Detraining from total body exercise ergometry in individuals with spinal cord injury. *Spinal Cord.* 36, 782-789.

Abstract: This study was designed to investigate the effects of detraining that occurred during an 8 week period of muscular inactivity following a 12 week training program of artificial computerized functional electrical stimulation cycle ergometry (CFES LE) and arm ergometry. Six spinal cord injured male individuals were followed through an 8 week detraining period that was preceded by a 12 week exercise program including CFES LE and arm ergometry. Maximal graded exercise tests were completed and measurements of peak oxygen consumption (VO_2), heart rate (HR), ventilation (VE) workload, and creatine kinase were taken. Testing occurred at initial training (0T), after 12 weeks of training (12T), and after 8 weeks of detraining (DT). After the training program, peak VO_2 increased significantly from 0.562 +/- 0.126 (0T) to 1.021 +/- 0.247 l/min (12T, $P < 0.05$). After DT, peak VO_2 decreased to 0.791 +/- 0.216 l/min, which was lower than 12T ($P < 0.05$), yet higher than 0T ($P < 0.05$). After DT, peak workload had decreased from 0.675 +/- 0.203 (12T) to 0.32 +/- 0.203 kp ($P < 0.05$), which was not different than 0T. Creatine kinase levels were significantly lower both at 12T and DT compared to 0T ($P < 0.05$). In addition, this training program induced linear increases in both VO_2 and HR with

workload, which were retained after DT. These increases did not reach statistical significance. however. No apparent relationship existed between these values at baseline. There were no significant differences in submaximal or peak HR of VE between the three testing periods. The results indicate that both peripheral muscular adaptations and central distribution adaptations in SCI individuals are partially maintained following 8 weeks of DT from CFES LE and arm ergometry

Hachen H.J. (1978) Psychological, neurophysiological and therapeutic aspects of chronic pain: preliminary results with transcutaneous electrical stimulation [proceedings]. *Paraplegia* 15, 353-367.

Abstract: Psychological, neurophysiological and therapeutic aspects of chronic pain are reviewed in the light of recent progress achieved in the respective fields (alpha-feedback training; gate-control theory; transcutaneous electrostimulation; percutaneous stereotaxic radio- frequency cordotomy). The efficacy of selective large fibre stimulation has been evaluated in 39 spinal cord injury patients suffering from chronic intractable pain of 6 to 35 months's duration. Stimulation was applied daily for 6 consecutive hours. Pain relief was assessed by verbal and visual analogue scales and McGill's pain questionnaire. After 1 week, total or almost total relief of pain was reported by 49 per cent, moderate relief by 41 per cent and no improvement by 10 per cent of the cases; at a 3-months follow-up the figures were 28 per cent, 49 per cent and 23 per cent respectively

Haleem A.S., Boehm F., Legatt A.D., Kantrowitz A., Stone B., and Melman A. (1993) Sacral root stimulation for controlled micturition: prevention of detrusor-external sphincter dyssynergia by intraoperative identification and selective section of sacral nerve branches. *J. Urol.* 149, 1607-1612.

Abstract: Electrical stimulation of the S2 nerve root can be used to produce detrusor contraction and voiding in patients with spinal cord injury, but concurrent stimulation of the external urethral sphincter causes detrusor-sphincter dyssynergia. This has been managed with a second surgical procedure, peripheral transection of the pudendal nerve. In this study, performed in dogs after spinal cord transection, laminectomy and ventral foraminotomy permitted tracing of the S2 root into the pelvis, where its branches were identified by electrical stimulation and urodynamic recording. The pudendal (somatic) branch was sectioned; the autonomic branch innervating the detrusor was preserved. Electrical stimulation of the proximal S2 root then produced detrusor contraction without contraction of the external urethral sphincter. This approach, which requires a single operation and spares pudendal nerve functions mediated by nerve roots other than S2, may enable a neurostimulator to provide effective voiding, without detrusor-external sphincter dyssynergia, in man

Hambrecht F.T., Reswick J.B. (1977) *Functional electrical stimulation: applications in neural prostheses*. New York, Marcel Dekker, Inc.

Handa Y., Hoshimiya N. (1987) Functional electrical stimulation for the control of the upper extremities. *Med Prog Through Technol* 12, 51-63.

Handa Y. (1992) Functional electrical stimulation (FES) systems for restoration of motor function of paralyzed muscles. *Front Med Biol Eng* 4, 241-255.

Handa Y. (1997) Current topics in clinical FES in Japan. *J. Electromyogr. Kinesiol.* 7, 269-274.

Abstract: This paper reviews recent topics of clinical application of functional electrical stimulation (FES) for the paralyzed extremities in Japan. Transcutaneous and percutaneous FES systems have been clinically used in Japan. Candidates of extremity FES are mostly stroke and spinal cord injury patients. By using percutaneous FES system, all of the joints of the upper extremity including the shoulder have been controlled for activities of daily living in the hemiplegic patient. Simultaneous FES control of the hand and wrist and the bilateral hands have also been achieved in C5 and C6 quadriplegics, respectively. Hybrid FES systems using percutaneous and surface electrodes, where FES is used in combination with orthoses, have been applied to the paraplegics because they are highly practical for assisting their locomotive activities. Percutaneous FES have been also provided the amyotrophic lateral sclerosis patients with standing up motion. A total implant FES system with 16 output channels is currently developing as a next generation FES system

Hartkopp A., Murphy R.J., Mohr T., Kjaer M., and Biering-Sorensen F. (1998) Bone fracture during electrical stimulation of the quadriceps in a spinal cord injured subject. *Arch. Phys. Med. Rehabil.* 79, 1133-1136.

Abstract: We report a fracture through the lateral femoral condyle of a paraplegic subject caused by electrical stimulation (ES). The subject was a 50-year-old man who 4 years earlier had sustained a complete spinal cord injury (SCI) at level T6. The fracture occurred during ES-induced measurement of maximal isometric torque of the quadriceps with the knee flexed at an angle of 90 degrees. ES was delivered through surface electrodes with biphasic square wave pulses from a constant current stimulator. The torque was calculated to be 93Nm, corresponding to 20.8kg at the ankle. The regional bone mineral density of the entire lower extremities was .83g/cm², corresponding to 60% of sex- and age- matched able-bodied reference values. Several factors are suspected to have contributed to the fracture: maximal ES in combination with a muscle spasm, severe osteoporosis, increased muscular strength induced by regular ES cycling (twice a week), and testing position with the knee locked in 90 degrees flexion. The risk of fracture as well as various precautions are discussed and should be taken into consideration in future studies

Hjeltnes N., Lannem A. (1990) Functional neuromuscular stimulation in 4 patients with complete paraplegia. *Paraplegia* 28, 235-243.

Hooker S.P., Figoni S.F., Rodgers M.M., Glaser R.M., Mathews T., Suryaprasad A.G., and Gupta S.C. (1992) Physiologic effects of electrical stimulation leg cycle exercise training in spinal cord injured persons. *Arch. Phys. Med. Rehabil.* 73, 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 less than or equal to .05) higher posttraining peak PO (+45%), oxygen uptake ($[O_2]$, + 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 ($[a-vO_2diff]$, + 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. (ABSTRACT TRUNCATED AT 250 WORDS)

Hooker S.P., Scremin A.M., Mutton D.L., Kunkel C.F., and Cagle G. (1995) Peak and submaximal physiologic responses following electrical stimulation leg cycle ergometer training. *J. Rehabil. Res. Dev.* 32, 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 \pm SD = 38.1 \pm 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 \pm 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 ($P < \text{or} = 0.05$) increase was observed for peak VO_2 ; (+10%, 1.29 \pm 0.30 to 1.42 \pm 0.39 $l \cdot \text{min}^{-1}$). No other statistically significant differences were noted for any other peak variable (VCO_2 , $VO_2 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, VE, WR, HR, RER) pre- to posttraining. During submaximal NMES leg cycle testing, a significant decrease was noted for RER (-9.2%, 1.19 \pm 0.14 to 1.08 \pm 0.09). No other submaximal variable ($VO_2 \text{ l} \cdot \text{min}^{-1}$, $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, VCO_2 , HR, VE) showed significant changes as a result of the training. Although the improvement in peak VO_2 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

Hopman M.T., Dueck C., Monroe M., Philips W.T., and Skinner J.S. (1998) Limits to maximal performance in individuals with spinal cord injury. *Int. J. Sports Med.* 19, 98-103.

Abstract: The purpose of this study was to examine the effect of four conditions that might improve oxygen transport and/or utilization during maximal exercise performance in individuals with spinal cord injury (SCI). Five males with tetraplegia (TP) and four males with paraplegia (PR) performed maximal arm cranking exercise in the following positions: 1) sitting; 2) supine; and 3) sitting with the addition of a) anti-gravity suit (anit-G), b) elastic stockings and abdominal binder, and c) functional electrical stimulation (FES) of the paralysed leg muscles. Peak power output (PO peak), peak oxygen uptake (VO_{2peak}), peak heart rate (HR peak) and maximal systolic blood pressure were significantly lower in TP compared to PR for all conditions. A significant decrease in HR peak for PR, and a significant increase in VO_{2peak}/kg for TP was seen during the supine compared to sitting condition. Respiratory exchange ratio (R) decreased significantly during the FES compared to

the sitting condition in TP. No other changes were observed for any of the other conditions in either group. Improvements in central circulation previously reported during submaximal exercise for these four conditions did not result in a concomitant rise in maximal exercise performance. The results of this study suggest that the limitation in VO₂peak for individuals with SCI is located peripherally (small active muscle mass) rather than centrally (heart or lungs)

Hopman M.T., Monroe M., Dueck C., Phillips W.T., and Skinner J.S. (1998) Blood redistribution and circulatory responses to submaximal arm exercise in persons with spinal cord injury. *Scand. J. Rehabil. Med.* 30, 167-174.

Abstract: The purpose of this study was to evaluate responses to submaximal arm exercise (20%, 40%, and 60% of peak power output) using four conditions to support the circulatory redistribution in persons with spinal cord injury (SCI). Five males with tetraplegia (TP) and four males with paraplegia (PR) exercised 1) sitting, 2) supine, and 3) sitting with the addition of a) an anti-gravity suit (anti-G), b) elastic stockings and abdominal binder, and c) functional electrical stimulation of the leg muscles.

Compared to sitting, the following significant changes were observed: in the supine position, heart rate (HR) decreased (PR: 104 vs 118 b/min, TP: 76 vs 92 b/min) and stroke volume (SV) increased (PR: 132 vs 116 ml, TP: 96 vs 83 ml). The anti-G suit induced a decrease in heart rate (PR: 104 vs 118 b/min, TP: 87 vs 92 b/min) and a decrease in oxygen uptake (VO₂) in PR. Stockings only affected TP, i.e. a decrease in heart rate with 5 b/min and an increase in stroke volume with 13 ml/beat.

Functional electrical stimulation produced an increase in VO₂ (PR: 1.00 vs 0.95 l/min, TP: 0.68 vs 0.53 l/min) and a rise in stroke volume in TP. Results indicate that the methods employed to support the circulatory redistribution have different working mechanisms and, in addition, that the effects are different for TP and PR probably because of differences in active muscle mass, sympathetic impairment and blood pressure values

Hoshimiya N., Naito A., Yajima M., and Handa Y. (1989) A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: a respiration-controlled system for multijoint upper extremity. *IEEE Trans. Biomed. Eng* 36, 754-760.

Abstract: A multichannel functional electrical stimulation (FES) system for the restoration of quadriplegic upper extremity function is described. The system is composed of a personal computer NEC PC-8801mkII, peripheral electronic circuits, CRT display and respiratory sensors for volitional control by the patient, and percutaneous electrodes. A C4 quadriplegic patient could drink canned tea by herself by using this FES system. Distinct features of the system are as follows: 1) Versatile volitional control was realized by controlling the memory allocation of the stored stimulation data by voluntary respiratory signals. 2) Sophisticated fine control of the fingers, wrists, and elbow was realized by creating the multichannel stimulation data from recorded myoelectric activities of normal subjects during movements of the upper limb

Hoshimiya N., Naito A., Yajima M., Handa Y. (1989) A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: a respiration-controlled system for multijoint upper extremity. *IEEE Trans Biomed Eng* 36, 754-760.

- Ijzerman M.J., Stoffers T., Groen F., Klatte M., Snoek G., Vorsteveld H., Nathan R., Hermans H. (1996) The NESS Handmaster orthosis: restoration of hand function in C5 and stroke patients by means of electrical stimulation. *J Rehab Sciences* 9, 86-89.
- Illis L.S. (1982) Rehabilitation following brain damage: some neurophysiological mechanisms. The effects of repetitive stimulation in recovery from damage to the central nervous system. *Int. Rehabil. Med.* 4, 178-184.
Abstract: There is a growing body of evidence that the central nervous system (CNS), even in the adult animal, is capable of adaptation and reorganization not only as a result of partial damage to the CNS but also in response to stimulation. Environmental stimulation produces changes including expansion of visual cortex, increases in dendritic branching, glia and cholinesterase. Environmental stimulation also produces behavioural changes. Experimental electrical stimulation produces changes in synapse size, synaptic vesicle change, dendritic branching and changes in synaptic transmission. In man, repetitive electrical stimulation via epidural electrodes increases plasma levels of norepinephrine, epinephrine, and dopamine, and CSF levels of norepinephrine. Repetitive electrical stimulation in man dates back to 1967 and has been used for the control of pain, to improve spasticity, bladder control, motor deficit and the autonomic hyperreflexia of spinal cord injury. In addition, improvement has been reported in epilepsy, cerebral palsy, torticollis and peripheral vascular diseases. The best controlled studies are in multiple sclerosis and peripheral vascular disease, and these results will be presented in more detail
- Ingram R.R., Suman R.K., Freeman P.A. (1989) Lower limb fractures in the chronic spinal cord injured patient. *Paraplegia* 27, 133-139.
- Ishigooka M., Ishii N., Hashimoto T., Suzuki Y., Adachi M., Nakada T., Saito C., Ichie M., and Handa Y. (1992) Electrical stimulation of pelvic floor musculature by percutaneous implantable electrodes: a case report. *Int. Urol. Nephrol.* 24, 277-282.
Abstract: A forty-year-old man with reflex urinary incontinence due to spinal cord injury was treated with electrical stimulation of the pelvic floor musculature. In this case we employed percutaneous implantable electrodes and an external pulse regulator. After 4 weeks of stimulation incontinence was improved and urodynamically maximum cystometric capacity increased from 220 ml to 350 ml. Our method is easy and not invasive. This technique can be an alternative for the electrical stimulation for urinary incontinence
- Ishigooka M., Hashimoto T., Hayami S., Suzuki Y., Nakada T., and Handa Y. (1996) Electrical pelvic floor stimulation: a possible alternative treatment for reflex urinary incontinence in patients with spinal cord injury. *Spinal Cord.* 34, 411-415.
Abstract: The present study demonstrates the clinical experience of pelvic floor stimulation using percutaneous implantable electrodes and implantable electrical stimulator for the treatment of reflex urinary incontinence in patients with spinal cord injury. Pelvic floor stimulation was carried out on six paraplegic patients who had urinary incontinence from an overactive bladder. After the percutaneous implantation of a pair of electrodes, chronic stimulation was carried out by employing an implanted receiver or an external pulse regulator. Within 4 to 16 weeks of electrical stimulation urinary incontinence was improved in four of the six patients. In two of these six patients, incontinence was completely abolished subjectively. Urodynamic investigations demonstrated an increased volume at the first unstable contraction ($P < 0.01$) in all of the patients. Inhibition of detrusor overactivity was obtained from this

procedure. The stimulation effect appeared to be constant during chronic stimulation. This new procedure probably provides a stable and reliable stimulation effect for long term treatment, and may be an alternative treatment for previous external electrical pelvic floor stimulation

Jacobs P.L., Nash M.S., Klose K.J., Guest R.S., Needham-Shropshire B.M., and Green B.A. (1997) Evaluation of a training program for persons with SCI paraplegia using the Parastep 1 ambulation system: part 2. Effects on physiological responses to peak arm ergometry. *Arch. Phys. Med. Rehabil.* 78, 794-798.
Abstract: OBJECTIVE: To examine the task-nonspecific effects of functional neuromuscular stimulation (FNS)-assisted ambulation training on the physiological responses of persons with paraplegia to upper extremity exercise challenge. DESIGN: Before-after trial. SETTING: Human spinal cord injury (SCI) applied research laboratory. PARTICIPANTS: Twelve men and three women with motor- and sensory-complete thoracic-level SCI (T4- T11), mean age 28.2 +/- 6.8yrs (range, 21.1 to 45.2yrs), mean injury duration 3.7 +/- 3.0yrs (range, 7 to 8.8yrs). INTERVENTION: Thirty-two sessions of FNS ambulation training using a commercial six-channel system (Parastep 1). This system is composed of a microprocessor-controlled electrical stimulation unit and a walking frame outfitted with finger switches that allow the user to independently control the system and stimulation parameters. OUTCOME MEASURES: Peak and subpeak physiological responses to arm ergometry testing and upper extremity strength measures, obtained before and after the FNS ambulation training. RESULTS: Statistically significant increases in peak values for time to fatigue, peak power output, and peak VO₂ (all $p < .001$). Heart rate was significantly lower throughout subpeak levels of arm ergometry after the ambulation training ($p \# .05$). Values of upper extremity strength were not significantly altered after training. CONCLUSIONS: FNS ambulation by persons with SCI paraplegia results in task-nonspecific training adaptations. Central cardiovascular adaptations were indicated as the primary source of these beneficial alterations in exercise responses

Jaeger R.J. (1986) Design and simulation of closed-loop electrical stimulation orthoses for restoration of quiet standing in paraplegia. *J. Biomech.* 19, 825-835.
Abstract: Simulation models of quiet standing have been developed to study the potential use of closed-loop stimulation orthoses in mid-thoracic spinal cord injury. The first model (static) consists of a multi-link inverted pendulum. The second model (dynamic) consists of a single-link inverted pendulum, with electrically stimulated muscles providing balancing activation at the ankle joint and stabilization of the knee and hip joints. The initial simulations have shown that it may be possible to restore quiet standing in paraplegic individuals within certain limits subject to biomechanical constraints and to the available torque produced by the stimulated muscle

Jaeger R.J., Yarkony G.M., Roth E.J., and Lovell L. (1990) Estimating the user population of a simple electrical stimulation system for standing. *Paraplegia* 28, 505-511.
Abstract: Many laboratory demonstrations have been reported on standing or walking with the aid of electrical stimulation. These demonstrations have typically been in small numbers of selected spinal cord injured individuals. The extent to which this technology might ultimately be applicable to the spinal cord injured population at large is not presently known. This study reports estimates of the size of the potential user population of a specific surface electrical stimulation device and

protocol. The medical records were reviewed of 192 patients with traumatic thoracic, lumbar, or sacral spinal cord injury resulting in paraplegia. Based on the inclusionary criteria, between 20 and 48 patients (10.4% and 25%) of this sample population could be considered eligible for this surface stimulation protocol. As approximately 45% of the USA population of spinal cord injured individuals have paraplegia, the results suggest that between 4.7% and 11.25% of all spinal cord injured persons in the USA might be potential users of this particular electrical stimulation technology

Jaeger R.J., Turba R.M., Yarkony G.M., and Roth E.J. (1993) Cough in spinal cord injured patients: comparison of three methods to produce cough. *Arch. Phys. Med. Rehabil.* 74, 1358-1361.

Abstract: Pulmonary complications are the major causes of morbidity and mortality for persons with cervical spinal cord injury. Diminished ability to cough constitutes a major contribution to the high incidence of pulmonary morbidity in this population. This article reports preliminary results for a new technique for providing assisted cough in this population. In this study, efficacy of cough (as measured by peak expiratory flow rate) was measured under three conditions: volitionally with no assistance, with manual assist of a therapist, and with electrical stimulation of abdominal muscles. Coughs produced by electrical stimulation were approximately as effective as manually assisted coughs. The results suggest this technique is worthy of more detailed study and may be a potentially effective new modality for assisting spinal cord injured persons to clear their airways

Jaeger R.J., Langbein E.W., Kralj A.R. (1994) Augmenting cough by FES in tetraplegia: a comparison of results at three clinical centers. *Basic and Applied Myology* 4, 195-200.

Jaeger R.J. (1996) Principles Underlying Functional Electrical Stimulation Techniques. *J Spinal Cord Med* 19, 93-96.

Kameyama J., Handa Y., Hoshimiya N., and Sakurai M. (1999) Restoration of shoulder movement in quadriplegic and hemiplegic patients by functional electrical stimulation using percutaneous multiple electrodes. *Tohoku J. Exp. Med.* 187, 329-337.

Abstract: The purpose of this study is to restore the motion of the paralyzed shoulder caused by upper motor neuron disorders using functional electrical stimulation (FES). Percutaneous wire electrodes were implanted into twelve muscles of the shoulder in six patients with stroke or cervical spinal cord injury. The motion of the paralyzed shoulder was controlled by a portable FES computer system, with the three standard stimulation patterns for restoring motion of 90 degrees flexion to 90 degrees horizontal abduction, 90 degrees flexion to 20 degrees horizontal adduction, and 90 degrees abduction to 90 degrees horizontal adduction. Shoulder movements were repeatedly controlled according to the created stimulation patterns in five of the patients. The two dimensional motion analyzer also confirmed shoulder control over a satisfactorily broad range of excursion. One hemiplegic patient, who was a signboard painter, had his paretic left upper extremity improved by FES, and he drew a large picture on a board with his normal right hand and, with his affected left arm against the wall, to support his trunk. This may be a world first case of producing shoulder motion through FES

Katz R.T., Green D., Sullivan T., Yarkony G. (1987) FES to enhance systemic fibrinolytic activity in spinal cord patients. *Arch Phys Med Rehabil* 68, 423-426.

Keith M.W., Peckham P.H., Thrope G.B., Stroh K.C., Smith B., Buckett J.R., Kilgore K., Jatich J.W. (1989) Implantable functional neuromuscular stimulation in the tetraplegic hand. *J Hand Surg* 14A, 524-530.

Keith M.W., Lacey S. (1991) Surgical rehabilitation of the tetraplegic upper extremity. *J Neurol Rehabil* 5, 75-87.

Keith M.W., Kilgore K.L., Peckham P.H., Wuolle K.S., Creasey G., and Lemay M. (1996) Tendon transfers and functional electrical stimulation for restoration of hand function in spinal cord injury. *J. Hand Surg. [Am.]* 21, 89-99.

Abstract: Spinal cord injury at the C5 and C6 level results in loss of hand function. Electrical stimulation of paralyzed muscles is one approach that has demonstrated significant capacity for restoring grasp and release function. One potential limitation of this approach is that key muscles for stimulation may have lower motor neuron damage, rendering the muscles unexcitable. We have used surgical modification of the biomechanics of the hand to overcome this limitation. Tendon transfer of paralyzed but lower motor neuron intact muscles can compensate for potential function lost owing to muscles with lower motor neuron damage. Such procedures have been performed to provide finger extension, thumb extension, finger flexion, and wrist extension. Additional surgical procedures have been performed to enhance the function provided with electrical stimulation. These are side-to-side synchronization of the finger flexor and extensor tendons, the flexor digitorum superficialis Zancolli-lasso procedure, and thumb interphalangeal joint arthrodesis. These procedures have been performed in 11 patients with C5 and C6 level spinal injuries and functional electrical stimulation neuroprostheses. In these patients, 41 different functional electrical stimulation-related procedures were performed and 38 gave the desired result after surgery. One procedure resulted in no increase or decrease in function or muscle output, and two procedures resulted in a decrease in muscle force or joint range of motion. The issues that must be considered in performing functional electrical stimulation-related tendon transfers are discussed

Kern H., Hofer C., Strohhofer M., Mayr W., Richter W., and Stohr H. (1999) Standing up with denervated muscles in humans using functional electrical stimulation. *Artif. Organs* 23, 447-452.

Abstract: The use of electrical stimulation for denervated muscles is still considered to be a controversial issue by many rehabilitation facilities and medical professionals because prior clinical experience has shown that treating denervated muscle tissue using exponential current over a long time period constitutes an impossible task. Despite this fact, we managed to evoke tetanic contractions in denervated muscle using a long duration stimulation with anatomically shaped electrodes and sufficiently high amplitudes. The pulse amplitudes, which were being used for this purpose, exceeded by far the MED-GV and EC regulations (300 mJ/impulse). For this reason, an application has recently been submitted to have the EC regulations changed accordingly. It takes a tetanic contraction to achieve the desired muscle fiber tension, constituting a hypertrophic stimulus. It is also an appropriate means of exercise, which is capable of creating the metabolic and structural conditions needed (e.g, increased mitochondrial volume and capillary density) to obtain satisfactory muscle performance. With patients suffering from a complete spinal cord injury at level D12/L1, having motor and sensory loss in both lower extremities, we were able to train denervated muscle using long- duration stimulation, evoking single muscle

contractions at first, soon followed by tetanic contractions against gravity. To increase the efficacy of this functional electrical stimulation (FES) strengthening program, we used ankle weights. With daily FES training over a period of 1-2 years, denervated muscle was exercised until it produced torques between 16 and 38 Nm in the m. quadriceps. With that muscle force, it is possible to stand up from a sitting position in parallel bars. Our results show that denervated muscle in humans is indeed trainable and can perform functional activities with FES. Furthermore, this method of stimulation can assist in decubitus prevention and significantly improve the mobility of paraplegics

Kessler K.M., Pina I., Green B.A., Burnett B., Laighold M., Bilsker M., Palomo A.R., Myerburg R. (1986) Cardiovascular findings in quadriplegic and paraplegic patients and in normal subjects. *Am J Cardiol* 58, 525-530.

King M.L., Lichtman S.W., Pellicone J.T., Close R.J., and Lisanti P. (1994) Exertional hypotension in spinal cord injury. *Chest* 106, 1166-1171.

Abstract: STUDY OBJECTIVE: To assess blood pressure (BP) response to continuous maximal arm ergometry in patients with spinal cord injury (SCI). DESIGN: Cross-sectional analysis of data collected for a prospective study of functional electrical stimulation in patients with SCI. SETTING: Short-term rehabilitation hospital. PARTICIPANTS: Twenty individuals with SCI; 4 cervical (C6 to C8), 10 high thoracic (T1 to T6), and 6 low thoracic (T7 to T12). MEASUREMENTS AND RESULTS: Each subject performed continuous maximal arm ergometry with expired gas analysis. Blood pressure was measured using a technician-assisted protocol. The BP at maximal exercise was compared with the highest submaximal BP reached during the test (Δ BP = final BP minus highest submaximal BP). All 20 subjects had a negative Δ BP (mean \pm SD; -22.8 ± 12.1 mm Hg) for mean BP and 19 of 20 had a negative Δ BP (-25.8 ± 14.4 mm Hg) for systolic BP. The Δ BP was not significantly related to maximum exercise parameters, resting BP, or level of lesion. Four able-bodied subjects and six wheelchair-bound individuals without SCI showed no exertional hypotension. Repeated testing on the four able-bodied subjects showed excellent reproducibility for mean BP (coefficient of variation [CV] = 3.6 percent; $r = 0.98$; $p < 0.01$) and systolic BP (CV = 2.2 percent; $r = 0.99$; $p < 0.01$) using this protocol. CONCLUSIONS: These data describe, for the first time to our knowledge, that exertional hypotension is present in all individuals with SCI during continuous arm ergometry. Further studies are needed to clarify the mechanisms responsible for this phenomenon and to evaluate the long-term consequences for individuals with SCI

Ko H.Y. and Kim K.T. (1997) Treatment of external urethral sphincter hypertonicity by pudendal nerve block using phenol solution in patients with spinal cord injury. *Spinal Cord*. 35, 690-693.

Abstract: We report our experience utilizing the technique of phenol block of the pudendal nerve in the treatment of voiding dysfunction due to hypertonicity of the external urethral sphincter. We have performed 13 pudendal nerve blocks using a 7% phenol solution in seven patients with spinal cord injury who could not obtain relaxation of the external urethral sphincter with a large postvoid urine residual (150 ml to 600 ml) despite large doses of antispasticity drugs and intermittent catheterisations over three weeks. These drugs were discontinued at least 48 hours before this procedure. The efficacy of the pudendal nerve block could also be tested by the ease of facilitating micturition during or just after the block and measuring the

amount of postvoid residual urine and intravesical leak pressure. A pudendal nerve block was produced by injecting a 7% phenol solution medial to the ischial tuberosity having specifically localized the nerve by electrical stimulation. This procedure improved the voiding pattern dramatically, leading to a full stream of urine and a remarkable decrease of postvoid residual volume and intravesical leak pressure. The mean difference of the postvoid residual volume and the intravesical leak pressure before and after pudendal nerve block was 255.7 ml and 57.5 cmH₂O, respectively. We conclude that pudendal nerve block with a phenol solution as a treatment of external urethral sphincter hypertonicity was effective, easy to perform, and had no complication. This treatment should be considered as a possible alternative to more invasive surgical procedures

Kohlmeyer K.M., Hill J.P., Yarkony G.M., and Jaeger R.J. (1996) Electrical stimulation and biofeedback effect on recovery of tenodesis grasp: a controlled study. *Arch. Phys. Med. Rehabil.* 77, 702-706.

Abstract: OBJECTIVE: Evaluate the effectiveness of electrical stimulation and biofeedback on the recovery of tenodesis grasp in tetraplegic individuals during the initial phase of acute rehabilitation. DESIGN: A 2 x 2 block design was used with subjects randomized to treatment groups. Forty-five subjects completed the study. SETTING: Inpatient occupational therapy department. SUBJECTS: Inpatients with tetraplegia, first admission for rehabilitation after an acute spinal cord injury. INTERVENTIONS: The four treatment groups were: conventional treatment, electrical stimulation, biofeedback, and combined electrical stimulation and biofeedback. The treatment period was between 5 and 6 weeks. MAIN OUTCOME MEASURES: Manual muscle testing and scoring of activities of daily living performance by a blinded evaluator. RESULTS: All four treatment groups showed improvements. No treatment group was superior to the others. CONCLUSIONS: Biofeedback and electrical stimulation alone or in combination offer no advantages over conventional rehabilitation treatment of wrist extensors in tetraplegic patients after spinal cord injury

Krajl A., Bajd T., Turk R., and Benko H. (1986) Posture switching for prolonging functional electrical stimulation standing in paraplegic patients. *Paraplegia* 24, 221-230.

Abstract: The presently employed posture for Functional Electrical Stimulation (FES) assisted standing in spinal cord injury (SCI) patients utilises the active locking of knee joints by tetanically stimulating the quadriceps muscle. The hip joints are in hyperextension and the ankle joints remain free. The upper limbs are used for balancing. This posture requires minimal corrective forces exerted by the hands, the weight is transferred across the legs, while very limited forward- backward sway is permitted. Knee jack-knifing may occur in the instance when the gravity knee bending moment exceeds the moment generated by the quadriceps muscle. Because of these effects and fatiguing of the M. quadriceps the standing time is short, lasting from several minutes up to an hour, depending on the condition of the patient's muscles. Cyclical FES with a duty cycle of 10-20 seconds (on/off) fatigues muscle considerably less. The use of different postures for standing requiring activation of different muscles permits the application of cyclical FES. The cyclic FES results in prolonging standing times by a factor of two to five. Utilising this improvement some patients can stand for up to five hours at a time. This functional achievement is comparable to the standing time of a normal man. The incorporation of the principle of posture switching also prolongs standing in patients with weak

muscles, because of the possibility of cyclical coactivation of different synergistic muscle assemblies. It is shown that posture switching can be carried out automatically and that patients adapt quickly to it. In addition using co-contraction of two or three muscles with posture switching does further expand the range of suitable patients and improves standing with an increased permissible range of body sway. Also, the FES antigravity action obtained raises hopes for substantially improving FES induced reciprocal gait

Kralj A., Bajd T. (1989) *Functional electrical stimulation: standing and walking after spinal cord injury*. Boca Raton, CRC Press, Inc.

Kralj A., Bajd T., and Turk R. (1988) Enhancement of gait restoration in spinal injured patients by functional electrical stimulation. *Clin. Orthop.* 34-43.
Abstract: Functional electrical stimulation (FES) was applied in 50 spinal cord injury patients in an effort to restore standing and walking. All patients in the program with lesions from T4-T12 were able to stand by means of FES. Walking, utilizing a four-channel stimulator, was accomplished by 25 patients with lesions in the range from T4-T12. These 25 patients represent approximately 5% of all spinal cord injured patients treated in the authors' rehabilitation facility during this time period. After using the stimulation in a home environment for more than three months, the number of patients who continued to use the stimulation for walking declined, and 16 patients remained ambulatory. The discontinuance of FES was mainly because of the time required to put on and operate the FES system and difficulties adapting to a new home environment and living situation

Krause J.S., Sternberg M., Lottes S., Maides J. (1997) Mortality after spinal cord injury: an 11-year prospective study. *Arch Phys Med Rehabil* 78, 815-821.

Lanmuller H., Bijak M., Mayr W., Rafolt D., Sauermann S., and Thoma H. (1997) Useful applications and limits of battery powered implants in functional electrical stimulations. *Artif. Organs* 21, 210-212.
Abstract: Battery powered stimulation implants have been well-known for a long time as heart pacemakers. In the last few years, fully implantable stimulators have been used in the field of functional electrical stimulation (FES) for applications like dynamic cardiomyoplasty and electro-stimulated graciloplasty for fecal incontinence. The error rate of battery powered implants is significantly smaller than that for conventional stimulator systems, and the quality of life for the patients is increased because the need for an external power and control unit is eliminated. The use of battery powered implants is limited by the complexity of the stimulation control strategies and the battery capacity. Therefore, applications like the stimulation of lower extremities for walking, cochlea stimulation, or direct muscle stimulation cannot be supported. The improvement of implantable batteries, microcontrollers, and ultralow power products is ongoing. In the future, battery powered implants will also meet the requirements of complex applications. Systems for restoration of hand and breathing functions after spinal cord injury can be the next field of use for battery powered implants. For these purposes, we developed a battery powered multichannel implant with a sufficient life span for phrenic pacing. The problems during development and the limits of this system are described in this paper

Lee Y.H., Rah J.H., Park R.W., and Park C.I. (2001) The effect of early therapeutic electrical stimulation on bone mineral density in the paralyzed limbs of the rabbit.

Yonsei Med. J. 42, 194-198.

Abstract: The purpose of this animal experiment was to evaluate the changes of bone mineral density in paralyzed limbs, and to assess the effects of electrically stimulating muscle contraction upon bone mineral density (BMD) in paralyzed limbs during the four week period immediately following spinal cord injury (SCI). Ten rabbits were used for the study, spinal cords were totally transected at the T11 spine level. The paralyzed quadriceps femoris of one limb was contracted by electrical stimulation for 60-minutes daily, while the other side was not stimulated as a control. The BMD of each lower limb was measured by Dual Photon Absorptiometry before and four weeks after acute SCI. BMD of both limbs decreased in all rabbits four weeks after SCI. The decrease in BMD for stimulated and non-stimulated limbs was 6.130 +/- 3.212% and 9.098 +/- 3.831%, respectively during the four-week period after SCI. The BMD of stimulated limbs decreased significantly less than that of the non-stimulated limbs. Electrically induced muscular contraction reduced bone mineral loss in the paralyzed limb during the early stage of SCI in the rabbit

Leeds E.M., Klose K.J., Ganz W., Serafini A., and Green B.A. (1990) Bone mineral density after bicycle ergometry training. *Arch. Phys. Med. Rehabil.* 71, 207-209. Abstract: The effect of functional electrical stimulation (FES) cycle ergometry on bone mineral density (BMD) was investigated in six spinal cord injury (SCI) quadriplegic men. Each subject trained three days a week for six months on an FES cycle ergometer. Pretraining and posttraining BMD measurements of the proximal femur were performed using dual photon absorptiometry. Mean pretraining BMD (percent norm) for the femoral neck, Ward triangle, and trochanter were 66.65, 57.43, and 57.67, respectively. After six months of FES cycle ergometry, mean BMD measurements were 66.15, 57.07, and 55.13, respectively. There was no statistically significant difference between the pretraining and posttraining BMD measurements. All subjects were found to have osteoporotic proximal femurs when BMD was expressed as a percent of their age-matched controls. Bone mineral density measurements were subsequently performed on three additional men with SCI who had exercised for three years with the FES cycle ergometry modality. Their mean BMDs were not significantly different from the experimental group. This study demonstrated that six months of FES cycle ergometry did not produce an increase in BMD

Lenman A.J., Tulley F.M., Vrbova G., Dimitrijevic M.R., and Towle J.A. (1989) Muscle fatigue in some neurological disorders. *Muscle Nerve* 12, 938-942. Abstract: Fatigue of tibialis anterior (TA) was induced by repetitive electrical stimulation. Using this test, patients with upper motor neuron muscle weakness owing to multiple sclerosis (MS) and injuries to the spinal cord showed greater fatigability of their TA muscles, suggesting that the muscle fiber population changed toward that typical of fatigable motor units. During repetitive stimulation, in addition to the decrement in tension there was an increase in half-relaxation time of tetanic contractions at 40 Hz in both subjects and patients. The increase in half relaxation during repeated activity was greater in patients with MS and spinal cord injury than in healthy subjects, suggesting that the long-term inactivity affected the efficiency of the Ca²⁺ uptake mechanism of their muscle fibers. Thus long-term inactivity of patients with upper motoneuron dysfunction leads to increased fatigability of their muscles and exaggerates the slowing of muscle relaxation after prolonged exercise

Levine S.P., Kett R.L., Cederna P.S. (1990) Electrical muscle stimulation for pressure sore prevention: Tissue shape variation. *Arch Phys Med Rehabil* 71, 210-215.

Lin K.H., Lai Y.L., Wu H.D., Wang T.Q., and Wang Y.H. (1998) Effects of an abdominal binder and electrical stimulation on cough in patients with spinal cord injury. *J. Formos. Med. Assoc.* 97, 292-295.

Abstract: We explored the effect of an abdominal binder, with or without electrical stimulation, on peak expiratory flow rate (PEFR) in 12 paraplegics with complete thoracic cord (T2-T12) injury (mean age 36.0 +/- 1.5 yr) and 12 quadriplegics with complete cervical cord (C4-C8) injury (mean age 36.2 +/- 1.9 yr). The cough was assessed by measuring the PEFR during forceful expiration in a sitting position. The subjects underwent the following experimental maneuvers in a random order with a 10-minute interval between any two maneuvers: 1) voluntary coughing, 2) voluntary coughing with an abdominal binder, and 3) voluntary coughing with an abdominal binder and electrical stimulation. The electrical stimulator (50 Hz with 300 microseconds pulse width) was applied to the abdominal wall. Data were analyzed using multivariate analysis of variance for repeated measures. The abdominal binder did not significantly increase PEFR in either paraplegics or quadriplegics; the abdominal binder combined with electrical stimulation significantly increased PEFR by 15% in the paraplegics and 18% in the quadriplegics. These results indicate that electrical stimulation combined with an abdominal binder improves the cough ability in patients with cervical or thoracic spinal cord injury

Linder S.H. (1993) Functional electrical stimulation to enhance cough in quadriplegia. *Chest* 103, 166-169.

Abstract: Respiratory problems are a major cause of death in the acute and chronic phases of cervical spinal cord injury (CSCI); CSCI paralyzes the intercostal and abdominal muscles, reducing ability to cough and clear secretions. Impaired cough due to neuromuscular disorders can be assessed with the maximum expiratory pressure (MEP). This study consists of two experiments with CSCI patients. In the first, MEP measurements were recorded with the following maneuvers performed: (1) spontaneous cough attempts, (2) manually assisted cough, and (3) cough attempts with functional electrical stimulation (FES) applied to the abdominal wall. In the second, spontaneous cough attempts and cough attempts with a portable FES unit were recorded. These CSCI patients were found to have a greatly reduced MEP when they coughed spontaneously. Either FES-assisted or manually assisted coughing increased the MEP in all patients studied. By increasing the MEP, abdominal muscle FES could enhance cough in quadriplegics

Loeb G.E., Zamin C.J., Schulman J.H., Troyk P.R. (1991) Injectable microstimulator for functional electrical stimulation. *Med Biol Eng Comput* 29, NS13-19.

Long D.M. (1983) Stimulation of the peripheral nervous system for pain control. *Clin. Neurosurg.* 31, 323-343.

Abstract: Transcutaneous stimulation is a proven effective way to relieve pain. Its optimal use requires an accurate patient diagnosis. Treatment of pain as a symptom only is likely to fail. There must be a careful psychosocial evaluation, for the majority of patients who come to the doctor complaining of pain have major psychological, social, or behavioral factors that are most important in the genesis of the complaint. Drug abuse must be corrected. Related symptoms, such as anxiety and depression, must be treated. Then, a thorough trail of transcutaneous stimulation is mandatory. A

desultory use will undoubtedly lead to failure. This trial must begin with patient education by experienced personnel. Then the electrodes must be properly applied, and there must be a regular follow-up of stimulation to be certain the patient is utilizing it correctly. The patient must be supported through an adequate trial which should extend over 2-4 weeks before purchase of the device is contemplated. Furthermore, all related nursing and physician personnel must be educated in the proper use of the technique. The uninformed professional who denigrates the therapy is a very effective deterrent to appropriate use. In this situation, transcutaneous electrical stimulation will be of great value in the treatment of acute musculoskeletal injury and acute postoperative pain. It will be effective in the treatment of peripheral nerve injury pain, chronic musculoskeletal abnormalities, chronic pain in the patient who has undergone multiple operations upon the low back and neck, visceral pain, some of the reflex sympathetic dystrophies, and postherpetic neuralgia. Stimulation will not help a complaint which is psychosomatic in origin. It will not influence drug addiction. It is not likely to be useful in any situation where secondary gain is important. The metabolic neuropathies, pain of spinal cord injury, and pain from cerebrovascular accident will not respond frequently enough to warrant more than hopeful trials. The technique is inexpensive, places the patient in control of his own pain, and has no known serious side effects. Its widespread application awaits the development of reasonable systems to provide this service to physicians and patients. Stimulation-induced analgesia deserves a place in the armamentarium of every physician dealing with the complaint of pain

Marsolais E.B., Kobetic R. (1987) Functional electrical stimulation for walking in paraplegia. *J Bone & Joint Surg* 69A, 728-733.

Matthews J.M., Wheeler G.D., Burnham R.S., Malone L.A., and Steadward R.D. (1997) The effects of surface anaesthesia on the autonomic dysreflexia response during functional electrical stimulation. *Spinal Cord*. 35, 647-651.
Abstract: Recently, increases in blood pressure (BP) and concomitant bradycardia, suggestive of autonomic dysreflexia (AD), have been documented during functional electrical stimulation (FES) in individuals with a high spinal cord injury (SCI). If uncontrolled, this response could preclude the safe use of FES among such individuals. FES induced pain is partly related to stimulation of skin nociceptors. Therefore, measures to reduce skin sensitivity may reduce the risk of AD during FES. The purpose of this study was to determine if topical anaesthetic applied over the site of electrical stimulation could minimize the AD cardiovascular and hormonal responses to FES in individuals with SCI above the T6 level. Seven subjects with a SCI above T6 received FES to the quadriceps muscle of each leg under two conditions on two different testing days. The two treatment conditions, topical anaesthetic and placebo creams, were double blinded and randomized. The cream was administered to an area the size of the electrode (10 x 10 cm) 1 h prior to stimulation. Stimulation began at 0 mAmps and increased by 16 mAmps every 2 min until an intensity of 160 mAmps was achieved. HR and BP were measured at each stimulation intensity level. Catecholamines were analyzed three times during the stimulation protocol (pre, mid and post stimulation intensities). At the end of the stimulation protocol, FES induced isometric quadriceps contraction force at 160 mAmps intensity was measured using a hand held dynamometer. As FES stimulation intensity increased, significant rises in systolic and diastolic BP were seen, with a concomitant progressive drop in HR. The AD response to stimulation was not significantly different between the topical anaesthetic and placebo

conditions. Serum catecholamine (epinephrine and norepinephrine) levels tended to rise with increasing FES intensity levels but did not reach statistical significance. The two treatment conditions did not significantly affect serum catecholamine levels or FES-induced quadriceps contraction force. In summary, FES application to the quadriceps muscle in high level SCI subjects resulted in significant increases in BP, decreases in HR (AD- like response), a trend towards elevations in catecholamine levels, and no difference in quadriceps muscular strength. However, these responses were unaffected by the use of topical anaesthetic cream on the skin at the stimulation site. This suggests that other mechanisms than skin nociception are operative in FES-induced AD

McCagg C. (1986) Postoperative management and acute rehabilitation of patients with spinal cord injuries. *Orthop. Clin. North Am.* 17, 171-182.

Abstract: The mortality and morbidity rates of patients with spinal cord injury have decreased greatly. Prior to World War II, few patients survived their acute injuries. Now even severely involved respiratory-dependent patients may return to live in the community. Advanced surgical procedures, when appropriately applied, are decreasing the time of immobility and preventing late spinal deformities. Exciting new developments in basic science research such as the use of thyrotropin- releasing hormone and functional electrical stimulation may alter the whole course of recovery for patients within the foreseeable future. It is likely, however, that the acute management of the patient with spinal cord injury will still demand systematic care by an experienced, multidisciplinary team of professionals

Merli G.J., Crabbe S., Paluzzi R.G., and Fritz D. (1993) Etiology, incidence, and prevention of deep vein thrombosis in acute spinal cord injury. *Arch. Phys. Med. Rehabil.* 74, 1199-1205.

Abstract: This article provides a critical review of the literature on the etiology, incidence, and prevention of deep-vein thrombosis in acute spinal cord injured patients. Stasis and hypercoagulability are the two major factors contributing to the development of thrombosis in this patient population. This has been supported by studies that demonstrate an impaired venous return from the lower extremities and abnormal coagulation factors, which predispose to thrombogenesis. The incidence of deep vein thrombosis secondary to the above etiologies varies from 49% to 100% in the first 12 weeks with the first 2 weeks having the highest rate following acute injury. This high rate of complication has led to numerous studies to identify the most effective regimens of prophylaxis. Studies using noninvasive testing and venography in acute spinal cord injury have supported two approaches for preventing deep- vein thrombosis. Single agent pharmacologic therapy with adjusted dose heparin is effective but does carry some risk of bleeding. Combination therapy with external pneumatic compression sleeves plus either aspirin/dipyridamole or low-dose heparin and electrical stimulation plus low-dose heparin have significantly reduced the incidence of deep vein thrombosis. The duration of prophylaxis with the above modalities has varied between 8 and 12 weeks following acute injury. Further large scale studies are required in this high-risk population to better delineate the incidence of deep vein thrombosis and pulmonary embolism, to identify the best modalities, and to define the duration of treatment for the prevention of these complications.(ABSTRACT TRUNCATED AT 250 WORDS)

Mohr T. (2000) [Electric stimulation in muscle training of the lower extremities in persons with spinal cord injuries]. *Ugeskr. Laeger* 162, 2190-2194.

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

Moynahan M., Mullin C., Cohn J., Burns C.A., Halden E.E., Triolo R.J., and Betz R.R. (1996) Home use of a functional electrical stimulation system for standing and mobility in adolescents with spinal cord injury. *Arch. Phys. Med. Rehabil.* 77, 1005-1013.

Abstract: OBJECTIVE: Functional electrical stimulation (FES) is a technology that may allow some patients with spinal cord injury (SCI) to integrate standing and upright mobility with wheelchair mobility. The purpose of this study was to document the patterns of home and community use of a FES system for standing and mobility. DESIGN: A telephone questionnaire was administered every 1 to 4 weeks for a minimum of 1 year. An interview was given at the end of the study to probe the motivators and barriers to home use. SETTING: Training for use of the FES system was performed in an inpatient pediatric rehabilitation setting. Data collection began after the subjects were discharged to home. PARTICIPANTS: Five adolescents with complete, thoracic-level SCI. INTERVENTION: Subjects participated in a program of FES exercise followed by training in basic mobility skills such as standing transfers, maneuvering, level ambulation, one-handed and reaching activities, and stair ascent/descent. MAIN OUTCOME MEASURE: The frequency with which the FES system was used at home and the activities for which it was utilized were documented. Motivators and barriers to FES home use were examined. RESULTS: Subjects donned the FES system on the average once every 3 to 4 days. Between 51% and 84% of the times donned, the system was used for exercise. The remaining times it was used for standing activities, most commonly reaching, one-handed tasks, and standing for exercise. "Motivators" included being able to do things that would otherwise be difficult, perceiving a healthful benefit or a sense of well-being from standing and exercise, and feeling an obligation to stand as a participant in a research study. "Barriers" to FES use included not finding time to use the system, having difficulty seeing opportunities to stand, and being reluctant to wear the FES system all day

Mulcahey M.J., Betz R.R., Smith B.T., Weiss A.A., and Davis S.E. (1997) Implanted functional electrical stimulation hand system in adolescents with spinal injuries: an evaluation. *Arch. Phys. Med. Rehabil.* 78, 597-607.

Abstract: OBJECTIVE: To study the utility and functional benefits of an implanted functional electrical stimulation (FES) system for hand grasp and release in adolescents with tetraplegia secondary to spinal cord injuries. DESIGN: Intervention study with before-after trial measurement with each subject as his or her own control. SETTING: Nonprofit pediatric orthopedic rehabilitation facility specializing in spinal cord injury. PARTICIPANTS: A convenience sample of five adolescents between 16

and 18 years of age with C5 or C6 level tetraplegia at least 1 year after traumatic spinal cord injury. Key muscles for palmar and lateral grasp and release were excitable by electrical stimulation. INTERVENTIONS: A multichannel stimulator/receiver and eight electrodes were surgically implanted to provide stimulated palmar and lateral grasp and release. In conjunction with implantation of the FES hand system, surgical reconstruction in the form of tendon transfers, tendon lengthenings and releases, and joint arthrodeses was performed to augment stimulated hand function. Rehabilitation of the tendon transfers and training in the use of the FES hand system were provided. MAIN OUTCOME MEASURES: Measurements of pinch and grasp force, the Grasp and Release Test (GRT), and an assessment of six activities of daily living (ADL) were administered before implantation of the FES hand system and at regular follow-up intervals. Results of the stimulated response of individual muscles and surgical reconstruction were evaluated using standard and stimulated muscle testing techniques and standard assessment of joint range of motion. All subjects completed followup testing. RESULTS: Lateral and palmar forces were significantly greater than baseline forces ($p = .043$). Heavy objects on the GRT could only be manipulated with FES, and FES increased the level of independence in 25 of 30 ADL comparisons (5 subjects, 6 activities) as compared to baseline. After training, FES was preferred in 21 of 30 comparisons over the typical means of task completion. Of the 40 electrodes implanted, 37 continue to provide excellent stimulated responses and all of the implanted stimulators have functioned without problems. The surgical reconstruction procedures greatly enhanced FES hand function by either expanding the workspace in which to utilize FES (deltoid to triceps transfer), stabilizing the wrist (brachioradialis to wrist extensor transfer), or stabilizing joints (intrinsic tenodesis transfer, FPL split transfer). CONCLUSION: For five adolescents with tetraplegia, the combination of FES and surgical reconstruction provided active palmar and lateral grasp and release. Laboratory-based assessments demonstrated that the FES system increased pinch force, improved the manipulation of objects, and typically increased independence in six standard ADL as compared to pre-FES hand function. The study also showed that the five adolescents generally preferred FES for most of the ADL tested. Data on the benefits of the implanted FES hand system outside of the laboratory are needed to understand the full potential of FES

Mulcahey M.J., Smith B.T., and Betz R.R. (1999) Evaluation of the lower motor neuron integrity of upper extremity muscles in high level spinal cord injury. *Spinal Cord*. 37, 585-591.

Abstract: PURPOSE: To evaluate the lower motor neuron (LMN) integrity of upper extremity muscles of persons with high tetraplegia (C1-C4) in order to determine muscles available for stimulation. METHODS: Fourteen subjects (23 arms) were evaluated for LMN integrity. Muscles that elicited a functional response (grade 3 or better) to surface electrical stimulation were considered to have intact LMN and good candidates for FES. Strength-duration (S-D) curves were generated on muscles that showed weak (less than grade 3) or no response to surface stimulation. Muscles were considered denervated if S-D curves were discontinuous or depicted steep, increasing amplitude for pulse durations greater than 1 m. RESULTS: Muscles for grasp and release had intact LMN in 19 of 23 (83%) arms. The wrist extensors and flexors and pronator were excitable in 17 (74%), 20 (87%) and 19 (83%) arms, respectively. The supinator demonstrated LMN lesion in 80% of the arms. Over 90% of the biceps muscles were unresponsive to electrical stimulation and 85% and 87% of the deltoid and supraspinatus muscles, respectively, were not electrically

excitable. The latissimus dorsi and triceps muscles were typically innervated (78% and 91%, respectively) and slightly more than half (52%) of the pectoralis major muscles were excitable. CONCLUSION: These data suggest that application of FES in high tetraplegia for hand and arm function would require augmentation because of the inability to stimulate the elbow flexors, deltoid and rotator cuff muscles. These data also show that several paralyzed proximal muscles with intact LMN that have been historically transferred to address shoulder paralysis in other patient populations are available for transfer and stimulation in the population with high level spinal injuries

- Mutton D.L., Scremin A.M., Barstow T.J., Scott M.D., Kunkel C.F., and Cagle T.G. (1997) Physiologic responses during functional electrical stimulation leg cycling and hybrid exercise in spinal cord injured subjects. *Arch. Phys. Med. Rehabil.* 78, 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 I, progressive FES-LCE to 30 minutes of exercise (n = 11); phase II, 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 [VO₂], heart rate [HR], blood lactate [BLA-])—measurement of these during constant work rate exercise and a training effect. RESULTS: VO₂ (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 VO₂ 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

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Nathan R.H., Ohry A. (1990) Upper limb functions regained in quadriplegia: a hybrid computerized neuromuscular stimulation system. *Arch Phys Med Rehabil* 71, 415-421.

Nash M.S., Bilsker S., Marcillo A.E., Issac M., Botelho L.A., Klose K.J., Green B.A., Roundtree M.T.,

Shea J.D. (1991) Reversal of adaptive left ventricular atrophy following electrically stimulated exercise training in human tetraplegics. *Paraplegia* 29, 590-599.

Nash M.S., Tehranzadeh J., Green B.A., Rountree M.T., and Shea J.D. (1994) Magnetic resonance imaging of osteonecrosis and osteoarthritis in exercising quadriplegics and paraplegics. *Am. J. Phys. Med. Rehabil.* 73, 184-192.

Abstract: Degenerative bone and joint diseases that commonly accompany spinal cord injury (SCI) may be exacerbated by physical activity of the lower extremities. To determine if orthopaedic stress imposed by electrically stimulated cycling exercise is associated with osteonecrosis or osteoarthritis in persons with chronic SCI, ten quadriplegics and paraplegics who had each undergone electrical stimulation cycle ergometry exercise two or three times weekly for longer than 1.5 years underwent magnetic resonance examinations of the femoral heads and the dominant knee. Three of the ten subjects had no evidence of meniscal or bone marrow pathologies, osteochondritis dessicans, avascular necrosis, joint effusion or accumulation or soft tissue tears. The magnetic resonance scans of six subjects were noted to have very mild effusion, slight meniscal degeneration and minimal chondromalacia patellae. Consistent patterns of bone or joint pathology were not discernible among these scans, and the positive findings did not represent threatening clinical states. The scans of one subject showed heterogenous regions of bone infarct characteristic of osteochondritis and avascular necrosis, observations that were atypical of all other subjects. No injuries consistent with the biomechanics of cycling exercise were observed in any subject. Despite the high sensitivity of magnetic resonance imaging in detecting bone and joint deterioration, significant bone and joint findings represented only 14 of 150 observations, less than previously reported in sedentary subjects with SCI. This study suggests that electrical stimulation cycle ergometry does not foster bone or joint deterioration in individuals with chronic SCI

Nash M.S. (1995) Effects of electrically-stimulated exercise and passive motion on echocardiographically-derived wall motion and cardiodynamic function in tetraplegic persons. *Paraplegia* 33, 80-89.

Nene A.V., Hermens H.J., Zilvold G. (1996) Paraplegic locomotion: a review. *Spinal Cord* 34, 507-524.

Nygaard I.E. and Kreder K.J. (1996) Spine update. Urological management in patients with spinal cord injuries. *Spine* 21, 128-132.

Abstract: In the past, urologic complications contributed greatly to spinal cord injury mortality. With improved evaluation and treatment, this is no longer the case. Treatment should be guided by urodynamic data gathered after the resolution of spinal shock symptoms. Goals of treatment are to facilitate voiding, reduce incontinence, and prevent renal damage. Indwelling catheters are almost never indicated for long-term treatment of the neurogenic bladder. Commonly used treatments include intermittent catheterization, condom catheter drainage with sphincter ablation, and pharmaceutical manipulation. Electrical stimulation of sacral nerve roots shows promise for future therapy

Peckham P.H. (1987) Functional electrical stimulation: current status and future prospects of applications to the neuromuscular system in spinal cord injury. *Paraplegia* 25, 279-288.

Abstract: Functional electrical stimulation (FES) is a means of eliciting activation of the nervous system in order to elicit either a therapeutic or functional effect. The results of research performed over the past 10 years has provided a scientific

knowledge base for clinical studies. The results of clinical studies demonstrate the viability of utilising FES to restore function to the spinal injured individual. This article focuses on applications to the neuromuscular system which are relevant to the care of these individuals

- Peckham P.H. and Creasey G.H. (1992) Neural prostheses: clinical applications of functional electrical stimulation in spinal cord injury. *Paraplegia* 30, 96-101.
Abstract: Function lost in spinal cord injury can be partially restored in some patients by electrical stimulation of remaining neurons. Neural prostheses designed for this purpose have been under development for several decades and are now in increasing clinical use. Applications are outlined for restoration of respiration, bladder, bowel and sexual function, exercise, hand grasp and standing and walking
- Perry J., Waters R.L. (1975) Orthopaedic evaluation and treatment of the stroke patient. *AAOS Instr Course Lect* 24, 40-44.
- Perry J. (1977) Surgical treatment of the paralytic hand. In: Pierce D.S., Nickel V.L. [Eds]: *The Total Care of Spinal Cord Injuries*. Boston, Little Brown, pp 103-133.
- Perry J., Easterday C.S., Antonelli D.J. (1981) Surface versus intramuscular electrodes for electromyography of superficial and deep muscles. *Phys Ther* 61:7-15.
- Perry J. (1998) The contribution of dynamic electromyography to gait analysis. In: Rehabilitation Research and Development Service [Eds]: *Gait Analysis in the Science of Rehabilitation*. Washington, D.C., Department of Veterans Affairs, pp 33-48.
- Petrofsky J.S. (1992) Thermoregulatory stress during rest and exercise in heat in patients with a spinal cord injury. *Eur. J. Appl. Physiol Occup. Physiol* 64, 503-507.
Abstract: Twelve subjects with spinal cord injuries and four controls (all male) were exposed to heat while sitting at rest or working at each of three environmental temperatures, 30, 35 and 40 degrees C, with a relative humidity of 50%. Exercise was accomplished at a load of 50 W on a friction-braked cycle ergometer which was armcranked or pedalled. Functional electrical stimulation of the legs was provided to the subjects with quadriplegia and paraplegia to allow them to pedal a cycle ergometer. The data showed that individuals with quadriplegia had the poorest tolerance for heat. As an example, in this group, accomplishing armcrank ergometry while working at an environmental temperature of 40 degrees C resulted in an increase in aural temperature of 2 degrees C in 30 min. The aural temperature of individuals with paraplegia working for the same length of time under the same conditions rose approximately 1 degree C. There was virtually no change in the aural temperature in the control subjects
- Phillips W.T., Kiratli B.J., Sarkarati M., Weraarchakul G., Myers J., Franklin B.A., Parkash I., and Froelicher V. (1998) Effect of spinal cord injury on the heart and cardiovascular fitness. *Curr. Probl. Cardiol.* 23, 641-716.
Abstract: The use of various FES protocols to encourage increases in physical activity and to augment physical fitness and reduce heart disease risk is a relatively new, but growing field of investigation. The evidence so far supports its use in improving potential health benefits for patients with SCI. Such benefits may include more efficient and safer cardiac function; greater stimulus for metabolic,

cardiovascular, and pulmonary training adaptations; and greater stimulus for skeletal muscle training adaptations. In addition, the availability of relatively inexpensive commercial FES units to elicit muscular contractions, the ease of use of gel-less, reusable electrodes, and the increasing popularity of home and commercial upper body exercise equipment mean that such benefits are likely to be more accessible to the SCI population through increased convenience and decreased cost. The US Department of Health and Human Services has identified those with SCI as a "special population" whose health problems are accentuated, and so need to be specifically addressed. FES presents "a clear opportunity.... For health promotion and disease prevention efforts to improve the health prospects and functional independence of people with disabilities." As a corollary to this, the Centers for Disease Control and Prevention have recommended the development of techniques to prevent or ameliorate secondary disabilities in persons with a SCI. Patients with SCI have an increased susceptibility to cardiac morbidity and mortality in the acute and early stages of their injury. Most of these patients make an excellent adaptation except when confronted with infection or hypoxia. SCI by itself does not promote atherosclerosis; however, in association with multiple secondary conditions related to SCI, along with advancing age, patients with SCI are predisposed to relatively greater risk of heart disease. The epidemiologic significance of this is reflected in demographic studies that indicate an increasing number of SCI patients becoming aged. Currently 71,000 (40%) of the total 179,000 patients with SCI living in the United States are older than 40 years, and 45,000 have injuries sustained more than 20 years earlier. In addition, new injuries in the older population are increasing (currently 11% of all injuries), and some of these new patients with SCI already have pre-existing cardiac disease. Studies have demonstrated that improved lifestyle, physical activity, lipid management, and dietary restrictions can affect major risk factors for coronary artery disease. Therefore an aggressive cardiac prevention program is appropriate for patients with SCI as part of their rehabilitation. At a given submaximal workload, arm exercise is performed at a greater physiologic cost than is leg exercise. At maximal effort, however, physiologic responses are generally greater in leg exercise than arm exercise. Arm exercise is less efficient and less effective than lower body exercise in developing and maintaining both central and peripheral aspects of cardiovascular fitness. The situation is further compounded in SCI because of poor venous return as a result of lower-limb blood pooling, as a result of lack of sympathetic tone, and a diminished or absent venous "muscle pump" in the legs. This latter mechanism perhaps contributes the greatest diminution in the potential for aerobic performance in the SCI population. Obtaining a cardiopulmonary training effect in individuals with SCI is quite possible. Current studies indicate decreases in submaximal HR, respiratory quotient, minute ventilation, and oxygen uptake, with increases in maximal power output, oxygen uptake, minute ventilation, and lactic acid. Individuals with SCI have been shown to benefit from lower limb functional electrical stimulation (FES)-induced exercise. Studies have consistently reported increases in lower limb strength and cycle endurance performance with these protocols, as well as improvements in metabolic and

Phillips W.T. and Burkett L.N. (1998) Augmented upper body contribution to oxygen uptake during upper body exercise with concurrent leg functional electrical stimulation in persons with spinal cord injury. *Spinal Cord*. 36, 750-755.
Abstract: The purpose of this pilot study was to compare the contribution of upper body musculature to VO₂ with and without concurrent leg FES (LFES). Eight subjects with spinal cord injury, lesion levels range C6- T12, performed upper body

exercise (UBE) during no LFES (NOS), LFES at 40 mA (LOS), and 80 mA (HIS), at rest, 60% and 80% of VO₂peak. Resting VO₂ values were obtained during NOS, LOS and HIS conditions and were then subtracted from their respective whole body VO₂ values to give an estimate of upper body VO₂. Small and non significant increases were found in the HIS vs NOS condition at 60% VO₂peak. Larger differences of 7.8% were found in the HIS vs NOS condition at 80% VO₂peak (11.35±3.8 ml kg⁻¹ min⁻¹ to 12.24±4.0 ml kg⁻¹ min⁻¹), although this too was not significant, perhaps due to the small number of subjects in this study and the consequently low statistical power to detect a significant difference. We discuss the implications for these preliminary results in the context of the existing literature on this topic

Pinder R.M., Brogden R.N., Speight T.M., and Avery G.S. (1977) Dantrolene sodium: a review of its pharmacological properties and therapeutic efficacy in spasticity. *Drugs* 13, 3-23.

Abstract: Dantrolene sodium or dantrolene 1 is 1-[5-(nitrophenyl)furfurylidene] amino) hydantoin sodium hydrate. It is indicated for use in chronic disorders characterised by skeletal muscle spasticity, such as spinal cord injury, stroke, cerebral palsy and multiple sclerosis. Dantrolene is believed to act directly on the contractile mechanism of skeletal muscle to decrease the force of contraction in the absence of any demonstrated effects on neural pathways, on the neuromuscular junction, or on the excitable properties of the muscle fibre membranes. Controlled trials have demonstrated that dantrolene is superior to placebo in adults or children with spasticity from various causes, as evidenced by clinical assessments of disability and daily activities, and by muscle and reflex responses to mechanical and electrical stimulation. It is somewhat less effective in patients with multiple sclerosis than in those with spasticity from other causes. There has been a general clinical impression in controlled trials that dantrolene caused less sedation than would have been expected from therapeutically comparable doses of diazepam. In 2 controlled trials, there was no significant difference between dantrolene and diazepam in terms of reductions in spasticity, clonus, and hyperreflexia, but side-effects such as drowsiness and inco-ordination occurred significantly more frequently on diazepam. Long-term studies have indicated continuing benefit for patients taking dantrolene, though the incidence of side-effects has often been high and there has been a suggestion of exacerbation of seizures in children with cerebral palsy. Dantrolene may be of value in the medical treatment of spasm of the external urethral sphincter due to neurological and non-neurological disease, and animal studies suggest a potential use in the management of malignant hyperpyrexia. Chemical evidence of liver dysfunction may occur in 0.7 to 1% of patients on long-term treatment with dantrolene, with symptomatic hepatitis in 0.35 to 0.5% and fatal hepatitis in 0.1 to 0.2%. The drug commonly causes transient drowsiness, dizziness, weakness, general malaise, fatigue and diarrhoea at the start of therapy. Muscle weakness may be the principal limiting side-effect in ambulant patients, particularly in those with multiple sclerosis, and therapy could be hazardous in patients with pre-existing bulbar or respiratory weakness. The dosage of dantrolene has been fixed in most controlled trials, though long-term studies have indicated the need for individualisation of dosage. The initial dose is usually 25mg once daily, increasing to 25mg two, three or four times daily, and then by increments of 25mg up to as high as 100mg two, three or four times daily. The lowest dose compatible with optimal response is recommended

Pinter M.M., Gerstenbrand F., and Dimitrijevic M.R. (2000) Epidural electrical stimulation of posterior structures of the human lumbosacral cord: 3. Control Of spasticity. *Spinal Cord*. 38, 524-531.

Abstract: OBJECTIVES: The purpose of this study was to evaluate the effect of spinal cord stimulation (SCS) on severe spasticity of the lower limbs in patients with traumatic spinal cord injury (SCI) under close scrutiny of the site and parameters of stimulation. MATERIALS AND METHODS: Eight SCI patients (four women, four men) were included in the study. Levels of spasticity before and during stimulation were compared according to a clinical rating scale and by surface electrode polyelectromyography (pEMG) during passive flexion and extension of the knee, supplemented by a pendulum test with the stimulating device switched either on or off over an appropriate period. RESULTS: Both the clinical and the experimental parameters clearly demonstrated that SCS, when correctly handled, is a highly effective approach to controlling spasticity in spinal cord injury subjects. The success of this type of treatment hinges on four factors: (1) the epidural electrode must be located over the upper lumbar cord segment (L1, L2, L3); (2) the train frequency of stimulation must be in the range of 50 - 100 Hz, the amplitude within 2 - 7 V and the stimulus width of 210 microsecond; (3) the stimulus parameters must be optimized by clinically assessing the effect of arbitrary combinations of the four contacts of the quadripolar electrode; and (4) amplitudes of stimulation must be adjusted to different body positions. CONCLUSIONS: Severe muscle hypertonia affecting the lower extremities of patients with chronic spinal cord injuries can be effectively suppressed via stimulation of the upper lumbar cord segment

Popovic D., Stojanovic A., Pjanovic A., Radosavljevic S., Popovic M., Jovic S., and Vulovic D. (1999) Clinical evaluation of the bionic glove. *Arch. Phys. Med. Rehabil.* 80, 299-304.

Abstract: OBJECTIVE: Clinical evaluation of the Bionic Glove, a prototype of a new functional electrical stimulation device designed to improve the function of the paralyzed hand after spinal cord injury. PATIENTS: Twelve people with spinal cord injury at C5-C7 who had used the device 6 months or more. SETTING: Measurements were made at the Institute "Dr Miroslav Zotovic" in Belgrade as a part of a multicenter clinical trial. METHODS: Measures include Upper Extremity Function Test, Functional Independence Measure, and Quadriplegia Index of Function. RESULTS: The daily use of a Bionic Glove had two major effects: (1) increasing the power grasp; and (2) increasing the range of movements. Active force was significantly greater than passive tenodesis force, as shown in other studies. Most manual tasks improved significantly with the use of the assistive system, as judged by the time needed to complete a task or the subject's qualitative ratings of a task difficulty. Most subjects who retained some dexterity without the assistive system hesitated to use the assistive system to manipulate small objects. CONCLUSION: The Bionic Glove can significantly improve independence in people with C5-C7 spinal cord injury if their initial Functional Independence Measure and Quadriplegia Index of Function scores are 20% to 50% of the maximum values

Popovic D., Stein R.B., Oguztoreli N., Lebedowska M., and Jonic S. (1999) Optimal control of walking with functional electrical stimulation: a computer simulation study. *IEEE Trans. Rehabil. Eng* 7, 69-79.

Abstract: Bipedal locomotion was simulated to generate a pattern of activating muscles for walking using electrical stimulation in persons with spinal cord injury (SCI) or stroke. The simulation presented in this study starts from a model of the

body determined with user-specific parameters, individualized with respect to the lengths, masses, inertia, muscle and joint properties. The trajectory used for simulation was recorded from an able-bodied subject while walking with ankle-foot orthoses. A discrete mathematical model and dynamic programming were used to determine the optimal control. A cost function was selected as the sum of the squares of the tracking errors from the desired trajectories, and the weighted sum of the squares of agonist and antagonist activations of the muscle groups acting around the hip and knee joints. The aim of the simulation was to study plausible trajectories keeping in mind the limitations imposed by the spinal cord injury or stroke (e.g., spasticity, decreased range of movements in some joints, limited strength of paralyzed, externally activated muscles). If the muscles were capable of generating the movements required and the trajectory was achieved, then the simulation provided two kinds of information: 1) timing of the onset and offset of muscle activations with respect to the various gait events and 2) patterns of activation with respect to the maximum activation. These results are important for synthesizing a rule-based controller

Previnaire J.G., Soler J.M., Perrigot M., Boileau G., Delahaye H., Schumacker P., Vanvelcenaher J., and Vanhee J.L. (1996) Short-term effect of pudendal nerve electrical stimulation on detrusor hyperreflexia in spinal cord injury patients: importance of current strength. *Paraplegia* 34, 95-99.

Abstract: Twenty patients with chronic suprasacral spinal cord injury presenting with detrusor hyperreflexia were examined. In a preliminary study in ten patients we investigated the reproducibility of bladder capacity through the repetition of three cystometries. The effect of electrical stimulation (ES) on detrusor hyperreflexia was then investigated in ten patients during three consecutive cystometries, the first one without ES (baseline) and the other two with continuous ES of the dorsal penile or clitoris nerve via surface electrodes. Parameters of stimulation were 5 Hz frequency, 0.50 msec pulse duration, and stimulation strength of 1 and 2 times the bulbocavernosus reflex threshold. No significant differences in bladder capacity were found between the three consecutive cystometries without ES (respectively 97.0 ml, 101.5 ml and 105.6 ml). A current at the bulbocavernosus threshold (mean 24.4 mA) failed to induce a significant increase in bladder capacity compared to baseline (173.0 ml vs 155.5 ml, $P = 0.17$) whereas a current of twice the bulbocavernosus threshold (mean 48.9 mA) was highly significant (318.5 ml vs 155.5 ml, $P < 0.007$). ES of twice the threshold resulted in perineal contraction in all of the patients, the threshold ES never did. Our results emphasise the decisive roles of perineal contraction and of current strength for achieving short-term bladder inhibition in spinal cord injury patients. The carry-over effect may also be dependent on the current strength. If so, maximal pudendal ES could represent an alternative procedure in the treatment of detrusor hyperreflexia in these patients

Previnaire J.G., Soler J.M., and Perrigot M. (1998) Is there a place for pudendal nerve maximal electrical stimulation for the treatment of detrusor hyperreflexia in spinal cord injury patients? *Spinal Cord*. 36, 100-103.

Abstract: The aim of the study is to determine whether pudendal nerve maximal electrical stimulation (MES) could represent an alternative treatment for detrusor hyperreflexia in spinal cord injury (SCI) patients. Six suprasacral SCI patients participated in the study. The treatment consisted of daily stimulation periods of 20 min, repeated five times a week, during 4 weeks, with continuous electrical stimulation of the penis or of the clitoris via bipolar surface electrodes (rectangular

stimuli of 0.5 ms pulse duration, 5 Hz frequency), with the maximum tolerable stimulation strength (under the level of pain). In two patients, additional stimulation was administered by means of an anal plug during the last 2 weeks. The stimulus strengths ranged from 35 to 99 mA (mean 54 mA). One patient stopped MES after 2 weeks. At the end of the treatment, neither the cystometric bladder capacities (153 ml vs 157 ml) nor the micturition charts had significantly improved for the five remaining patients. Only two patients experienced non lasting improvement of nocturia at some time of the treatment. In conclusion, we were not able to demonstrate the efficacy of MES in inhibiting detrusor hyperreflexia in SCI patients. To reach therapeutic effects, other parameters may be needed, such as higher stimulation strengths (currents above or equal to 99 mA) or other currents (such as interferential therapy). Chronic stimulation with external or implanted electrodes using lower currents may represent an alternative

Prochazka A., Gauthier M., Wieler M., and Kenwell Z. (1997) The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Arch. Phys. Med. Rehabil.* 78, 608-614.

Abstract: OBJECTIVE: This report describes the operation of the Bionic Glove, a new functional electrical stimulation (FES) device designed to improve the function of the paralyzed hand after spinal cord injury (SCI) or stroke. DESIGN: Signals from a sensor in the glove detecting voluntary wrist movement are used to control FES of muscles either to produce hand-grasp or to open the hand. When the glove is donned, conductive areas on its inside surface automatically make contact with self-adhesive electrodes on the skin. SETTING AND PATIENTS: This report concerns nine people with SCI who have used the device in their daily lives for up to a year or more. Measurements were made at clinics in Edmonton, Miami, and Chicago as part of a multicenter clinical trial. OUTCOME MEASURES AND RESULTS: The mean peak force of tenodesis grasp in the nine subjects increased from 2.6N (passive) to 11.3N (glove active). Active force was significantly greater than passive grasp force even when muscles were fatigued after repetitive grasp-release cycles. Most manual tasks improved significantly with the use of the glove, as judged by the number of tasks completed in a minute or the subjects' qualitative ratings of task difficulty. CONCLUSION: The Bionic Glove can provide significant improvement of hand function in people with C6-C7 SCI

Quintern J., Riener R., and Rupperecht S. (1997) Comparison of simulation and experiments of different closed-loop strategies for functional electrical stimulation: experiments in paraplegics. *Artif. Organs* 21, 232-235.

Abstract: Open-loop and closed-loop stimulation of the knee extensors for the control of the knee joint angle and torque were tested as a potential basis for more complex functional electrical stimulation (FES) systems to be used in human locomotion. The output of the biomechanical simulation model described previously was compared with stimulation experiments in patients with complete thoracic spinal cord injury. Good correspondence between simulation and experiments was obtained under both isometric conditions and conditions with a freely swinging shank. For closed-loop control, a simple proportional integral derivative (PID) controller yielded sufficient performance only under isometric conditions, especially if combined with (linear) feedforward. Because of additional nonlinearities of musculotendon and body segmental dynamics, more complex strategies have to be applied to the control of unconstrained movements. To compensate for these nonlinearities, an inverse model was derived from the direct biomechanical model. This inverse model had

satisfactory agreement between the measured knee angle and the desired trajectory already under open-loop conditions. A combination of the inverse model in the feedforward part of the control loop and a PID controller provided robust and precise control of the knee angle. Further improvement may be achieved by including elements of spasticity into the simulation model and by controlling both agonistic and antagonistic muscles

Ragnarsson K.T., Pollack S., O'Daniel W., Jr., Edgar R., Petrofsky J., and Nash M.S. (1988) Clinical evaluation of computerized functional electrical stimulation after spinal cord injury: a multicenter pilot study. *Arch. Phys. Med. Rehabil.* 69, 672-677. Abstract: This study investigated the safety and effects of computerized functional electrical stimulation (FES) on spinal cord injured individuals. Nineteen subjects two to ten years postinjury, with clinically complete motor and sensory lesions between C4 and T10, participated. All subjects met the specific selection criteria. None had received lower extremity electrical stimulation before. In phase I, subjects received surface electrical stimulation to the quadriceps muscle bilaterally for resistive knee extension 3 times a week for four weeks. The resistance and number of completed lifts was recorded daily. In phase II, 36 sessions provided sequential surface electrical stimulation to the quadriceps, hamstrings, and gluteus muscles bilaterally in order for subjects to pedal a lower extremity ergometer with resistance varied depending on completed run time. For each session, heart rate, blood pressure, temperature, and work performance were recorded. Tests done before and after the training program included fasting blood chemistries, 24-hour urinalysis, arm-crank ergometer stress testing, and midthigh girth measurement. Results indicate that this form of FES is safe, that quadriceps strength and endurance is increased, that endurance for ergometer pedaling is increased, and that there may be a training effect as more work is done at a similar heart rate and systolic blood pressure and as muscle bulk is increased. The FES effect on cardiovascular conditioning and general health requires further research to precisely determine its benefits

Ragnarsson K.T. (1988) Physiologic effects of functional electrical stimulation-induced exercises in spinal cord-injured individuals. *Clin. Orthop.* 53-63. Abstract: Spinal cord injury (SCI) results in multiple degenerative changes that may in part be related to physical inactivity. There are indications that some of these changes may be reversed by exercise and fitness training. Computerized functional electrical stimulation (FES) allows active exercise of limbs paralyzed by upper motor neuron lesions. Thirty SCI subjects safely participated in an FES-induced exercise program for lower extremity strengthening and endurance training. Increased strength, endurance, and bulk of stimulated muscles were noted. The subjects were able to perform a greater amount of work on a lower extremity ergometer, both per unit of time and per length of time, indicating a training effect. A multistage stress test showed evidence that the subjects had increased their aerobic metabolism during the training program. Twitch time tests showed slowing of muscle contraction, and computed tomography showed increased muscle density

Ragnarsson K.T. (1992) Functional electrical stimulation and suppression of spasticity following spinal cord injury. *Bull. N. Y. Acad. Med.* 68, 351-364.

Rajasekaran M., Hellstrom W.J., Sparks R.L., and Sikka S.C. (1994) Sperm-damaging effects of electric current: possible role of free radicals. *Reprod. Toxicol.* 8, 427-432. Abstract: The generation of reactive oxygen species (ROS) and sperm damage was

evaluated in (a) samples obtained during electroejaculation (EE) of men with spinal cord injury and (b) in electrolyzed HAM's F-10 medium subjected to electric current in vitro. Chemiluminescence data showed a significant increase in ROS in the ejaculates (6×10^7) photons/ml) collected immediately after EE and in the electrolyzed medium (3 to 7×10^6) photons/ml) when compared to the control (4 to 7×10^4) photons/ml). Incubation of normal human sperm with the electrolyzed medium resulted in a significant threefold decrease in percent motility and a twofold decrease in percent viability. Sperm subjected to direct electric stimulation in vitro exhibited a significant twofold decrease in percent motility and percent viability. Superoxide dismutase (SOD) activity decreased significantly in sperm subjected to direct electric current in comparison to the control or the sample incubated with electrolyzed medium. These studies indicate that in vitro and in vivo electrical stimulation generate reactive oxygen species and affect SOD activity, which in part are responsible for decreased sperm motion and viability

Raymond J., Davis G.M., Fahey A., Climstein M., and Sutton J.R. (1997) Oxygen uptake and heart rate responses during arm vs combined arm/electrically stimulated leg exercise in people with paraplegia. *Spinal Cord*. 35, 680-685.

Abstract: The purpose of this study was to compare the oxygen uptake and heart rate responses during submaximal arm cranking to combined arm cranking + electrical stimulation (ES)-induced leg cycling in individuals with spinal cord injury (SCI). Seven subjects with paraplegia (T4-T12) performed combined arm and leg cycling exercise for 5 min, followed by arm cranking alone at the same power output for a further 5 min. During both exercise conditions, steady state oxygen consumption (VO_2), carbon dioxide output (VCO_2), expired ventilation (VE) and heart rate (HR) were determined. The respiratory exchange ratio (RER) and oxygen pulse were calculated from the measured variables. During combined arm + electrical stimulation-induced leg cycling exercise, the VO_2 was 25% higher (1.58 l min^{-1} vs 1.26 l min^{-1}), but the HR was 13% lower (132 b min^{-1} vs 149 b min^{-1}), than during arm cranking exercise alone. Oxygen pulse and VCO_2 were also significantly higher (by 42% and 25%, respectively) during combined arm + ES-induced leg exercise, but there were no differences between the two exercise conditions for VE or RER. These data suggest that the absence of the leg 'muscle pump' and a reduced venous return of blood to the heart elevate exercise heart rates during submaximal arm cranking. Conversely, combined arm cranking + ES-induced leg cycling exercise provides the body with a greater metabolic stress than arm cranking alone, while reducing the cardiac stress. The mechanism explaining the heart rate response, however, remains unclear, but may have been influenced by the blood pressure variations across the range of lesions. The findings from this study may have implications for the relative benefit of combined arm + ES- induced leg cycling training for people with paraplegia

Rebersek S., Vodovnik L. (1973) Proportionally controlled functional electrical stimulation of the hand. *Arch Phys Med Rehabil* 54, 378-382.

Riedy L.W., Chintam R., and Walter J.S. (2000) Use of a neuromuscular stimulator to increase anal sphincter pressure. *Spinal Cord*. 38, 724-727.

Abstract: OBJECTIVES: The objective of this study was to determine if short periods of electrical stimulation with perianal electrodes could increase anal pressures. MATERIAL AND METHODS: Anorectal responses to electrical stimulation were evaluated in five healthy SCI patients. Anorectal pressures were recorded with a

small pressure-recording balloon before, during, and immediately following stimulation. A battery-powered stimulator with self-adhering surface electrodes, two inches in diameter was used. Stimulating parameters consisted of 300 micro pulse duration, 35 Hz stimulating frequency. A current response study was conducted by using short periods of electrical stimulating with currents from 0-100 mA until a maximal pressure was recorded. Each current setting was conducted for 13.2+/-9.7 s before increasing to the next higher current, and fatigue was reduced by including a 5-minute rest between stimulations. RESULTS: Four of the five subjects had strong anal contractions with perianal stimulation. Increases in pressure ranged from 38 to 125 cm H₂O based on maximal responses at currents ranges of 60 to 100 ma. Even during the short periods of stimulation used here, fatigue was apparent. There was an average drop of 11% in anal pressure over the 13 s of stimulation. Rectal pressures were unchanged with perianal stimulation. CONCLUSIONS: Perianal stimulation with surface electrodes is an approach that might be considered in the future for management of fecal incontinence in individuals with spinal cord injury. Further studies are needed to assess the feasibility of using chronic perianal surface electrical stimulation to sustain anal sphincter contractions

Rijkhoff N.J., Wijkstra H., Van Kerrebroeck P.E., and Debruyne F.M. (1997) Urinary bladder control by electrical stimulation: review of electrical stimulation techniques in spinal cord injury. *Neurourol. Urodyn.* 16, 39-53.

Abstract: Evacuation of urine in paraplegics without the need for catheters would be possible when voiding could be induced by eliciting a bladder contraction. A challenging option to obtain detrusor contraction is electrical stimulation of the detrusor muscle or its motor nerves. This article reviews the 4 possible stimulation sites where stimulation would result in a detrusor contraction: the bladder wall, the pelvic nerves, the sacral roots, and the spinal cord. With respect to electrode application, sacral root stimulation is most attractive. However, in general, sacral root stimulation results in simultaneous activation of both the detrusor muscle and the urethral sphincter, leading to little or no voiding. Several methods are available to overcome the stimulation-induced detrusor-sphincter dyssynergia and allow urine evacuation. These methods, including poststimulus voiding, fatiguing of the sphincter, blocking pudendal nerve transmission, and selective stimulation techniques that allow selective detrusor activation by sacral root stimulation, are reviewed in this paper

Rischbieth H., Jelbart M., and Marshall R. (1998) Neuromuscular electrical stimulation keeps a tetraplegic subject in his chair: a case study. *Spinal Cord.* 36, 443-445.

Abstract: Pressure ulcers are an important complication of spinal cord injury which place an enormous burden on society due to their financial, psychosocial, and vocational implications. Although they are now rarely fatal, they can still have devastating consequences, often needing prolonged hospitalisation to be properly managed. This study reviews the use of electrical stimulation to overcome increasing debility due to sacral pressure ulcers and saddle soreness in a man with tetraplegia. After 24 months of regular cyclic stimulation he had increased circumferential dimensions across his buttocks by up to 21%, and increased his sitting tolerance

Rizzo M., Betz R.R., Mulcahey M.J., and Smith B.T. (1998) Magnetic resonance imaging data in the evaluation of effects of functional electrical stimulation on knee joints of adolescents with spinal cord injury. *J. Spinal Cord. Med.* 21, 124-130.

Abstract: Diagnostic imaging, consisting of roentgenograms and magnetic resonance

images (MRIs), was performed as part of an evaluation of the effects of a functional electrical stimulation (FES) program on the knee joints of 29 adolescents with spinal cord injuries following implantation of fine-wire intramuscular electrodes in their lower extremity muscles. The subjects underwent a regimen consisting of stimulated exercise, standing and/or walking. The effects of FES on knee joints were prospectively studied by reviewing diagnostic imaging data. Evaluation of MRIs and plain radiographs showed no evidence of knee joint pathology secondary to FES exercise or weight bearing. In fact, based on follow-up of MRI scan, many of the joints improved following participation in the program. The MRI data supported the clinical examination of the knee joints of these children. Clinical examination appears adequate for screening for potential knee joint problems

Robinson C.J., Kett N.A., and Bolam J.M. (1988) Spasticity in spinal cord injured patients: 2. Initial measures and long-term effects of surface electrical stimulation. *Arch. Phys. Med. Rehabil.* 69, 862-868.
Abstract: Electrical stimulation of paralyzed muscles has been shown to affect their spasticity, especially in patients with hemiplegia. But little has been reported on the long-term effects of such stimulation on individuals with spinal cord injury. This paper documents initial quadriceps spasticity in 31 spinal cord injured subjects, and the effect of four to eight weeks of reconditioning using electrical stimulation. Spasticity was quantified through the use of a normalized relaxation index (R2n) obtained from a pendulum drop test. The reconditioning protocol consisted of twice daily 20-minute exercise sessions at least four hours apart, six days per week. Spasticity and stimulated quadriceps torque were measured during one to three evaluations performed at least one day apart at the beginning of the program, and at four and eight weeks. There was no significant difference in average initial measures of spasticity between left and right legs and no effect of time since injury on average R2n values. Significant differences were seen for right leg average baseline R2n values when grouped by lesion level or completeness. Quadriplegic individuals were more spastic than paraplegic individuals, and subjects with incomplete lesions were more spastic than those with complete lesions. These findings are interrelated since most of the quadriplegic subjects (14 of 16) had incomplete lesions. Most participants had increased spasticity after four weeks of reconditioning but not after eight weeks. However, only eight subjects completed eight weeks of reconditioning. Subjects who had the greatest increases in spasticity also had the greatest gains in stimulated torque, both after four and eight weeks. (ABSTRACT TRUNCATED AT 250 WORDS)

Rodgers M.M., Glaser R.M., Figoni S.F., Hooker S.P., Ezenwa B.N., Collins S.R., Matthews T., Suryaprasad A.G., Gupta S.C. (1991) Musculo-skeletal responses of spinal cord injured individuals to functional neuromuscular stimulation-induced knee extension exercise training. *J of Rehabil Res* 28, 19-26.

Sampson E.E., Burnham R.S., and Andrews B.J. (2000) Functional electrical stimulation effect on orthostatic hypotension after spinal cord injury. *Arch. Phys. Med. Rehabil.* 81, 139-143.

Abstract: OBJECTIVE: To investigate the possibility of using functional electrical stimulation (FES) to control orthostatic hypotension in patients with spinal cord injury (SCI) and to clarify the mechanism of the response. DESIGN: Subjects were tilted by 10 degree increments with varying intensities of lower-extremity FES. Stimulation over muscles was compared to stimulation over noncontractile sites. SETTING:

Physical therapy department of a major rehabilitation center. PATIENTS: Six patients with SCI above T6 (3 with recent injury recruited consecutively from an inpatient spinal cord rehabilitation unit, and 3 from the community with longstanding injury, recruited as volunteers). MAIN OUTCOME MEASURES: Blood pressure, heart rate, and perceived presyncope score recorded at each tilt angle and analyzed using a multivariate analysis of variance statistical methodology. RESULTS: Systolic and diastolic blood pressure increased with increasing stimulation intensities (systolic, $p = .001$; diastolic, $p = .0019$) and decreased with increasing angle of tilt ($p < .001$) regardless of the site of stimulation. Subjects tolerated higher angles of incline with electrical stimulation than without ($p = .03$). CONCLUSIONS: FES causes a dose-dependent increase in blood pressure independent of stimulation site that may be useful in treating orthostatic hypotension

Scremin A.M., Kurta L., Gentili A., Wiseman B., Perell K., Kunkel C., and Scremin O.U. (1999) Increasing muscle mass in spinal cord injured persons with a functional electrical stimulation exercise program. *Arch. Phys. Med. Rehabil.* 80, 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 done at baseline (before subjects started the program), at first follow-up, typically after 65.4 \pm 5.6 (SD) weekly sessions, and at second follow-up, typically after 98.1 \pm 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

Scremin O.U., Cuevas-Trisan R.L., Scremin A.M., Brown C.V., and Mandelkern M.A. (1998) Functional electrical stimulation effect on skeletal muscle blood flow measured with H₂(15)O positron emission tomography. *Arch. Phys. Med. Rehabil.* 79, 641-646. Abstract: OBJECTIVE: To test the hypothesis that the limitation in muscle power development with functional electrical stimulation (FES) results from an insufficient increase in muscle blood flow (MBF) in response to activity. SUBJECTS AND METHODS: Five subjects with neurologically complete spinal cord injury (SCI) were tested to measure the MBF response to FES-induced knee extension. The MBF

response to voluntary knee extension was measured in five age-matched, able-bodied controls. MBF was measured with positron emission tomography (PET) using H₂(15)O as a tracer. Three scans were performed with muscle at rest (baseline), immediately after 16min of FES-induced or voluntary knee extension (activity), and 20min after the second scan (recovery). RESULTS: In SCI subjects, mean +/-SE MBF (mL/100g/min) values were: baseline = 1.85 +/- .48; post-FES = 31.9 +/- 5.65 (p = .0058 vs baseline); recovery = 6.06 +/- 1.52 (p = .0027 vs baseline). In able-bodied controls, mean +/-SE MBF values were: baseline = 8.52 +/- 3.24, post-voluntary exercise = 12.62 +/- 3.03 (p = .023 vs post-FES in SCI subjects); recovery = 10.7 +/- 6.01. CONCLUSIONS: MBF does not appear to be the limiting factor in muscle power generation with FES. The greater increase in MBF observed with FES in SCI subjects when compared with able-bodied subjects performing a similar task (unloaded knee extension against gravity) may relate to abnormal metabolism in FES-stimulated muscle

Solomonow M., Aguilar E., Reisin E., Baratta R.V., Best R., Coetzee T., D'Ambrosia R. (1997) Reciprocating Gait Orthosis Powered with Electrical Muscle Stimulation (RGO II): Part I: Performance Evaluation of 70 Paraplegic Patients. *Orthopaedics* 20, 315-324.

Solomonow M., Reisin E., Aguilar E., Baratta R.V., Best R., Coetzee T., D'Ambrosia R. (1997) Reciprocating Gait Orthosis Powered with Electrical Muscle Stimulation (RGO II): Part II: Medical Evaluation of 70 Paraplegic Patients. *Orthopaedics* 20, 411-418.

Sorli J., Kandare F., Jaeger R.J., and Stanic U. (1996) Ventilatory assistance using electrical stimulation of abdominal muscles. *IEEE Trans. Rehabil. Eng* 4, 1-6. Abstract: Nine neurologically intact subjects were studied to demonstrate the feasibility of stimulating the muscles of expiration during, and in synchrony with, naturally occurring breathing. A breath-by-breath analysis showed that both tidal volume and the frequency of respiration could be increased during periods of electrical stimulation. A single subject with complete spinal cord injury was studied to eliminate the possibility that the results from the normal subjects could be attributed entirely to either subconscious or conscious volitional response to the stimulation. The results provide a basis for future studies with patients in borderline ventilatory failure

Spoltore T., Mulcahey M.J., Johnston T., Kelly K., Morales V., and Rebeck C. (2000) Innovative programs for children and adolescents with spinal cord injury. *Orthop. Nurs.* 19, 55-62. Abstract: A few innovative programs have enabled children with SCI to surpass traditional levels of independence defined solely on preservation of motor function. Implementation of unique upper extremity and bladder surgical programs has provided children with tetraplegia the ability to manipulate objects without equipment and to independently empty their bladder, respectively. Innovative surgical programs have also restored privacy, dignity, and spontaneity. These are important gains previously unachievable by young persons with tetraplegia. Functional electrical stimulation has advanced children's abilities in upright mobility and has made significant impact on their quality of life by restoring hand and bladder capacities. Nurses play a leadership role in the delivery and integration of these dynamic programs

Stanic U., Acimovic-Janezic R., Gros N., Trnkoczy A., Gajd T., Kljajic M. (1978) Multichannel electrical stimulation for correction of hemiplegic gait. *Scand J Rehabil Med* 10, 75-92.

Stanic U., Kandare F., Jaeger R., and Sorli J. (2000) Functional electrical stimulation of abdominal muscles to augment tidal volume in spinal cord injury. *IEEE Trans. Rehabil. Eng* 8, 30-34.

Abstract: Functional electrical stimulation (FES) of abdominal muscles as a method of enhancing ventilation was explored in six neurologically intact subjects and five subjects with spinal cord injury (SCI) who had levels of injury between C4 and C7. Pulmonary ventilation was augmented in both groups predominantly due to an increase in tidal volume. The average increase in tidal volume during FES for the neurologically intact group was 350 ml, while in the SCI group it was 220 ml. The FES caused active volume decreases in both the lower thorax and upper abdomen, which together appear to be the mechanism behind the increases seen in tidal volume. Therefore, the proposed method might be useful in future clinical practice. The results indicate that FES of abdominal muscles should be more thoroughly explored as a potential technique of ventilatory support in SCI. The results also point to the necessity for further studies of maintaining the condition of the chest wall in the pulmonary rehabilitation of individuals with tetraplegia

Stefanovska A., Rebersek S., Bajd T., Vodovnik A. (1991) Effects of electrical stimulation on spasticity. *CRC Phys Rehab Med* 3, 59-99.

Stein R.B., Gordon T., Jefferson J., Sharfenberger A., Yang J.F., de Zepetnek J.T., and Belanger M. (1992) Optimal stimulation of paralyzed muscle after human spinal cord injury. *J. Appl. Physiol* 72, 1393-1400.

Abstract: Muscle properties change profoundly as a result of disuse after spinal cord injury. To study the extent to which these changes can be reversed by electrical stimulation, tibialis anterior muscles in complete spinal cord-injured subjects were stimulated for progressively longer times (15 min, 45 min, 2 h, and 8 h/day) in 6-wk intervals. An index of muscle endurance to repetitive stimulation doubled (from 0.4 to 0.8), contraction and half-relaxation times increased markedly (from 70 to approximately 100 ms), but little or no change was measured in twitch or tetanic tension with increasing amounts of stimulation. The changes observed with 2 h/day of stimulation brought the physiological values close to those for normal (control) subjects. A decrease in the stimulation period produced a reversal of the changes. No effects were observed in the contralateral (unstimulated) muscle at any time, nor was there evidence of decreased numbers of motor units in these subjects secondary to spinal cord injury. Motor unit properties changed in parallel with those of the whole muscle. The occasional spasms occurring in these subjects are not sufficient to maintain normal muscle properties, but these properties can largely be restored by 1-2 h/day of electrical stimulation

Stein R.B., Belanger M., Wheeler G., Wieler M., Popovic D.B., Prochazka A., and Davis L.A. (1993) Electrical systems for improving locomotion after incomplete spinal cord injury: an assessment. *Arch. Phys. Med. Rehabil.* 74, 954-959.

Abstract: Simple systems for electrical stimulation (1-4 channels) with either surface, percutaneous, or implanted electrodes during locomotion were assessed in 10 subjects who had chronic, incomplete spinal cord injury (SCI). On average, the speed of locomotion was increased by 4 m/min independently of the subject's speed

of locomotion without stimulation (0-50 m/min) while oxygen consumption was reduced somewhat. These simple systems can provide practical help, particularly for incomplete SCI subjects who can stand but are lacking or have very limited ability to walk. Further improvement in locomotion requires stabilization and reduction in the duration of the stance phase of locomotion

Stein R.B., Zehr E.P., Lebedowska M.K., Popovic D.B., Scheiner A., and Chizeck H.J. (1996) Estimating mechanical parameters of leg segments in individuals with and without physical disabilities. *IEEE Trans. Rehabil. Eng* 4, 201-211.
Abstract: Methods are described for estimating the inertia, viscosity, and stiffness of the lower leg around the knee and of the whole leg around the hip that are applicable even to persons with considerable spasticity. These involve: 1) a "pull" test in which the limb is slowly moved throughout its range of motion while measuring angles (with an electrogoniometer) and torques (with a hand-held dynamometer) to determine passive stiffness and 2) a "pendulum" test in which the limb is moved against gravity and then dropped, while again measuring angles and torques. By limiting the extent of the movement and choosing a direction (flexion or extension) that minimizes reflex responses, the mechanical parameters can be determined accurately and efficiently using computer programs. In the sample of subjects studied (nine with disability related to spinal cord injury, head injury, or stroke, and nine with no neurological disability), the inertia of the lower leg was significantly reduced in the subjects with disability ($p < 0.05$) as a result of atrophy, but the stiffness and viscosity were within normal limits. The values of inertia were also compared with anthropometric data in the literature. The identification of these passive parameters is particularly important in designing systems for functional electrical stimulation of paralyzed muscles, but the methods may be widely applicable in rehabilitation medicine

Stein R.B. (1999) Functional electrical stimulation after spinal cord injury. *J. Neurotrauma* 16, 713-717.
Abstract: This article reviews work mainly from my own laboratory on the effects of electrical stimulation for therapy and function following spinal cord injury. One to two hours per day of intermittent stimulation can increase muscle strength and endurance and also reverse some of the osteoporosis in bones that are stressed by the stimulation. Stimulation during walking can also be used to improve speed and other parameters of the gait. Surface stimulation systems with 1-4 channels of stimulation were used in a multicenter study. Initial increases of almost 20% in walking speed were seen and overall increases of nearly 50% in subjects who continued to receive stimulation for a year on average. Some changes were due to improved strength and coordination with stimulation and additional walking, but a specific effect of stimulation persisted throughout the trial. Improved devices will soon be available commercially that were developed on the basis of feedback from users

Strojnjk P., Acimovic-Janezic R., Vavken E., Simic V., Stanic U. (1987) Treatment of drop foot using an implantable peroneal underknee stimulator. *Scand J Rehabil Med* 19, 37-43.

Subbarao J.V. (1991) Walking after spinal cord injury. Goal or wish? *West J. Med.* 154, 612-614.
Abstract: Less than a third of patients walk again after a spinal cord injury, whereas every one of them wants to try. Residual function, energy expenditure, the extent of

orthotic support needed, and patient motivation will determine the outcome. Functional electrical stimulation and other new orthotic designs have not notably increased the number of persons able to walk after a spinal injury. Rehabilitation professionals can use patient education, illustrating relearning to walk with examples of infants' and toddlers' progress, to assist patients in understanding their abilities and limitations. The final decision on ambulation and orthotic prescriptions can be made in stages after a patient adjusts to a wheelchair-independent level

Subbarao J.V. (1996) Ambulation in Spinal Cord Injured Patients - Options: Where Do We Stand? *J Spinal Cord Med* 19, 88.

Taylor P.N., Ewins D.J., Fox B., Grundy D., and Swain I.D. (1993) Limb blood flow, cardiac output and quadriceps muscle bulk following spinal cord injury and the effect of training for the Odstock functional electrical stimulation standing system. *Paraplegia* 31, 303-310.

Abstract: As part of the assessment of the Odstock functional electrical stimulation (FES) standing system for mid to low thoracic lesion spinal cord injured (SCI) subjects, cardiac output, high blood flow and quadriceps muscle thickness were measured before and following an electrical stimulation muscle retraining programme. The same parameters were also measured in a group of uninjured subjects and in SCI subjects. It was found that there was no difference in cardiac output between the groups. However thigh blood flow was found to be around 65% of normal values in the spinally injured group. This returned to normal values following the retraining programme. The quadriceps muscle wasted to approximately 50% of its original thickness in the first 3 weeks following spinal cord injury. The retraining programme increased the muscle thickness to near normal values

Taylor P.N., Burridge J.H., Dunkerley A.L., Lamb A., Wood D.E., Norton J.A., and Swain I.D. (1999) Patients' perceptions of the Odstock Dropped Foot Stimulator (ODFS). *Clin. Rehabil.* 13, 439-446.

Abstract: OBJECTIVE: To determine the perceived benefit, pattern and problems of use of the Odstock Dropped Foot Stimulator (ODFS) and the users' opinion of the service provided. DESIGN: Questionnaire sent in a single mailshot to current and past users of the ODFS. Returns were sent anonymously. SETTING: Outpatient-based clinical service. SUBJECTS: One hundred and sixty-eight current and 123 past users with diagnoses of stroke (CVA), multiple sclerosis (MS), incomplete spinal cord injury (SCI), traumatic brain injury (TBI) and cerebral palsy (CP). INTERVENTION: Functional electrical stimulation (FES) to correct dropped foot in subjects with an upper motor neuron lesion, using the ODFS. MAIN OUTCOME MEASURES: Purpose-designed questionnaire. RESULTS: Return rate 64% current users (mean duration of use 19.5 months) and 43% past users (mean duration of use 10.7 months). Principal reason cited for using equipment was a reduction in the effort of walking. Principal reasons identified for discontinuing were an improvement in mobility, electrode positioning difficulties and deteriorating mobility. There were some problems with reliability of equipment. Level of service provided was thought to be good. CONCLUSION: The ODFS was perceived by the users to be of considerable benefit. A comprehensive clinical follow-up service is essential to achieve the maximum continuing benefit from FES-based orthoses

Teeter J.O., Kantor C., Brown D.L. (1995) *FES Resource Guide for persons with Spinal Cord Injury or Multiple Sclerosis*. Cleveland, FES Information Center.

Thomas A.J., Davis G.M., and Sutton J.R. (1997) Cardiovascular and metabolic responses to electrical stimulation-induced leg exercise in spinal cord injury. *Methods Inf. Med.* 36, 372-375.

Abstract: Electrical stimulation-induced leg muscle contractions provide a useful model for examining the role of leg muscle neural afferents during low-intensity exercise in persons with spinal cord-injury and their able-bodied cohorts. Eight persons with paraplegia (SCI) and 8 non-disabled subjects (CONTROL) performed passive knee flexion/extension (PAS), electrical stimulation-induced knee flexion/extension (ES) and voluntary knee flexion/extension (VOL) on an isokinetic dynamometer. In CONTROLS, exercise heart rate was significantly increased during ES (94 +/- 6 bpm) and VOL (85 +/- 4 bpm) over PAS (69 +/- 4 bpm), but no changes were observed in SCI individuals. Stroke volume was significantly augmented in SCI during ES (59 +/- 5 ml) compared to PAS (46 +/- 4 ml). The results of this study suggest that, in able-bodied humans, Group III and IV leg muscle afferents contribute to increased cardiac output during exercise primarily via augmented heart rate. In contrast, SCI achieve raised cardiac output during ES leg exercise via increased venous return in the absence of any change in heart rate

Twist D.J. (1990) Acrocyanosis in a spinal cord injured patient--effects of computer-controlled

neuromuscular electrical stimulation: a case report. *Phys. Ther.* 70, 45-49.

Abstract: This case report documents the treatment of a spinal cord injured patient with acrocyanosis of both feet. The 37-year-old white male patient sustained a traumatic spinal cord injury at the age of 16 years, which resulted in an incomplete vertebral fracture of the C5-C6 level. He was treated with computerized neuromuscular electrical stimulation (NMES) of the quadriceps femoris muscle with weights applied to the ankles an average of two times per week for six weeks. Improvements in the color of the patient's skin and toe ulcers, stronger pedal pulses bilaterally, decreased swelling bilaterally, and subjective reports of less discomfort were noted. The empirical findings of this case report suggest that computerized NMES may be effective for improving circulation in the spinal cord injured individual with acrocyanosis. Further study, however, is needed to determine whether a relationship may exist between blood flow and computerized NMES

Uhlir J.P., Triolo R.J., and Kobetic R. (2000) The use of selective electrical stimulation of the quadriceps to improve standing function in paraplegia. *IEEE Trans. Rehabil. Eng* 8, 514-522.

Abstract: Persons with spinal cord injury (SCI) can benefit significantly from functional neuromuscular stimulation (FNS) systems for standing if manual tasks can be performed while upright. Using FNS to sufficiently activate the knee extensors to rise from a sitting position often results in inadvertent activation of the rectus femoris and/or sartorius, which flex the hip. In this study, intramuscular electrodes implanted in the vastus lateralis and medialis of four subjects with SCI were used to activate these muscles individually and simultaneously to measure knee extension moment. Support forces applied to the arms and feet were measured while upright to quantify the effects of recruiting rectus femoris and/or sartorius. In three of the four subjects, vastus lateralis, by itself, generated adequate knee extension moment for rising from a chair and to maintain static standing. Simultaneous activation of the vastus lateralis and medialis using a bifurcated electrode generated adequate knee extension moment in one subject, and was within 10% of the required moment in another.

While upright, activation of the rectus femoris resulted in arm support force increases of 4-11% body weight, while deactivation resulted in arm support force decreases of 6-9% body weight. The results indicate that selective activation of the vastus lateralis, individually or in combination with vastus medialis, can improve current FNS standing systems by reducing the arm support forces required to remain upright

Van Kerrebroeck P.E. (1998) The role of electrical stimulation in voiding dysfunction. *Eur. Urol.* 34 Suppl 1, 27-30.

Abstract: Different forms of dysfunction of the lower urinary tract can be treated with electrical stimulation. Currently, two operative treatment modalities are available. In patients with spinal cord injury the combination of posterior sacral root rhizotomies with implantation of electrodes on the anterior roots produces excellent results in terms of restoration of continence and bladder evacuation. In patients with chronic problems of urge incontinence, urgency/frequency and voiding dysfunction, neuromodulation of a sacral nerve with an implantable system can reduce the symptomatology significantly. Both these treatments are a valuable addition to the modern neuro-urological practice

Varma J.S., Binnie N., Smith A.N., Creasey G.H., and Edmond P. (1986) Differential effects of sacral anterior root stimulation on anal sphincter and colorectal motility in spinally injured man. *Br. J. Surg.* 73, 478-482.

Abstract: The motility responses of the sigmoid colon, rectum and external anal sphincter to sequential electrical stimulation of the anterior sacral roots (S2, S3 and S4) were studied in five patients with traumatic spinal cord injury. Identical and reproducible results were obtained. S2 stimulation provoked isolated low-pressure colorectal contractions. S3 stimulation initiated high-pressure colorectal motor activity which appeared peristaltic and was enhanced with repetitive stimuli. This response appeared to be frequency-dependent. S4 stimulation increased colonic and rectal tone. External sphincter activity was stimulated in increasing order from S2 to S4. These observations directly elucidate the central control of colorectal motility and may have implications in the treatment of severe constipation following spinal injury

Vodovnik L., Karba R. (1992) Treatment of chronic wounds by means of electric and electromagnetic fields, Part 2: Literature review. *Med Biol Eng Comput* 30, 257-266.

Ward A., Rushton D., Graham J., Donaldson N. [Eds] (1997) *Neuroprostheses, Neuromodulators and Rehabilitation: A Report of the British Society of Rehabilitation Medicine*. London, British Society of Rehabilitation Medicine.

Waters R.L. (1996) Functional Prognosis of Spinal Cord Injuries. *J Spinal Cord Med* 19, 89-92.

Waters R.L., Campbell J.M., Nakai R. (1988) Therapeutic electrical stimulation of the lower limb by epimysial electrodes. *Clin Orthop Rel Res* 233, 44-51.

Waters R.L., Frazier J., Garland D. (1982) Electromyographic gait analysis before and after treatment for hemiplegic equinus and equinovarus deformity. *J Bone & Joint Surg* 64A, 284-288.

Waters R.L., McNeal D.R., Faloon W., Clifford B. (1985) Functional electrical stimulation of the peroneal nerve for hemiplegia: long-term clinical follow-up. *J Bone & Joint Surg* 67A, 792-793.

Waters R.L., Hislop H., Perry J., Antonelli D. (1978) Energetics: Application to the study and management of locomotor disabilities. *Orthop Clin North Am* 9:351-377.

Wheeler J.S., Jr., Robinson C.J., Culkun D.J., and Bolan J.M. (1986) The effect of thigh muscle reconditioning by electrical stimulation on urodynamic activity in SCI patients. *J. Am. Paraplegia Soc.* 9, 16-23.

Abstract: Various forms of electrical stimulation are being used more frequently for bladder and muscle rehabilitation following spinal injury. Fifteen patients with spinal cord injury underwent a four to eight week period of thigh muscle reconditioning by surface electrical stimulation. The accumulated effects of this program on bladder function were assessed by urodynamic evaluation before and after the test period. Seven patients had beneficial changes of either an increase in bladder capacity and/or a decrease in bladder pressure. Six patients had a decrease in bladder capacity and/or an increase in bladder pressure, although two of these six patients had resolution of spinal shock. Two patients with detrusor areflexia had no changes in pressure or capacity. There was no change in the basic urodynamic patterns, only the parameters of bladder capacity and pressure. Increasing the use of electrical stimulation for rehabilitation of the spinal cord population might alter bladder function, although not consistently. One should, therefore, be aware of these changes when setting up such rehabilitation programs

Wheeler J.S., Jr., Walter J.S., and Zaszczurynski P.J. (1992) Bladder inhibition by penile nerve stimulation in spinal cord injury patients. *J. Urol.* 147, 100-103.

Abstract: Detrusor hyperreflexia causing voiding dysfunction in spinal cord injury patients is a difficult problem and is not always treated effectively by anticholinergic agents. We have been investigating electrical stimulation methods to inhibit hyperreflexia and dorsal penile nerve stimulation is the most promising. Six chronic suprasacral spinal cord injury men (average age 36 years) underwent stimulation testing with water cystometry before, during and after stimulation. Dorsal penile stimulation was done with carbon rubber butterfly electrodes (Medtronic) with parameters of 5 pulses per second, 0.35 msec. pulse duration, and current at a level above the threshold for pelvic twitching activity and adjusted for optimal bladder effect (range 25 to 70 mamp.). In all 6 patients the cystometrogram during stimulation showed an increase in bladder volume over the prestimulation cystometrogram (range 27 to 150%). In 2 patients there was no detrusor activity after filling to 500 cc. Stimulation was then stopped and a spontaneous contraction occurred. The cystometrogram conducted after the stimulus also had less volume than that performed during stimulation but it was larger than the prestimulation volume. Penile nerve stimulation was painless with no side effects. Penile nerve electrical stimulation is effective for inhibiting bladder hyperreflexia and should be easily adaptable for chronic home use as an alternative to current therapy

Wieler M., Stein R.B., Ladouceur M., Whittaker M., Smith A.W., Naaman S., Barbeau H., Bugaresti J., and Aimone E. (1999) Multicenter evaluation of electrical stimulation systems for walking. *Arch. Phys. Med. Rehabil.* 80, 495-500.

Abstract: OBJECTIVE: To test the long-term benefits of several noninvasive systems for functional electrical stimulation (FES) during walking. DESIGN: Forty subjects

(average years since injury, 5.4) were studied in four centers for an average time of 1 year. Gait parameters were tested for all subjects with and without FES. Thus, subjects served as their own controls, since the specific effect of using FES could be separated from improvements resulting from other factors (e.g., training). SETTING: Subjects used the devices in the community, but were tested in a university or hospital setting. PATIENTS: Subjects with spinal cord injury (n = 31) were compared to subjects with cerebral damage (n = 9). MAIN OUTCOME MEASURES: Gait parameters (speed, cycle time, stride length). Acceptance was studied by means of a questionnaire. RESULTS: Some initial improvement in walking speed (average increase of >20%) occurred, and continuing gains were seen (average total improvement, 45%). The largest relative gains were seen in the slowest walkers (speeds of <0.3 m/sec). Acceptance of the FES systems was good and improved systems have been developed using feedback from the subjects. CONCLUSIONS: Based on the improvements in speed and the acceptance of these FES systems, a greatly increased role for FES in treating gait disorders is suggested

Wood J.M., Evans P.E., Schallreuter K.U. (1993) A multicenter study on the use of pulsed low-intensity direct current for healing chronic stage II and stage III decubitus ulcers. *Arch Dermatol* 129, 999-1009.

Yarkony G.M. (1994) Pressure ulcers: a review. *Arch. Phys. Med. Rehabil.* 75, 908-917. Abstract: This article reviews the etiology, pathology, description, risk factors, prevention, medical and surgical management, and complications of pressure ulcers. Pressure ulcers, which develop primarily from pressure and shear, are also known as decubitus ulcers, bed sores, and pressure sores. They continue to occur in hospitals, nursing homes, and among disabled persons in the community. Estimates of the prevalence of pressure ulcers in hospitalized patients range from 3% to 14% and up to 25% in nursing homes. Persons with spinal cord injury and the elderly are two groups at high risk. The most common sites of development are the sacrum, ischium, trochanters, and about the ankles and heels. Areas of ongoing research such as electrical stimulation and growth factors are discussed.