FES Cycling

Rik Berkelmans

***Abstract* — Many research with functional electrical stimulation (FES) has been done to regain mobility and for health benefits. Better results have been reported for FES-cycling than for FES-walking. The majority of the subjects during such research are people with a spinal cord injury (SCI), cause they often lost skin sensation. Besides using surface stimulation also implanted stimulators can be used. This solves the skin sensation problem, but needs a surgery. Many physiological effects of FES-cycling has been reported, e.g., increase of muscles, better blood flow, reduction of pressure ulcers, improved self-image and some reduction of bone mineral density (BMD) loss. Also people with an incomplete SCI benefit by FES-cycling, e.g. cycling time without FES, muscle strength and also the walking abilities increased. Hybrid exercise gives an even better cardiovascular training. Presently 4 companies are involved in FES-cycling. They all have a stationary mobility trainer. Two of them also use an outdoor tricycle. One combined with voluntary arm cranking. By optimizing the stimulation parameters the power output and fatigue resistance will increase, but will still be less compared to voluntary cycling.**

***Index Terms*—arm cranking, bicycle, electrical stimulation, exercise, hybrid exercise.**

I. INTRODUCTION

IN 1983 and 1984 different research groups Eichhorn *et al.* [3], Glaser *et al.* [12] and Petrofsky *et al.* [28, 29] published their attempts to use functional electrical stimulation (FES) for cycling. FES walking takes a lot of effort to reach a speed just over 1 km/h and has a high risk of falling. FES cycling with a tricycle is much safer. Cycling is also a more efficient way of transportation, although the majority of FES cycling is done with stationary bikes.

In FES cycling the quadriceps, hamstrings and gluteal muscles are stimulated. Sometimes also the calf muscles are stimulated. The power contribution of this muscle during FES cycling is almost zero. But it has been done to stimulate the blood circulation in the lower legs. All FES cycles have an angle encoder to measure the crank position. During a complete 360 degree cycle of the cranks every muscle has one stimulation period. The stimulation period of the hamstrings are the most difficult to determine because it’s a biarticulaire muscle. It flexes the knee and it extends the hips. These actions are during cycling in total different periods. The predominant period has to be chosen and depends on the anatomy and position of the subject on the bike.

Manuscript received December 11 2008.
F. A. Author is , BerkelBike BV, ‘s-Hertogenboch, The Netherlands, Fax, Phone, (e-mail): Info@BerkelBike.com

DOI:10.2298/JAC0802073B

The reason why people with a spinal cord injury (SCI) are dominating the FES cycling population is that they often have loss of sensation. To generate with surface electrodes any power output of the big lower extremity muscles, it is necessary to use relatively high currents, which feels like needles stinging the skin. The contraction of the muscle feels like a cramp and is less painful.

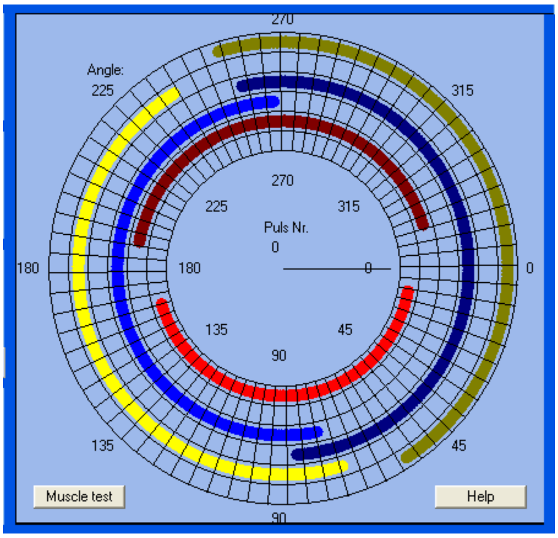

Figure 1: Shows an example of a stimulation pattern. Zero degrees is right pedal straight forward. In this case it is used at a recumbent tricycle. The seat and bottom bracket are almost on the same horizontal level. The stimulation periods in this example are longer then mostly used. The muscles from the inner circle outside: L quadriceps, R quadriceps, L hamstrings, R hamstrings, L gluteus, R gluteus.

By using large surface electrodes the density of the current (mA/cm2) can be lowered and so the tolerability improves. Implanted electrodes do not have the problem of skin sensation, but have the disadvantage of a surgery. A relatively small surgery is the injection of BIONs [21] these are injectable microstimulators. Each BION is placed near the nerve and is controlled by a controller outside the body. It makes it also possible to stimulate deeper laying muscles like the Iliopsoas. This muscle flexes the hip but cannot be directly stimulated by surface electrodes. It can only be activated indirect by stimulating the withdrawal reflex. The most important downside of the BION method would be the costs. Cycling needs at least 6 BION's this would be a quite expensive method.

To be able to use ordinary FES, the motor units should be intact so that the stimulation is just triggering the nerve. An extensive European project, called Rise, showed that even denervated muscles are also suited to be stimulated. But without an available nerve the stimulation has to trigger the muscle fibers directly. As a consequence the electrical energy (W) needed for stimulation is up to 100 times higher. The denervated muscles are also more difficult to train. They need around 3 times the training intensity. In the Rise project the subjects where trained to stand and sometimes walk. Walking proved to be not very practical because the power output is even worse compared with stimulation of innervated muscles and the stimulator is much bigger and heavier. Still the stimulation has a large therapeutic benefit [1, 18].

II. PHYSIOLOGICAL EFFECTS

In the first two years after the incidence of SCI, bone density markedly decreases. For instance bone mass in the proximal tibia equals approximately 50% of normal values [23]. FES cycling may not reverse these changes, but retard the progression if training starts in time [11]. To observe significant change in bone mineral density (BMD), a longer training period at a high intensity is needed. During a resent research of Frotzler *et al*. [6] 11 subjects FES-cycled on average 3.7 times a week, approximately 1 hour each session, at each individual's highest power output. After a year of FES-cycling their results indicate "that high-volume FES-cycling leads to site-specific skeletal changes in the paralyzed limbs, with an increase in bone parameters at the actively loaded distal femur but not the passively loaded tibia."

The muscle decline is even faster than the BMD, due to the lack of the ability to use them. Research studies have clearly indicated that several weeks of progressive FES cycling training not only induced hypertrophy, but also markedly improved strength and endurance of stimulated muscles [7, 37]. This indicates that muscle atrophy is reversible to some extent [35]. FES training also leads to changes in muscle fiber composition. The proportion of type 2 muscle fibers (fast-glycolytic) to type 1 muscle fibers (slow-oxidative) increases as a consequence of SCI. A shift back to more fatigue resistant type 1 muscle fibers was found after one year of training [8, 22, 32].

Some research groups, including Glaser, claimed FES cycling reduced spasticity in SCI individuals. However, the opinions about spasticity are divided. Spasticity may become less present, but the spasticity that will occur is stronger than before, because of improved muscle strength [17].

Bremner *et al*. [2] and Glaser [11] reported an increase in range of motion after FES cycling, which can be useful when making transfers and performing activities in daily life.

FES cycling has proven to be a useful tool to regain and improve some cardiovascular parameters. Peripheral changes in capillary density and an increase in arterial inflow are reported by Gerrits *et al*. [8]. They found relatively normal vessel diameters after a long period of FES cycling training. In addition, metabolic and cardiopulmonary responses increased which resulted in better blood availability and therefore improved O_2 delivery and removal of metabolic end products.

One of the most important advantages of FES cycling is the improvement of cardiopulmonary fitness [5, 16, 22, 30, 34]. Endurance levels increase, indicated by increased total training durations and higher power outputs [30]. Correspondingly, there are significant increases in heart rate, stroke volume, cardiac output, blood pressure, pulmonary ventilation and VO_2 peak levels [5, 9, 16, 22, 30, 34]. Raymond *et al*. [34] and Hooker *et al*. [16] found higher VO_2 peak levels of SCI individuals after 19 weeks of FES training. FES cycling can regain VO_2 peak levels from 50 to 60% of the normal values of able-bodied individuals [16]. Hooker *et al*. also reported an increase of 23% in VO_2 peak levels after 12 to 16 weeks of FES cycling, two to three times a week in persons with SCI who were previously untrained in this activity [14].

In a recent investigation by Griffin *et al*. [13], significant reductions occurred in all inflammatory markers tested (CRP, IL-6 and TNF-alfa). This is the first study to demonstrate these improvements in the SCI population and suggests that FES may be an effective mechanism for reducing the incidence of cardiovascular disease in this population. It is also important to acknowledge that elevations in plasma TNF-alfa have been associated with insulin resistance and type 2-diabetes [31]. Their finding of an improvement in glucose tolerance and insulin sensitivity following 10 weeks (2-3 times a week, 30 minutes each session) of FES cycling with 18 subjects, therefore, could be, in part, due to lowering of plasma TNF-alfa.

Muscle can also be seen as a valuable tissue, which act as a cushion. Active muscle encourages good blood flow. Due to the muscle wasting, pressure sores are prevalent amongst people with SCI. Pressure sores are demoralizing and can take many months to heal involving a lengthy stay in bed [41]. Another important benefit of FES training is its' ability to reduce the incidence of pressure sores. Petrofsky [27] reported a 90% reduction of pressure sores in a group of individuals with SCI who participated in a 2-year FES exercise program. This reduction improves the quality of life significantly.

Besides physiological effects has FES cycling also mental benefits. Due to the activity of the muscles, the body releases beta-endorphin, which gives the person a good feeling. Sipsky *et al*. [36] also ascertained that the majority of a group of 52 subjects with SCI reported an improved self-image and that they perceived their appearance to be better after a period of FES training ranging from 1.5 months to 2.5 years.

III. PHYSIOLOGICAL EFFECTS FOR PEOPLE WITH AN INCOMPLETE SCI

Less FES research has been done with people with an incomplete SCI, because they often have sensation below the lesion. Page *et al*. [26] developed and tested a FES cycling protocol for incomplete, chronic SCI subjects: a 2-phase, 10 weeks FES cycling intervention occurring 3 days a week. Phase 1 provided 30 minutes FES cycling sessions at increasing resistance. Phase 2 required cycling independently (i.e., without stimulation) at maximal effort for increasing lengths of time. During all phase 1 sessions, the subject required stimulation because his mean rotations per minute (RPM) was consistently below 50. Only after 2 visits in phase 2, the subject was able to sustain adequate effort to cycle without stimulation (RPM > 50). During this phase the time the subject was able to cycle independently increased to eventually 10 minutes.

This cycling training also increased the subject's walking velocity, mean step length and mean stride length. He also derived several other functional benefits, including new hip flexion that allowed greater ease of transfers to his car and toilet. He also could discontinue some medications.

During a research of Liu *et al*. [20] 18 subjects with various degrees of incomplete SCI were FES cycling thrice a week for 8 weeks. This resulted in significant increase in thigh muscle mass after 4 weeks and muscle peak torque after 8 week period of training. Besides, the more residual muscle strength there was, the more percentage of strength was regained.

IV. HYBRID EXERCISE

Hybrid exercise, the combination of FES cycling and arm exercise, simultaneously, has been investigated by a couple of research groups [4, 10, 11, 15, 24, 33, 34]. They all concluded that hybrid exercise gives better cardiovascular training results than arm cranking exercise or FES-cycling alone; showing higher VO_2 (peak) values, greater work rates and higher stroke volumes. Raymond *et al*. [34] showed that the VO_2 value was 25% higher during hybrid (sub-maximal) training compared to arm crank exercise alone (1.58 vs. 1.26 l/min). They also showed a significantly higher work rate for hybrid exercise compared to arm cranking alone (34.9 +/-7.4 W vs. 29.6 +/-6.3 W) [33, 34]. Researchers were not consistent about the heart rate response. Hooker *et al*. [15] found higher heart rate responses for hybrid exercise in comparison to FES cycling or arm crank exercise alone. Raymond *et al*. [34] found higher stroke volumes, but lower heart rates during hybrid exercise. Raymond *et al*. concluded that the increased venous return of blood to the heart made it unnecessary to level up the heart rate [34]. Higher magnitudes of responses during the hybrid exercise improves aerobic capacity better than arm cranking or FES cycling alone [4, 10, 11, 15, 24, 33, 34].

V. EXISTING FES CYCLING PRODUCTS

FES cycling is more then 30 years old. For home use it is much saver and easier than FES walking. Despite the medical advantages not many SCI patient are using FES cycling. The last 5 years one company (Electrologic, 2005) stopped, but 3 companies started to sell FES cycles. At this moment 4 companies are involved in FES cycling. Due to their efforts, FES cycling is promoted and becomes more popular.

Therapeutic Alliances Inc. (USA) [45] is the oldest one. They brought the first commercial available FES leg cycle ergometer in 1984 on the market. Patients have to make a transfer to the immobile ergometer. To ensure movement from the leg in one plane they use a guider on the upper leg. A second person has to rotate the legs for 2 minutes to warm up the legs. Then the stimulation can be started and the stimulation intensity is regulated to maintain a muscle driven 50 rpm. If the stimulation intensity has reached 100% the revolution speed will as a result of fatigue. At 35 rpm the stimulation will be stopped automatically.

RTI (USA) [44] uses a stationary mobility trainer from Medica Medizintechnik GmbH [42] and integrate their stimulation equipment. Hasomed (Germany) [40] does the same with the stationary mobility trainer from RECK [43], but they can also put their equipment on an outdoor tricycle from Hase [39]. Both mobility trainers have a motor inside. This motor can assist when the muscles are fatigued and it can provide resistance when the muscles have enough power.

Figure 2: Stationary FES cycle ergometer. [45]

BerkelBike BV (Netherlands) [38] has three different models. All of them have voluntary arm cranking and FES leg cycling. The arm cranking is added for the physiological effects, to give a higher driving speed and better fatigue resistance. Two of these models can also be used for outdoor cycling. One can even be attached to and detached from a normal wheelchair as shown in fig 3.

Figure 3: This bike combines armcranking and FES cycling and is coupled to a wheelchair. [38]

Stimulation parameters. A lot of effort has been put in to optimizing the stimulation parameters to boost the power output and raise the fatigue resistance. The difficulty with optimization is the almost endless parameter combinations, table 1.

Table 1. FES parameters

PARAMETER	RANGE	COMMON
FREQUENCY	20 - 60 HZ	30 HZ
MAX. CURRENT	120 - 300 MA	150 MA
PULSE DURATION	0,1 - 1 MS	0,4 MS
PULSE FORM	BLOCK, SINUS, TRIANGEL	BLOCK
POLARITY	MONO- BIPHASIC	BIPHASIC
PULSE TRAIN	RAMP UP, RAMP DOWN, INITIAL DOUBLET	RAMP UP
TIMING	START - STOP MOMENT EVERY MUSCLE	-
PRE SET	100 - 150 MS	125 MS

Each person has his one optimum parameter combination. The stimulation timing depends not only on the anatomy of the FES cyclist but also on his position in the chair, especially the angle in the hip is important.

By optimizing all the stimulation parameters, the power output of a spinal cord-injured person is still less than that of an able-bodied person. According to Newham [25] has most of this difference due to the change of muscle type after a SCI. An interesting finding is that when healthy able-bodied people perform FES cycling after being temporarily paralyzed by an epidural anesthetic, they produce approximately half of the power output achieved at the same oxygen consumption and heart rate with voluntary effort [19].

REFERENCES

[1] Ashley Z, Sutherland H, Russold MF, Lanmuller H, Mayr W, Jarvis JC, Salmons S: Therapeutic stimulation of denervated muscles: The influence of pattern. Muscle Nerve 2008, 38:875-886.

[2] Bremner LA, Sloan KE, Day RE, Scull ER, Ackland T: A clinical exercise system for paraplegics using functional electrical stimulation. Paraplegia 1992, 30:647-655.

[3] Eichhorn KF, Schubert W, David E: Maintenance, training and functional use of denervated muscles. J Biomed Eng 1984, 6:205-211.

[4] Figoni SF, Glaser RM: Hemodynamic responses of quadriplegics to arm, ES leg and combined ES leg and arm ergometry. Med.Sci.Sports Exerc. 1989, 21(S96):

[5] Figoni SF, Rodgers MM, Glaser RM, Hooker SP, Feghri PD, Ezenwa BN, Mathews T, Suryaprasad AG, Gupta SC: Physiologic responses of paraplegics and quadriplegics to passive and active leg cycle ergometry. J Am Paraplegia Soc 1990, 13:33-39.

[6] Frotzler A, Coupaud S, Perret C, Kakebeeke TH, Hunt KJ, Donaldson Nde N, Eser P: High-volume FES-cycling partially reverses bone loss in people with chronic spinal cord injury. Bone 2008, 43:169-176.

[7] Gerrits HL, De Haan A, Hopman MT, van Der Woude LH, Jones DA, Sargeant AJ: Contractile properties of the quadriceps muscle in individuals with spinal cord injury. Muscle Nerve 1999, 22:1249-1256.

[8] Gerrits HL, Haan Ad, Kuppevelt HJMv, Langen Hv, Hopman MT: Het effect van FES-fiets training bij een dwarslaesie. Geneeskunde en Sport 2000, 33(6):7-15.

[9] Glaser RM, Figoni SF, Hooker SP, Rodgers MM, Ezenwa BN, Suryaprasad AG, Gupta SC, Mathews T: Efficiency of FNS leg cycle ergometry. IEEE Eng in Med & Biology 1989, :961-963.

[10] Glaser RM, Strayer JR, May KP: Combined FES leg and voluntary arm exercise of SCI patients. IEEE Eng in Med & Biology soc (Chicago) 1985, :308-313.

[11] Glaser RM: Functional neuromuscular stimulation: exercise conditioning of spinal cord injured patients. Int J Sports Med 1994, 15:142-148.

[12] Glaser RM, Gruner JA, Feinberg SD, Collins SR: Locomotion via paralyzed leg muscles: Feasibility study for a leg-propelled vehicle. J Rehabil R D 1983, 20:87-92.

[13] Griffin L, Decker MJ, Hwang JY, Wang B, Kitchen K, Ding Z, Ivy JL: Functional electrical stimulation cycling improves body composition, metabolic and neural factors in persons with spinal cord injury. J Electromyogr Kinesiol 2008,

[14] Hooker SP, Figoni SF, Rodgers MM, Glaser RM, Mathews T, Suryaprasad AG, Gupta SC: Physiologic effects of electrical stimulation leg cycle exercise training in spinal cord injured persons. Arch Phys Med Rehabil 1992, 73:470-476.

[15] Hooker SP, Figoni SF, Rodgers MM, Glaser RM, Mathews T, Suryaprasad AG, Gupta SC: Metabolic and hemodynamic responses to concurrent voluntary arm crank and electrical stimulation leg cycle exercise in quadriplegics. J Rehabil Res Dev 1992, 29:1-11.

[16] Hooker SP, Scremin AM, Mutton DL, Kunkel CF, Cagle G: Peak and submaximal physiologic responses following electrical stimulation leg cycle ergometer training. J Rehabil Res Dev 1995, 32:361-366.

[17] Janssen TWJ, Glaser RM, Shuster DB: Clinical efficacy of electrical stimulation exercise training: Effects on health, fitness, and function. Spinal Cord Injury Rehab 1998, 3:33-49.

[18] Kern H, Hofer C, Modlin M, Forstner C, Raschka-Hogler D, Mayr W, Stohr H: Denervated muscles in humans: Limitations and problems of currently used functional electrical stimulation training protocols. Artif Organs 2002, 26:216-218.

[19] Kjaer M, Perko G, Secher NH, Boushel R, Beyer N, Pollack S, Horn A, Fernandes A, Mohr T, Lewis SF: Cardiovascular and ventilatory responses to electrically induced cycling with complete epidural anaesthesia in humans. Acta Physiol Scand 1994, 151:199-207.

[20] Liu CW, Chen SC, Chen CH, Chen TW, Chen JJ, Lin CS, Huang MH: Effects of functional electrical stimulation on peak torque and body composition in patients with incomplete spinal cord injury. Kaohsiung J Med Sci 2007, 23:232-240.

[21] Loeb GE, Richmond FJ, Baker LL: The BION devices: Injectable interfaces with peripheral nerves and muscles. Neurosurg Focus 2006, 20:E2.

[22] Mohr T, Andersen JL, Biering-Sorensen F, Galbo H, Bangsbo J, Wagner A, Kjaer M: Long-term adaptation to electrically induced cycle training in severe spinal cord injured individuals. Spinal Cord 1997, 35:1-16.

[23] Mohr T, Podenphant J, Biering-Sorensen F, Galbo H, Thamsborg G, Kjaer M: Increased bone mineral density after prolonged electrically induced cycle training of paralyzed limbs in spinal cord injured man. Calcif Tissue Int 1997, 61:22-25.

[24] Mutton DL, Scremin AM, Barstow TJ, Scott MD, Kunkel CF, Cagle TG: Physiologic responses during functional electrical stimulation leg cycling and hybrid exercise in spinal cord injured subjects. Arch Phys Med Rehabil 1997, 78:712-718.

[25] Newham DJ, Donaldson Nde N: FES cycling. Acta Neurochir Suppl 2007, 97:395-402.

[26] Page SJ, Levine P, Strayer J: An electric stimulation cycling protocol for gait in incomplete spinal cord injury. Arch Phys Med Rehabil 2007, 88:798-800.

[27] Petrofsky JS: Functional electrical stimulation, a two-year study. J Rehabil 1992, :29-34.

[28] Petrofsky JS, Phillips CA, Heaton H,3rd, Glaser RM: Bicycle ergometer for paralyzed muscle. J Clin Eng 1984, 9:13-19.

[29] Petrofsky JS, Heaton H,3rd, Phillips CA: Outdoor bicycle for exercise in paraplegics and quadriplegics. J Biomed Eng 1983, 5:292-296.

[30] Petrofsky JS, Stacy R: The effect of training on endurance and the cardiovascular responses of individuals with paraplegia during dynamic exercise induced by functional electrical stimulation. Eur J Appl Physiol Occup Physiol 1992, 64:487-492.

[31] Plomgaard P, Nielsen AR, Fischer CP, Mortensen OH, Broholm C, Penkowa M, Krogh-Madsen R, Erikstrup C, Lindegaard B, Petersen AM, Taudorf S, Pedersen BK: Associations between insulin resistance and TNF-alpha in plasma, skeletal muscle and adipose tissue in humans with and without type 2 diabetes. Diabetologia 2007, 50:2562-2571.

[32] Ragnarsson KT: Physiologic effects of functional electrical stimulation-induced exercises in spinal cord-injured individuals. Clin Orthop Relat Res 1988, (233):53-63.

[33] Raymond J, Davis GM, Climstein M, Sutton JR: Cardiorespiratory responses to arm cranking and electrical stimulation leg cycling in people with paraplegia. Med Sci Sports Exerc 1999, 31:822-828.

[34] Raymond J, Davis GM, Fahey A, Climstein M, Sutton JR: Oxygen uptake and heart rate responses during arm vs combined arm/electrically stimulated leg exercise in people with paraplegia. Spinal Cord 1997, 35:680-685.

[35] Scremin AM, Kurta L, Gentili A, Wiseman B, Perell K, Kunkel C, Scremin OU: Increasing muscle mass in spinal cord injured persons with a functional electrical stimulation exercise program. Arch Phys Med Rehabil 1999, 80:1531-1536.

[36] Sipski ML, Delisa JA, Schweer S: Functional electrical stimulation bicycle ergometry: Patient perceptions. Am J Phys Med Rehabil 1989, 68:147-149.

[37] Stein RB: Functional electrical stimulation after spinal cord injury. J Neurotrauma 1999, 16:713-717.

[38] BerkelBike BV,'s-Hertogenbosch, Netherlands [www.berkelbike.com]

[39] Hase Spezialräder, Waltrop, Germany [www.hasebikes.com]

[40] Hasomed GmbH, Magdenburg, Germany [www.hasomed.de]

[41] INtegrated SPInal REhabilitation [www.inspire.demon.co.uk]

[42] Medica Medizintechnik GmbH, Hochdorf, Germany [www.medica-medizin.de]

[43] RECK-technik GmbH & co. KG, Betzenweiler, Germany [www.motomed.de]

[44] Restorative Therapies Inc., Baltimore, Maryland, USA [www.restorative-therapies.com]

[45] Therapeutic Alliances Inc., Fairborn, Ohio, USA [www.musclepower.com]