Chapter Seven

Functional Electrical Stimulation Leg Exercise: From Technology to Therapy

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7.1 INTRODUCTION

Functional electrical stimulation (FES) is the application of external electrical currents to elicit muscle contractions using a neuromuscular stimulator, thereby bypassing the central nervous system (Holsheimer 1998). Muscle contractions via transcutaneous FES employs a control switch, a stimulator and a pair of electrodes over the muscle belly. (Sisto, 2009). When electrical stimulation is applied these muscles contract to produce motion, force and power.

Electrically stimulated contractions are employed to achieve ‘functional’ outcomes such as walking, standing or cycling, and to reverse foot-drop during gait in hemiplegic patients (Currier, 1992). In spinal cord injury (SCI) rehabilitation, FES is used to maintain or increase range of motion, ablate contractures, strengthen muscles, facilitate voluntary motor function, reduce spasticity, and prevent circulatory or orthostatic hypotension. In addition, FES is extensively used as a way of making possible exercise using the paralysed limbs. (Sisto, 2009). Although not strictly “functional”, FES-induced leg cycling has known benefits (Hamzaid, 2009) and it is broadly included because such benefits enhance functional outcomes.

7.2 EXERCISE FOR PEOPLE WITH NEUROLOGICAL DISABILITIES

Regular physical activity is beneficial not only for the able-bodied population, but also for people with neurological disabilities. (Myslinski 2005). Regular exercise induces numerous adaptations towards improved whole body fitness, particularly within the skeletal muscles. These adaptations have positive sequelae
for the prevention and treatment of metabolic disorders (Hawley, 2009), especially amongst individuals with neurological pathophysiology.

Regular muscle strength and aerobic fitness training are normally prescribed to people with neurological disabilities to enhance their psychosocial and physical wellbeing (Skidmore, 2008). Individuals with stroke may perform exercise (Aziz, 2008) or task-oriented training (Rensink, 2009) to preserve and restore their fitness and functional capacity. People with traumatic brain injury (Bateman, 2001; Ross, 2009) may require regular exercise and physical training to improve their severely impaired wellbeing. (Mayo Clinic 2009).

### 7.2.1 Spinal Cord Injury and Exercise

SCI generally results from a traumatic lesion to the neural tracts within the spinal canal that result in sensory loss, motor deficit and bladder/bowel dysfunction (Anderson, 2002; Lifshutz, 2004). The most common causes of spinal cord injury are motor vehicle accidents (55%), followed by violence, falls, and recreational sports participation (Yeo, 1998).

Since the affected population is primarily young adults, and with improved medical treatment, lifespan after SCI has significantly increased. However, as cervical or thoracic lesion SCI may lead to loss of lower limb movements, tetraplegia and paraplegia almost always result significant physical deconditioning. Consequently, individuals with SCI often have significant reduction of their physical fitness due to a limited movement capacity, which can lead to secondary degenerative disorders such as diabetes, hypertension and the early onset of cardiovascular disease (Jacobs, 2004). Effective rehabilitation, including aerobic fitness and muscular strength training can be useful preventive measures against secondary health problems.

Exercise is one possible strategy to reduce or reverse some of these post-injury complications (Jacobs, 2004). In individuals with SCI, voluntary exercise improves cardiovascular health, and increases the strength and endurance of the limbs that undergo training (Hicks, 2003). In contrast to voluntary exercise, FES-evoked training, which uses electrical stimulation of paralysed muscles to produce coordinated movements offers unique benefits to the paralysed limbs (Creasey, 2004). Theoretically, greater physical fitness can be achieved by including the lower limbs in the exercise as they make up the greater muscle mass of the body (Jacobs, 2004). Therefore FES exercise systems are now being integrated into their rehabilitation to optimize training. (Sisto, 2009).

### 7.3 Electrical Stimulation of Muscles

Electrical stimulation-induced exercise applies trains of short, intense electrical pulses to generate muscle contractions and thereby elicit an exercise response (Dudley, 1999). Such artificially-evoked exercise usually involves the lower limbs, but may also involve the upper body via FES-assisted arm cycling in tetraplegics.
(Gollee, 2002) or wrist exercise (Hartkopp, 2003). The large muscle mass of the legs means that theoretically, FES leg exercise has greater potential than voluntary arm exercise to train and improve cardiovascular fitness (Shephard, 1988; Haennel, 1992; Glaser, 1994). The exercise performed during electrical stimulation can be as simple as isometric contractions through to more complex movements like leg raises (Hillegass, 1999), leg cycling (Fitzwater, 2002) or the lower-body component of rowing (Laskin, 1993).

The output of muscle stimulation using FES could be altered by modulating the current parameters, employing either monophasic or biphasic waveforms, current intensity, frequency, pulse duration and pulse train to elicit varied muscle contraction responses. (Kralj, 1989).

### 7.3.1 Stimulation Waveforms

Trains of closely spaced stimulation pulses (Fig. 1, upper panel) are used to evoke muscle contractions. At a pulse frequency above 10–20 Hz in humans, the muscle fibre twitches (40–100 msec) begin to overlap and summate forming an extended muscle contraction (Baker, 2000). Increasing the pulse frequency further causes greater overlap and earlier force summation, until the individual twitches completely fused into one smooth tetanic contraction. Tetanic summation depends upon the fibre characteristics of a particular muscle, but for de-efferented muscles it usually occurs about 40 Hz pulse frequency (Shields, 1997; Gerrits, 2002). By adjusting the stimulation frequency (i.e. frequency modulation), between the fusion and the tetanus frequencies, the summation of fibre twitches and resulting force can be modulated (Crago, 1980).

### 7.3.2 Pulse Frequency

During continuous stimulation, fatigue increases with higher stimulation frequency (Jones, 1979; Carroll, 1989; Hepple, 2003). There has been debate over whether the rate of fatigue is directly related to the frequency, the absolute number of pulses delivered (Marsden, 1983), both the frequency and the total number of pulses (Pace, 1990; Hokkanen, 1993).

#### Figure 7.1

Continuous stimulation (top panel) and intermittent stimulation (bottom panel). For intermittent stimulation the duty cycle is equal to the on-time divided by the period.

\[ \text{Duty Cycle} = \frac{\text{On-Time}}{\text{Period}} \]
of pulses (Garland, 1992), or the increased forces produced at higher frequencies (Russ, 2002). By trying to understanding what aspect of the stimulation frequency accelerates fatigue, researchers hope to develop new stimulation patterns such as variable frequency trains that will delay the occurrence of muscle fatigue (Bickel, 2003).

### 7.3.3 Intermittent Stimulation

Muscle stimulation during FES exercise can be continuous or intermittent. Intermittent stimulation (Fig. 1, lower panel) involves repeated rhythmic trains of stimulation separated by periods without stimulation. During intermittent stimulation the “period” of repetition denotes the time between the start of consecutive stimulation bursts (Franken, 1993). The on-time is the length of a sequence of stimulation pulse during one cycle. The “duty cycle” is the on-time divided by the period. Both the duty cycle and the period of the intermittent stimulation have significant effect upon FES muscle fatigue.

Initially, a greater duty cycle produces a greater force time-integral (Lieber, 1993). However, fatigue rate increases with stimulation duty cycle (Baker, 1988), such that over an extended session a greater force-time-integral may not necessarily be produced (Lieber, 1993). This relationship is not surprising because increased contraction times require more energy and produce more metabolic byproducts, plus there is less recovery time between contractions. However, because a large proportion of the energy cost of a contraction is used to attain the initial muscle force (Russ, 2002) there must be an optimum duty cycle that represents the best trade-off between force output, fatigue, and the biomechanics of the task.

During intermittent stimulation for protocols with equivalent duty cycles, fatigue rate decreases as stimulation period is prolonged (Bergström, 1988; Hogan, 1998). Bergstrom et al’s (1988) research, which investigated isometric muscle contractions, demonstrated that even though the total muscle contraction time and number of stimulation pulses were the same, fatigue developed faster in the protocols with shorter excitation periods. The metabolic cost of attaining a force is greater than maintaining the force. Hence, it is energetically ‘expensive’ and inefficient to produce short contractions (Bergström, 1988; Russ, 2002). However, if the length of the contraction is too long, then the amount of fatigue experienced will be greater (McTague, 1991). During long contractions ischemia may be induced by intramuscular pressure causing occlusion of blood circulation and an acceleration of fatigue (Petrofsky, 1975; Petrofsky, 2000). Higher contraction velocities also accelerate fatigue rate (Franken, 1993).

### 7.3.4 Electrode Types and Placements

A pair of electrodes is required to complete the circuit for current to flow through the muscles to evoke contractions. Spacing of the electrode pair effects the current
movement through muscle tissue. (Sisto, 2009). Electrodes closer to each other allow the current to travel more superficially. Electrodes spaced further apart facilitate current travel deeper inside the muscle tissues (Fig. 2).

The electrode pairs could be surface electrodes which are the most commonly used for FES. Also, percutaneous electrodes i.e. implanted in the muscle and exit through the skin; or implanted electrodes, i.e. completely implanted in the person’s spinal roots with radio frequency control outside the body could be used (Peckham 1987; Stein, 1992; Sisto, 2009). Implanted electrode always provides greater precision of muscle movements; however the procedure is more invasive.

7.3.5 FES Muscle Fatigue and Muscle Fibre Recruitment

Onset of fatigue occurs faster during FES contractions than voluntary movements. During voluntary muscle contractions, individual motor units are activated independently at different times and rates leading to an asynchronous muscle fibre contraction pattern (Baker, 2000) and a reduction in fatigue. Additionally, motor fibre recruitment order via FES is the reverse of voluntary recruitment order, further accelerating fatigue. Motor units are recruited according to motor neurone position and geometry, with respect to the electrodes, as well as fibre size. During FES the large fast twitch fatigable units are recruited first and small slow twitch fatigue resistant units are recruited last (Hamada, 2004). This is because the electrical stimulation thresholds for the large neurons, which innervate the fast twitch fibres, are less than the small neurons which innervate the slow twitch motor units (Eccles, 1958).

As stimulation pulse intensity is increased, additional motor units are recruited. As more motor units are recruited and contribute to the contraction there is a non-linear increase in the force produced by the muscle. (Kralj, 1989). If the stimulation intensity is high enough fibres from antagonist muscles may accidentally be recruited (Levin, 2000). At a given electrical muscle stimulation intensity there are no alterations in motor unit recruitment. Both the rapid fatigue during FES and the condition of paralysed muscle limit the functional outcomes or training benefits potentially delivered by any FES evoked systems. (Sinclair, 1996).
7.4 FES-EVOKED EXERCISE

Originally FES was explored as a technique to achieve standing and stepping amongst people with SCI (Vodovnik, 1965; Vodovnik, 1967). Individuals with SCI may be facilitated to perform upright ambulation with FES — sometimes with the assistance of orthoses. Nevertheless, the limitations in FES-evoked muscle contractions and the technology have to date made it impractical for walking outside of research laboratories (Kralj, 1989). However, more recently researchers have realized the potential of FES to produce exercise for peripheral and cardiorespiratory benefits in people with SCI (Phillips, 1984; Mutton, 1997). Even though the initial goal of FES for functional ambulation has yet to be achieved in a wider SCI population, the health benefits of FES evoked cycling exercise was discovered and has since been extensively acknowledged and investigated.

7.4.1 Benefits of FES-evoked Exercise

The health and fitness adaptation cycle continues as FES-evoked exercise is performed regularly. The regular muscle contractions accompanied by increased blood circulation can induce muscle hypertrophy which is also a well sought after cosmetic benefit amongst paraplegics and tetraplegics who normally have atrophied legs. An incomplete paraplegic may be able to perform better during training sessions if their muscular and cardiorespiratory capacities were enhanced, which might be a limiting factor before training (Postans, 2004). All these gains have the potential to increase ones psychological and social health and adaptation, which is important to reduce depression that is common amongst people with disabilities.

Increased muscle mass and size following electrical stimulation directly results in increased muscle strength and endurance (Kagaya, 1996), which further lead to increased functional exercise capacity (Petrofsky 1992; Petrofsky, 1992). With FES-evoked training, persons with SCI can perform exercise for longer training duration, at higher cadences, and increased resistance loads. Consequently, as FES-evoked functional capacity increases (i.e. evoked stepping distance, time or endurance), individuals who perform FES-evoked exercise will be able to exercise at higher cardiorespiratory intensity and eventually increase their aerobic fitness (Raymond, 2002). In short, if carefully prescribed, FES-evoked exercise has demonstrated the ability to increase physical activity, life satisfaction, and well being of people with SCI.

7.4.2 Performance Control

Research has been conducted to overcome the rapid muscle fatigue associated with FES and has limit the intensity of evoked exercise sessions. One way is to employ feedback control of the system. A user-controlled open-loop system is the most basic type of FES-system control, which is mostly employed during FES-evoked
standing, stepping or short ambulation. In an open loop control the system does not change its signal properties regardless of the user’s responses or performance, such as muscle fatigue when exercising or knee buckling during standing unless the user presses a switch. (Kralj, 1989). Therefore, the only feedback the system has is the user’s input which is based on the user’s perception of their performance.

FES-evoked cycling exercise employs closed-loop control as it modifies the stimulation parameters based training time, pedal or leg position, and in some modes based on the evoked forces. Position or motion sensors could be integrated as part of the closed loop system to detect critical body position or joint angles (Braz, 2006). Another example is the use of EMG to provide a signal that would indicate the initiation point during the start of an activity amongst people with incomplete SCI (Dutta, 2009). Surface EMG might also be utilized to detect early onset of muscle fatigue as a mode of fatigue compensation control (Winslow, 2003). The closed-loop systems allowed the stimulation parameters to be minimized and increased only as required to maintain a certain movement or position. This delays muscle fatigue thus prolonging a training session (Winslow, 2003).

7.5 TECHNICAL DEVELOPMENT OF FES EXERCISE MACHINES

7.5.1 FES Cycling

FES-cycling elicits leg muscle contractions in an appropriate sequence to produce a cycling motion (Petrofsky, 1984; Wilder, 2002; Petrofsky, 2003). Generally the quadriceps, hamstrings, and gluteal muscle groups are used during FES-cycling (Glaser 1994). Muscle contraction timing is controlled by a computer that stimulates each of the muscles at the correct crank angle to produce a pedalling motion (Petrofsky, 1984).

As the most popular mode of FES-evoked exercise, FES-evoked cycling may be the most economical way of training the leg muscles, and suitable for a wide range of persons with SCI. During FES cycling, the patient’s body weight is always supported by seating and the training is highly repetitive. Furthermore a simple controller can automate the session. Therefore, only one person is required to monitor and run the system, making FES cycling a convenient and efficient mode of exercise for SCI individuals. A SCI person can begin FES-evoked cycling without much pre-training, in comparison to FES-evoked standing or walking which needs the leg muscles and bones to be strong enough to bear body mass in an upright posture.

In the past, FES cycling ergometers were dominated by devices that relied upon the electrical stimulated muscles to provide pedal drive and a mechanically or electrically braked flywheel to provide resistive loading. Over the years, advances have been made to the electronic braking and stimulation systems (Chen, 1997). However, controlling cycling cadence in this manner becomes more difficult when the desired target cadence is below $35 \text{ rev-min}^{-1}$ and the resistive load is high.
7.5.2 Motorized FES Cycle Ergometers

An alternative to flywheel-braked cycling is to employ a motor to assist cycling (Eichhorn, 1984). For subjects with sufficient muscle power, the motor can be used to provide a pedalling resistance. The motor can also be used to calculate and correct for the energy required to passively move the legs and flywheel (Davis, 2001; Hunt, 2003). The motor has the advantage of enabling very weak subjects to perform FES cycling exercise, but a motorised system may pose an injury risk to the SCI subject’s lower limbs. Safety precautions must be taken to limit the torque that the motor applies to the limbs of paralysed individuals. Recent technological advances have lead to the development of specialized low-power motorized cycle ergometers with safety features that prevent muscle injury (e.g. Motomed VIVA, Reck Medizintechnik GmBH, Germany) and can be integrated with FES.

7.5.3 Isokinetic FES Cycling Exercise

Recently, an isokinetic functional electrical stimulation leg cycle ergometer (iFES-LCE; Fig. 3) for people with spinal cord injury was developed (Fornusek, 2004). The iFES-LCE system was created from a motorized cycle ergometer, a computer, custom-designed software, and laboratory-constructed six-channel transcutaneous neuromuscular stimulator.

It was designed to allow cycle training over a broad range of pedalling cadences (5-60 rev·min$^{-1}$), while providing accurate real-time feedback of muscle performance, to promote the development of both muscular strength and cardiorespiratory fitness. The inherent flexibility of the new system has made it very useful as research and development tool. Examples of the iFES-LCE being used for research include the testing of biomechanical model for FES-evoked cycling (Sinclair 2001; Sinclair, 2004) and physiological response during FES-evoked cycling (Theisen, 2002).

![Figure 7.3](image-url) The iFES-LCE exercise system. Shown are a Motomed Viva® (A), the DS2000 neuromuscular stimulator (B), the control computer (C), and a chair for the subject.
Isokinetic exercise has long been recognised as a type of exercise whereby the muscle gains strength evenly throughout its range of movement, and is the fastest way to increase muscle strength. By definition, isokinetic exercise involves “an external means of holding the speed of body movements to a constant rate irrespective of the magnitude of forces generated by the participating muscles” (Hislop, 1967). Isokinetic exercise has been found to be an efficient, adaptable and reliable method of exercise (Grooten, 2002), thus most suitable in muscle strength building by individuals with SCI.

7.5.4 Isokinetic Cadence Control

Isokinetic motorized FES cycling systems have the advantage that cadence control is not reliant upon muscle stimulation. Non-motorized FES cycle ergometers rely upon the muscle stimulation to maintain the pedalling cadence. Relying on muscle stimulation to control pedalling cadence restricts the stimulation patterns that can be employed. There is no reason to expect that a muscle stimulation pattern which controls cadence is optimal.

The mechanism of cadence control (i.e. motorized isokinetic vs. flywheel-braked isotonic FES-evoked cycling) at between 35–50 rev·min⁻¹ made no noticeable difference to the muscle powers generated or metabolic responses elicited (Fornusek 2005). Examples of stimulation intensity control schemes or modes that an isokinetic FES cycle can easily employ are manual control, a preset protocol, feedback control of power output, interval training, low cadence training, and eccentric training. Manual and preset protocol control of stimulation intensity is possible because the cycling motion does not rely on the muscle stimulation intensity; this is particularly useful for subjects who are very sensitive to muscle stimulation. Interval training has shown great potential to enhance the intensity of FES cycling (Janssen, 1996). Low cadence and eccentric training (Fornusek, 2009) may enhance the peripheral benefits of FES cycling.

The iFES-LCE is able to offer high-resistance low-cadence FES cycling. Muscle fatigue rates are lower at a slower pedal cadences (15 rev·min⁻¹) during FES-evoked cycling and low cadence cycling can produce higher muscle forces during FES-cycle training (Fornusek, 2004). Training with greater muscle forces has produced improved strength (Belanger, 2000; Hartkopp, 2003; Crameri, 2004) and hypertrophic gains (Dudley, 1999). Therefore, FES-LCE training at slow pedal cadences may confer improved strength and hypertrophic gains compared to higher pedal cadences (35-50 rev·min⁻¹). Although the pedalling cadence affects the power output, it does not appear to influence the potency of cardiovascular stress (Fornusek, 2008). Therefore, low cadence training should be as effective as higher cadences for cardiovascular fitness training.
7.5.5 Isokinetic FES Leg Stepping Exercise

A more recent approach towards maximizing FES-evoked leg exercise dose potency has been to employ an elliptical stepping movement (Hamzaid, 2009). An isokinetic FES leg stepping trainer (iFES-LST) was developed to integrate the features of isokinetic exercise with evoked muscle contractions and elliptical stepping movements (Hamzaid, 2009). The stepping movement had less vertical displacement than normal cycling would have and had greater ratio of horizontal:vertical displacement (Hamzaid, 2007). The authors hypothesised that the evoked muscle contractions would facilitate longer muscle activation times to produce the elliptical movement (Hamzaid, 2006), facilitated by a ‘slider-crank’ mechanism (Shigley, 1995) as illustrated in Fig. 4. Thus, leg training might approximate the known movements of walking, but in a seated posture, with potential benefits to the patient.

The primary leg muscles were stimulated in repetitive sequence based on the position of the legs. A continuous potentiometer was utilized to deduce the accurate crank angular position from which the leg position was derived. Evoked leg muscle contractions translated into the legs producing stepping power onto the pedals, which could be quantified given the muscles were conditioned enough and the stimulation current is sufficiently high.

The elliptical stepping trainer elicited greater metabolic cost and higher mechanical efficiency compared to traditional FES-evoked cycling (Hamzaid, 2009). The gain in power production by changing the mechanical foundation (i.e. cycling to stepping) was greater than the power production increase when optimizing the stimulation pattern during FES-evoked stepping (Hamzaid, 2008).

Another feature of the iFES-LST was the released ankle joint in plantar-dorsiflexion facilitated by a custom-made ankle foot orthoses (AFO). The AFO

![Figure 7.4](image_url)  
**Figure 7.4** Joint and linkages of an elliptical stepper. Primary muscles and the muscle stimulation path is illustrated.
supported the weight of the legs from the pedal while pivoting around the heel area (Kim, 2007). The main function of the AFO was as a cavity for the SCI users’ leg to control the involuntary lateral knee movements due to gravity and movement while they were seated on the exercise machine. However, the released ankle joint allowed constrained FES-induced leg movements to the sagittal plane.

The AFO produced greater ankle joint power than released-ankle cycling (Hamzaid, 2009). This feature may assist ankle joint restrengthening in which FES-evoked seated stepping is more relevant to walking as compared to cycling. Nevertheless, the current state of research does not support the use of released ankle joint during FES-evoked cycling. For example, ankle power was found to be 10% less when released than during fixed ankle cycling (van Soest, 2005). Further research has to be conducted to design the optimal of ankle foot orthoses during FES (Trumbower, 2005). A well designed constrained-ankle orthoses combined with FES would be able to achieve the best physio-therapeutic effects. In short, by optimizing the mechanical foundation of the system, a more dose-potent mode of exercise could be attained.

### 7.6 CONCLUSIONS

FES-evoked exercise systems can enhance the aerobic fitness, muscle strength and endurance, and improve physiological outlook in individuals with SCI. Future uses of these devices will play a role in “activity-based therapies”, both during acute rehabilitation and to provide benefits to those with long-standing SCI.

### References


References


References


References


