FES OF LOWER EXTREMITIES - CRITICAL REVIEW

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Abstract

The review demonstrates benefits of surface functional electrical stimulation for patients with upper motor neuron lesion, i.e. after stroke, with cerebral palsy, and with complete and incomplete spinal cord injury. The article is based on larger study, published recently.

INTRODUCTION

This review article is based on recently published invited review study (1). Functional electrical stimulation (FES) is a rehabilitative technology that uses electrical currents applied to the peripheral nerves. In this way FES provides restoration of movement or function, such as walking by a person with complete or incomplete spinal cord injury, stroke or cerebral palsy. FES is performed in a series of rectangular monophasic or biphasic (symmetrical or asymmetrical) electric pulses described by the following parameters: amplitude or intensity of pulses, frequency or pulse repetition rate, duration of single pulse, and duration of a pulse train (2). A surface stimulation electrode is a terminal through which electrical current passes into the underlaying tissue (3).

Four properties of surface stimulation electrodes and electrodes positioning are exerting an essential influence upon the effectiveness of electrical stimulation: electrode size, polarity of electrodes, resistance, and distance between the electrodes.

The design criteria for surface stimulation electrodes are as follows: physical comfort to the skin, electrical surface area greater than four square centimeters preventing skin irritation, use of hypoallergenic materials, flexibility to follow body surface, ease of attachment and ability to remain in position for the duration of at least one active day, reusable, low cost, reliable means of connection to stimulator, resistant to medical solvents and electrode gels, low and stable electrical resistance. The necessary electrical stimulator consists of an input circuit, pulse generator, output stage, and power supply. The current source of stimulation pulses provides a constant current irrespective of the resistance of the skin and the tissue between the electrodes. In the case of the voltage output stage the skin resistance is lower than that between the electrodes. The voltage source of stimulation pulses provides a constant voltage independently of the skin and tissue resistance. A power supply provides the energy necessary for the operation of particular electronic circuits (low voltage) and the electrical stimulation itself (high voltage). Electrical stimulator is usually battery powered. At the output of the stimulator stimulation pulses with an amplitude of more than 100 V are required. A high voltage for the output stage is obtained from low battery voltage by means of a voltage converter.

Stimulation frequency has noticeable influence on fatigue of the neuromuscular system. An electrically stimulated muscle fatigues more quickly than in the case of voluntary contraction. The main reason is the reversed recruitment order. In a voluntary contraction of a normally innervated muscle, the slow fibers are recruited first, and as increased muscle force is required, the fast fibers are recruited. Slow fibers are, therefore, activated frequently, while fast fibers are employed only infrequently, during a burst of intense activity. When applying electrical stimulation, fibers with a greater diameter respond earlier. These are motoneurons innervating fast muscles. The normal order of recruitment order is, therefore, inverted resulting in an increased fatiguing of electrically stimulated muscle.

WALKING AFTER STROKE

In 1961 Liberson started to use electrical stimulation for prevention of foot-drop in hemiplegic patients (4). The idea was further developed by Lojze Vodovnik who after Moe and Post (5) named the new method functional electrical stimulation - FES and defined it as follows: The purpose of FES is to provoke contraction of muscles deprived of nervous control, in order to obtain a useful functional movement (6-8).This distinguishes FES from a purely therapeutic electrical stimulation which is used predominantly to improve muscle strength, wound healing, to reduce pain, spasticity, and joint contractures. The prerequisite for FES is preserved excitability of the lower motoneuron and muscle that is able to contract. In Ljubljana at the beginning (in 1970) FES was planned mainly as an orthotic device for stroke patients but in later years the therapeutic use became more important in comparison to the orthotic one. Namely, the candidates for

gait stimulators were only selected after successful therapeutic program.

Interest for the clinical use of FES has recently increased because of its orthotic as well as possible therapeutic or carryover effect of FES. Systematic review of eight studies on the orthotic effect of FES on the improvement of walking in stroke patients was published in 2003 (9) and a positive effect on walking speed was suggested in six studies where walking speed was measured. The over-all improvement in walking speed was 0,13 m/s (0,07 - 0,2) or 38% (22,18 - 53,8%). The authors conclude that surface stimulators are useful devices for gait training in acute patients at rehabilitation centers. The advantage of further use of stimulator at home is that patients can practice as much as they want. However, good instruction in proper electrode placement is needed from physiotherapist. As for therapeutic effect of FES, it was noted already by Liberson (4) that some patients retained the ability for foot dorsiflexion for varying lengths of time after stimulation was stopped. Also other studies report on this phenomenon (10-12) which consists of increased voluntary movement and reduced spasticity but samples were small and few used convincing methodology (9).

An extensive review of development of drop foot stimulators is given by an international group of researchers (13). Three hard-wired single channel drop foot stimulators from Ljubljana are described. The first developed was the PO-8 (14) (1966), which was approved for use by the U.S. Board for Food and Medicines (the forerunner of today's FDA). FEPA-10 (1970) featured a large stimulation amplitude control knob, easily manipulated by patients (Fig. 7). MICRO-FES developed in the late 1970s was significantly smaller and lighter than FEPA-10 (65 g versus 190 g) (15,16).

The Odstock drop foot stimulator was described in 1997(17) with several clinically useful features like controlling the stimulation of the hemiplegic foot either by a heel switch worn on the hemiplegic or nonhemiplegic side. Miniature potentiometers allowed adjustment of both the rate at which stimulus was ramped up at toe-off and the rate at which stimulus was ramped down at heel strike. To asses the amount of use, a subject makes of the stimulator outside the clinic, recording of the time of stimulation was added (18).

WALKING OF CEREBRAL PALSY (CP) CHILDREN

The use of FES in children, mostly CP, reveals certain specific features that are absent in the case of adults. The position of electrodes is often atypical, the switch position on the foot is different from that common in adult patients. The differences are in the beginning of stimulation, mode of stimulation control, its duration, and the way the child carries the stimulator. The switch position should therefore be adapted to the site of the first contact of shoe at the beginning of the stance phase.

There have been few reports on the use of FES applied during walking on gait in spastic cerebral palsy. First results from Ljubljana on functional electrical stimulation (FES) applied to children were published already years ago (19). Since then it is routinely used in the unit for rehabilitation of children of the Institute for Rehabilitation, Ljubljana, Slovenia. From other centres than Ljubljana, positive experience and guidelines on FES use for children with cerebral palsy were published in 1997 (20-22).In Ljubljana most children with hemiplegia used a one-channel electrical stimulator and some with diplegia used a two-channel stimulator. Fifty percent of them used the electrical stimulator regularly in the home environment, at least 30 minutes daily. The parameters of stimulation, used in children are: frequency 25 - 40 Hz, impulse width 0,5 ms, while stimulation amplitude is individually adjusted. The most widely accepted approach to apply FES in children is the peroneal nerve stimulation so as to obtain functional movement of dorsiflexion and moderate eversion of the foot in the swing phase of the gait and thus correct equinovarus position of the foot in spastic hemi or diparesis. By means of surface electrodes, the peroneal nerve is stimulated in the popliteal region. Beside functional movement of foot dorsiflexion, other effects are achieved.

Kinesiological analysis of gait with and without FES showed that more normal movements in knee and hip joint are present when using FES. The gait shows greater symmetry and the basic parameters of gait are closer to normal. The position of the foot in dorsal flexion at the end of the swing phase enables full foot support instead of equinous position and tiptoe walking. With proprioceptive and biofeedback mechanisms activation, changes in sensory-motor organization are achieved with prolonged effects on posture and gait patterns. Effects of FES are better in hemiplegic than in diplegic children. Botulinum toxin therapy of spastic plantar flexors of the foot, facilitating the effect of peroneal FES in hemiplegic children (23, 24), has been recommended by research team from Ljubljana.

WALKING AFTER COMPLETE SCI

The Ljubljana FES walking system consists of two small two-channel stimulators attached to each leg. Only three electrodes are applied to single leg in order to produce knee extension and flexion response. As both activities never occur simultaneously, the distal electrode placed over knee extensor represents the common electrode for both stimulation channels (25).

The Ljubljana FES system was before 1989 delivered to 50 complete SCI patients (26).The energy efficiency of FES assisted walking in completely paralyzed SCI persons was

rather low. Considerable body weight was specially, during the leg or crutch transfer, supported by the arms. Four-channel FES gait pattern was also for about ten times slower than normal walking. However, FES walking exercise was found as an effective mechanism to improve fitness in completely paralyzed SCI persons providing health benefits similar to regular exercise in able-bodied individuals.

Using the same principles as Ljubljana FES system and adding two channels of stimulation to both hip extensors, the FDA approved Parastep surface stimulation system was developed (7).

WALKING WITH INCOMPLETE SCI

The first reports on application of FES to incomplete SCI patients go back to late eighties and early nineties of the past century (27, 28). The therapeutic electrical stimulation program was started immediately when the patients entered the rehabilitation center (27). The program consisted of cyclic stimulation of partially paralyzed knee extensor muscles, by alternate stimulation trains of 4 s and pauses of 4 s. The daily stimulation session lasted for one half hour. The training program lasted for three months. By applying a two-channel stimulator the patients could perform a smooth and aesthetic walking pattern. Here, the knee extensors were stimulated during the stance phase and the peroneal nerve of the ipsilateral extremity was excited to provoke the flexion withdrawal response during the swing phase of walking. In many cases stimulation of only peroneal nerve, resulting in simultaneous hip and knee flexion and ankle dorsiflexion, was found sufficient. The adequate FES control was accomplished by the use of hand switch built into a handle of a crutch. The therapeutic effects resulting from an FES gait program in incomplete SCI patients were studied also by Scottish researchers (28). Forty subjects (31 with incomplete spinal cord injury and 9 with cerebral damage) were studied in a multicenter trial across Canada for an average time of one year (29). Changes in maximal walking speed of incomplete SCI subjects with and without FES were studied by Ladouceur and Barbeau (30). The aim of another study performed by Canadian researchers was to quantify the effect of long-term FES assisted walking on the ankle joint of spastic incomplete SCI subjects (31).

A comparison of the effects of FES with that of an ankle-foot orthosis (AFO) for assisting foot clearance, gait speed, and endurance, was made by another Canadian research group (32).

In the period 1983-2000 57 peroneal stimulators were given to incomplete spinal cord injured persons in Ljubljana Institute of Rehabilitation for home use. 35 were tetraparetic and 22 paraparetic patients. A questionnaire evaluating the home use of FES and its influence on the quality of life was sent to the SCI persons. 32 patients used FES for walking and the rest for muscle strengthening only. 9 patients were able to walk outdoors, while 24 used FES only at home (25).

CONCLUSIONS

In the comprehensive review of functional and therapeutic applications of neuromuscular electrical stimulation, the authors33 focused also on transcutaneous peroneal nerve stimulation to treat ankle dorsiflexion weakness. They claim that despite demonstrated effectiveness, the method is not routinely prescribed in the USA for drop foot treatment in hemiplegia. However, they report on recent FDA approval of three surface peroneal nerve stimulators i.e. the Odstock dropped foot stimulator and the wireless NESS L300, which both use a heel switch to trigger ankle dorsiflexion. The third approved stimulator, the Walk Aide, uses a tilt sensor embedded into the stimulator attached to the shank to trigger the ankle dorsiflexion. More clinical prescription and usage of these devices is expected since the approval.

In feasibility study (34) the authors implanted percutaneous intramuscular electrodes into the gastrocnemius and tibialis anterior muscles of affected limbs. The results suggested that percutaneous FES might immediately improve the ankle kinematics in children with CP. However, the authors are aware of the invasive nature of implanting percutaneous electrodes, the risk of potential infection, and the lack of commercially available stimulators, the reasons which prevent the use of percutaneous FES in clinical settings.

It is clear now that electrical stimulation has in completely paralyzed SCI persons only the value of a general fitness exercising. In this respect combination of indoor or outdoor bicycle and FES can be more interesting for persons with complete paraplegia and in the same time also safer. In this view it is also not difficult to realize that implanted stimulation of extremities of SCI subjects is rather obsolete.

Surface FES in incompletely paralyzed patients is predominantly used for therapeutic purposes. It can be efficiently used together with treadmill and body weight support. In this way FES is competing with robotic exoskeletons. As FES is considerably less expensive and simpler to use, the expectations for broader future use of FES are realistic.

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