Abstract—The review investigates the objective evidences of benefits derived from surface functional electrical stimulation (FES) of lower and upper extremities for people after incomplete spinal cord injury (SCI) and stroke. FES can offer noticeable benefits in walking ability. It can be efficiently combined with treadmill and body weight support. Voluntary muscle strength and endurance gain can be achieved through FES assisted gait training together with increased gait velocity in absence of electrical stimulator. Cyclic FES, FES augmented by biofeedback, and FES used in various daily activities can result in substantial improvements of the voluntary control of upper extremities.

Index Terms—functional electrical stimulation, gait, manipulation, stroke, spinal cord injury.

I. INTRODUCTION

FUNCTIONAL electrical stimulation (FES) is a rehabilitative technology that uses electrical currents applied to the peripheral nerves. When a stimulating current, consisting from a series of rectangular monophasic or biphasic (symmetrical or asymmetrical) electric pulses, is applied to the electrodes placed on the skin overlaying sensory-motor nerve structures, an electric field is established between two electrodes and ions will create a current in the tissue. The ionic flow across the nerve causes the transmembrane potential and can generate an action potential. The action potential propagates along the nerve causing contraction of a paralyzed muscle. In this way FES provides restoration of walking or arm movements in a person with complete or incomplete spinal cord injury, stroke or other lesions to the upper motor neuron [1].

Surface stimulation electrode is a terminal through which electrical current passes into the underlying tissue [2]. At the electrode-tissue interface a conversion occurs between the current of electrons driven through the wires coupled to the stimulator and the current of ions in the tissue. An electrode is usually made of metal. However, it may be made of a nonmetal, commonly carbon. The design criteria for surface stimulation electrodes are as follows: physical comfort to the skin, sufficient electrical surface area preventing skin irritation, use of hypo-allergenic 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 simplest among the surface electrodes consists of a metal plate or metal wire mesh coated with fabric or sponge. The electrode is applied after having been moistened with plain water. Such electrodes are usually fixed on the extremity by means of Velcro or elastic bands. Surface electrodes made of silicone impregnated with carbon are applied to the skin surface with conductive gels and held in place with adhesive patches. An important property of the electrodes made of conductive rubber is their flexibility making them adaptable to any part of the body. Conductive adhesive gel electrodes provide self-adhesion when applied. A variety of electrically conductive polymers were developed, enabling good contact with the irregularities of the skin surface and uniform current density at the electrode-skin interface. These electrodes can be used for extended periods with minimal skin irritation.

In this review we will limit ourselves to the application of FES with surface electrodes. In the last decade it became evident that FES is most efficiently used with training of walking and arm movements in stroke patients or persons with an incomplete lesion to the spinal cord. Such therapeutic FES is predominantly used in rehabilitation centers after the injury or the onset of a disease and to some extent also at patients’ homes soon after being released from the rehabilitation environment.

II. WALKING EXERCISE IN INCOMPLETE SCI PERSONS

In the last few decades advances in traffic control and motor vehicle engineering together with more efficient first aid and improved transport to the emergency center have resulted in a reduction in the number of complete SCI patients. As a consequence, more incomplete cases are arriving in spinal units. There are more incomplete tetraplegic than paraplegic cases. In these patients FES can be efficiently used as therapeutic treatment in the early post-trauma phase. In a great number of patients one leg is severely paralyzed while the other leg is under sufficient voluntary control. In many cases stimulation of only peroneal nerve, resulting in simultaneous hip and knee flexion and ankle dorsiflexion, was found sufficient. Some incomplete SCI patients are candidates for additional FES therapy also after release from the rehabilitation center. In the period 1983-2000 57 peroneal stimulators were given to

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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 the rest used FES only at home [3].

Changes in maximal walking speed of incomplete SCI subjects with and without FES were studied by Ladouceur and Barbeau [4]. The investigation was performed in fourteen patients. FES assisted walking was accomplished by FES of peroneal nerve during swing phase of walking and quadriceps during the stance phase. Within one year of home use of electrical stimulator, the maximal walking speed while using FES increased on average by 0.26 m/s. The therapeutic increase of walking speed (without FES) was very similar (0.25 m/s). Similar changes occurred for three different groups of patients: community walkers, least community walkers, and household walkers. Further insight into the results shows that most of the increase of maximal walking speed during FES assisted walking stems from therapeutic effects which may be due to plasticity of the peripheral system and within the central nervous system.

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 [5]. Nineteen participants with incomplete SCI were recruited. Both FES and AFO demonstrated some walking benefits. A significant increase of 10% in gait speed occurred when participants used FES compared with no orthosis. The greatest increase of 18% occurred when FES was used in conjunction with an AFO. Also, the 6-minute walk distance for the AFO and FES condition was significantly higher than for the FES alone. Foot clearance was greatest when walking with FES and it was the only measure that resulted in significant difference between the two types of orthoses.

Growing attention is given to FES to facilitate exercise and to be used in temporary therapeutic interventions to improve voluntary function in subjects with incomplete lesion to the spinal cord. The authors of an FES gait training regimen hypothesized that direct muscle stimulation would have greater rehabilitative potential than the stimulation of reflexes [6]. A major disadvantage of stimulating the flexor withdrawal response is its high variability and rapid habituation. The authors are instead stimulating four muscle groups: quadriceps during the stance phase, gastrocnemius/soleus in late stance phase, and hamstrings and tibialis anterior during the swing phase of walking. The researchers are further emphasizing the importance of coordination of voluntary patient’s effort and simultaneous FES. Five chronic (usually defined as at least one year postinjury) incomplete SCI subjects were included into their study. In four subjects the electrical stimulator was only applied to the weak leg. Walking exercise was performed either on treadmill or overground in the hospital hallway two to five times per week for a period of 12-18 weeks. Each subject walked using the multichannel electrical stimulator for a total of 15-30 minutes per session. Four subjects demonstrated a steady increase in overground walking speed throughout the treatment period. The authors are concluding that the proposed FES training regimen was effective for improving voluntary walking function in a population for whom significant functional changes were not expected.

The motorized treadmill represents an important gait training environment. It assists with the retropulsion of the stance limb, which promotes hip extension. This hip extension further initiates the swing phase of walking. Body weight support is often used in conjunction with treadmill, allowing lower extremity loading to vary according the capabilities of the patient. The use of FES eliminates the need for therapist’s manual assistance [7]. Nineteen subjects who were at least one year postinjury were trained by the use of treadmill, body weight support and one-channel electrical stimulation of the peroneal nerve eliciting a flexion withdrawal response. Subjects were trained 1.5 hours per day, 3 day per week, for 3 months. As the main evaluation parameter, overground walking speed in the absence of both body weight support and FES, was selected. Over the course of training there was a significant increase in overground walking speed from 0.12 m/s to 0.21 m/s. In contradiction with application of purely efferent FES [6], the authors are claiming that their intervention takes advantage of spinal circuitry to assist with production of stepping. Sensory input is important for the modulation of the output of the locomotor generator and may facilitate locomotor recovery following a spinal lesion. FES combined with weight-bearing supported treadmill walking was applied also in patients in acute phase, when some spontaneous recovery is to be expected [8]. Fourteen subjects were included in the study where each subject acted as his/her own control. Namely, subjects underwent a control and an intervention period, each lasting four weeks. Subjects walked on a treadmill for up to 25 minutes a day, 5 days a week for 4 weeks. Two two-channel stimulators (FES of quadriceps and peroneal nerve) were used to deliver FES during treadmill walking. Stimulation was triggered by footswitches. All subjects increased their walking speed on the treadmill in the intervention period. A greater increase in overground walking endurance and speed was observed after intervention period as compared with controls.

Most interesting is a report on four different approaches to gait training: body weight support treadmill training with manual assistance, body weight support treadmill training with peroneal nerve stimulation, body weight support overground training with peroneal stimulation, and body weight support treadmill training with robotic exoskeleton (Lokomat, Hocoma AG, Zurich, Switzerland) assistance [9]. Twenty-seven subjects with chronic incomplete SCI were randomly assigned to one of four different training groups. Subjects in all groups were allotted a 60-minute intervention for each training day. Subjects were scheduled to train 5 days/week for 12 weeks. All forms of gait training were associated with improved walking performance. The differences between groups were not statistically significant. However, there was a trend toward greater improvement in the treadmill training with stimulation and overground training with stimulation. The chronic incomplete SCI subjects with the greatest deficits in walking function benefited the most from gait training with walking speed increasing by 85% in the slower group and by only 9% in the faster group. None of the patients reached the walking speeds of community ambulators (0.9 m/s), so none of them were able to discard their wheelchairs. In conclusion, combining body weight support with FES provides a task-
specific approach that is relatively low cost and highly accessible.

In another study four SCI patients, who were about three months postinjury and were unable to walk at all, were included into electromechanical gait training with electrical stimulation [10]. Subjects’ feet were placed on two plates, whose movements simulated stance and swing phases, and the movements of the pelvis were controlled by ropes attached to the harness. Dual channel electrical stimulators of the quadriceps and biceps femoris muscles of both sides assisted knee extension during the stance phase. The patients received 25 minutes of gait training and practiced each workday for 5 weeks. Gait ability improved in all four patients. Three patients could after the training walk independently on the floor with the help of technical aids. Important to notice is also that the therapists appreciated the reduced effort on the machine as compared to the manual treadmill training or gait practice on the floor.

III. GAIT RE-EDUCATION SYSTEMS

The aim of a gait re-education system is not only to provide actuation (FES or robotic assistance), but also to assess the sensory information from the paralyzed extremity. This sensory information can be used for three purposes. First, it can be used for evaluation of patient’s performance. The results measured can be compared to the results assessed on previous days, or can be compared with parameters of non-affected contralateral limb or parameters obtained from a healthy person. Second, the sensory information can be in a form of cognitive feedback sent back to the patient controlling voluntarily the actuation system. Finally, the sensory information can directly influence the actuation system (Fig. 1).

![Diagram of gait re-education system]

Figure 1: The concept of the gait reeducation system.

There are different possibilities how to transfer the sensory information to the patient. Sensory electrical stimulation or vibration of different skin areas can be used. Voice control also appears to be a promising solution. Visual feedback using computer screen together with tracking methods and virtual environments is another challenging approach.

The aim of the FES gait re-education system for incomplete SCI subjects was to estimate the quality of the swing phase of walking [11]. As the actuation system simple one-channel FES was proposed. In order to accomplish the swing phase of walking, the peroneal stimulation has been considered. A multisensor system was developed employing single-axial gyroscope, and two pairs of single-axial accelerometers. The accelerometers were measuring the tangential and radial acceleration components of the swinging movement. The gyroscope was used to measure the angular velocity of the shank. Data assessed from accelerometers and gyroscope were used to determine the numerical value, which represented a comparison with the desired reference swing. The reference swing movement was captured from the less affected lower extremity of the incomplete SCI patient. The numerical value, representing swing quality, was provided to the patient as auditory feedback at three different levels. The levels were presented as three different frequencies. The low frequency indicated a poor swing, the middle frequency indicated a sufficient swing and the high frequency represented a well performed swing phase. The feedback was simple enough to be understood during walking and enabled the patient voluntarily to improve the swing of his/her affected leg. The swing quality value was in the same time used also to control the stimulation amplitude. The stimulation amplitude was first pre-set by the physiotherapist at the beginning of the session. During treadmill walking the stimulation of amplitude was adjusted based on the quality of the swing phase. A succession of pre-set number of good swings meant that the patient has managed to walk adequately; therefore the level of FES augmentation was decreased. Conversely, in the case of a number of successive poor swings, the level of FES motor augmentation was not sufficient and the stimulation amplitude was increased. The system developed was tested in a patient with incomplete C4-5 SCI injury whilst walking on treadmill. The incomplete SCI patient was concentrated on the audio feedback signal and was able to achieve symmetrical gait pattern. The walking subject was active participant in the gait re-education process what resulted in reducing of the level of FES augmentation initially preset by the therapist.

A virtual mirror was designed – a large screen which showed a simplified human figure in virtual environment (Fig. 2), displaying the patient’s lower extremity movements in real time [12]. An optical system with active markers was used to assess the movements of a training subject. Another figure – a virtual instructor, also included in the display, showed the reference movements to be tracked by the patient as accurately as possible. This approach included patient’s visual feedback interactively in the training process. The system was first evaluated in a group of healthy persons. Afterwards, we investigated training abilities of an incomplete tetraplegic patient, undergoing a rehabilitation process, two years after an accident. He was instructed to track the virtual instructor’s stepping-in-place movements as performed by a healthy person. In the second part of the investigation, functional electrical stimulation triggering flexion reflex in the less able of the lower extremities was included. The virtual mirror provided a tight temporal coordination between the patient and the experienced therapist who triggered the stimulation,
they want. However, good instruction in proper electrode placement is needed from physiotherapist. As for therapeutic effect of FES, it consists of increased voluntary movement and reduced spasticity but samples were small and few investigators used convincing methodology.

An extensive review of development of drop foot stimulators is given by an international group of researchers [14]. Three hard-wired single channel drop foot stimulators from Ljubljana are also described. The first developed was the PO-8 (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. MICROFES developed in the late 1970s was significantly smaller and lighter than FEPA-10 (65 g versus 190 g).

In the comprehensive review of functional and therapeutic applications of neuromuscular electrical stimulation, the authors [15] 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 prescriptions and usage of these devices are expected since the approval.

Researchers from Hong Kong [16] investigated whether FES, delivered during acute stroke combined with a standard rehabilitation (SR) program was more effective than SR given with placebo stimulation or alone in promoting the recovery of motor function and functional mobility. Forty-six subjects aged between 45 to 85 years, 9.2 ± 4.1 days after stroke were assigned randomly to one of three groups receiving SR with FES or SR with placebo stimulation with disconnected stimulator or SR alone (control). Fifteen sessions of FES (30 minutes per session plus SR, 5 days per week) improved motor recovery and functional mobility more than placebo stimulation and SR, or SR only. 84.6% of subjects who received FES and SR returned home in comparison with 53.3% and 46.2% of those receiving placebo stimulation and SR or SR alone respectively. In Hong Kong criteria for stroke survivor to return home are that the patient should be able to perform self-care and live safely at home.

Researchers from Southampton and Salisbury [17] using Odstock drop foot stimulator examined its effect on an even and uneven surface. There were 13 stroke and 7 multiple sclerosis patients who had used the stimulator for at least 3 months. They also completed a questionnaire. Walking speed and physiological cost index were recorded under four conditions: with and without stimulation over an even and uneven surface. A trend toward greater effect of stimulation on uneven compared to even surfaces was found. They concluded that participants’ perceived benefit of stimulation may relate more to a reduction in effort than to increase in speed of walking.
V. FES TRAINING OF UPPER EXTREMITIES MOVEMENT

In their recent review Sheffler and Chae devoted important consideration to usage of electrical stimulation to motor relearning [15]. They claim that there are three types of electrical stimulation available for motor relearning in upper limbs: cyclic FES, electromyography (EMG) or biofeedback mediated FES, and application of neuroprostheses. In the first case, the patient is passive participant in the FES training, and no cognitive investment is necessary. The second type of exercises combines afferent feedback information with FES induced repetitive movements. During training by the use of neuroprosthesis, functional tasks can be performed that might have important advantage over cyclical or biofeedback FES approaches. The authors found the double-blinded and randomized investigation based on EMG triggered FES of particular interest [18]. The study was performed in 16 chronic stroke subjects. EMG triggered FES was delivered to their paralyzed forearm in order to facilitate hand opening. The group of patients which was FES treated demonstrated significant improvements in grasping and releasing of the objects. Even more interesting are the results of the fMRI (functional magnetic resonance imaging) study demonstrating increased cortical intensity in the ipsilateral somatosensory cortex following FES training.

In another review D.B. Popović et al. first define the term neurorehabilitation which relates to the methods and technologies maximizing the functioning of impaired sensory-motor mechanisms in humans after lesion to the central nervous system [19]. One of such neurorehabilitation technologies is functional electrical therapy (FET) which encompasses three elements: control of movements that are compromised because of the impairment, enhanced exercise of paralyzed extremities, and augmented activity ofafferent neural pathway. Two modalities of FET are described in the paper, bionic glove and the Belgrade grasping/reaching system. Signals from a sensor built into the bionic glove are used to control FES of the muscles which produce either hand grasping or opening. The Belgrade FES system provides sensory triggered preprogrammed control over palmar and lateral grasping and control of elbow joint flexion and extension. Both systems were tested with a group of tertaparetic patients. Both electrotherapies resulted in immediate and carry-over effects. Externally applied electrical stimuli provided a strong central sensory input which could be responsible for the changes in the organization of impaired sensory-motor mechanisms.

In the paper by M.B. Popović et al. FET of upper extremities is defined as an intensive exercise that integrates voluntary maximized manipulation and augmented grasping by electrical stimulation of forearm and hand muscles [20]. In well-designed randomized, single blinded clinical evaluation both acute and chronic stroke patients were evaluated. The hemiplegic subjects triggered the programmed multichannel electrical stimulation and used it while performing typical daily activities. As the outcome measures the upper extremity functioning test, drawing test, and modified Ashworth scale were used. The first test showed how many times a subject can perform a task in a given time interval. The drawing test demonstrated the coordination of the arm joint movements, while the five grade Ashworth scale evaluated the level of spasticity for the key muscles of the upper extremity. The authors are concluding that FET works best if applied in acute phase of hemiplegia and that the chances for recovery are much better in hemiplegic patients who have some residual wrist and finger extension shortly after stroke. The improvements assessed in chronic hemiplegic patients were not statistically significant. It is possible that a longer treatment time would be required for chronic hemiplegic subjects to show more substantial gains.

In another similar study only hemiplegic patients with severe paralysis were treated by neuroprosthesis enabling retraining of reaching and grasping functions [21]. The selection of patients was based on authors’ experience that patients who do not show any signs of spontaneous recovery during the first three weeks after stroke, typically do not have significant spontaneous recovery of the arm and hand in the following months and years. The stroke patients were randomly assigned either to the control or the treatment group. In the first group there were patients from 19 up to 47 days after stroke, while in the second group the treatment started between 16 and 338 days after stroke. The main characteristic of the study was FES treatment tailored and adjusted to the needs of a particular patient. In the study the muscles governing finger flexion and extension, thumb opposition and flexion, wrist flexion and extension, elbow flexion and extension, and shoulder flexion and extension were stimulated with surface electrodes. FES was assisted by the physiotherapist ensuring that all movements were carried out in a physiologic way. As the patients improved, the neuroprosthesis assistance was reduced. The evaluation tests applied in the study can be divided into subjective, however clinically accepted tests and more quantitative tests proposed and developed by the authors. In the second group of the tests instrumented cylinder, dynamometer, and special torque measuring device were used to assess lateral and palmar grasps. Patients from the control group, who received only standard physiotherapy and occupational therapy, showed substantial improvement in some of the clinical tests and no improvement in the quantitative assessments of their grasping abilities. In contrary, the stroke subjects from the treatment group showed considerable improvement in all tests. The authors are concluding that the neuroprosthesis therapy gives rise to greater improvement in arm and hand functions, compared to traditional physiotherapy and occupational therapy alone. All patients from the treatment group reached a functional plateau after 12-16 weeks of usage of neuroprosthesis.

Another study investigating the therapeutic effects of functional electrical stimulation in chronic hemiplegic patients with very limited hand function was carried out by Gritsenko and Prochazka [22]. The most original highlight of this investigation is the so-called exercise workstation. It consists of several instrumented objects such as a doorknob and a handle instrumented with potentiometers and rectangular blocks and cylinders equipped with infrared sensors. The exercise workstation is providing kinematic data on reaching and grasping movements which were supplemented by three clinically accepted tests. The wrist and finger extensor muscles were stimulated in six stroke patients who triggered the FES by pushing a button on the workstation. This pilot study indicated that 12 hours exercise on the workstation resulted in modest improvements in upper extremity function in six subjects with chronic hemiplegia.

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The investigation by Mann et al. is based on observations that early intervention may be more effective, that patients with some residual control are more likely to respond well, and that stimulation of several muscle groups resulting in a functional pattern of movement may be beneficial [23]. The authors posed a hypothesis that simultaneous stimulation of elbow, wrist, and finger extension using cyclical FES may produce more efficient therapeutic effects than stimulation of wrist and finger extensors alone. The objectives of the study were to investigate the effects of FES of the wrist and elbow extensor muscles (treatment group) on recovery of hand function, compared to passive stretching exercise (control group). The outcome measure test was a validated action research arm test. Sensation was tested using two-point discrimination. There were significant differences between grasp and grip scores assessed in control and treatment group, however the differences in sensation scores were not significant.

Figure 3: Training of hand movements by the use of tracking approach

An original tracking system for the assessment and training of grip force control was developed [24]. The system is aimed at training finger flexors and extensors. Two force/torque sensors are built into the device (Fig. 3). One sensor is intended for measuring the thumb force, and the other sensor is used for measuring the compound force of the other four fingers. The device can be connected to a personal computer for visual feedback and data acquisition. The task requires the patient to track the target signal on screen (sinusoidal signal with a superimposed DC component) by applying appropriate force to the grip-measuring device. The target signal is presented with a blue ring moving vertically in the centre of the screen. The applied force is indicated with a red spot. When the grip force is applied, the red spot moves upwards or downwards. The aim of the task is to continuously track the position of the blue ring by dynamically adapting the grip force to the measuring device. FES was added to augment the compromised force generated by paralyzed upper extremities. The difference between the momentary value of reference force and measured force serves as the input to the proportional-integral controller that transforms the difference between both signals into the pulse width of the stimulation current. Two channels of stimulation were used to stimulate the finger flexors and finger extensors independently. FES training with biofeedback lasted for four weeks in two tetraparetic subjects. The first subject (four years after C5/C6 incomplete SCI lesion) demonstrated a steady improvement of maximal voluntary hand closing and opening during the whole training period. His hand opening force was increased by 240% and his hand closing force was improved by 40%. The second subject (less than one year after incomplete C3/C4 SCI lesion) achieved improvement of maximal voluntary force in hand opening only. He improved his hand opening force by more than 100%. It was found that visual feedback provided through the tracking task considerably promotes subject’s voluntary involvement in the rehabilitation process. In another similar study performed in 20 chronic stroke patients, it was shown that EMG triggered FES delivered to the finger extensors in combination with simultaneous voluntary finger tracking movements can result in significant association between functional improvement and cortical reorganization demonstrated by fMRI data [25].

VI. Conclusion

Surface FES in incompletely paralyzed patients is predominantly used for therapeutic purposes. In therapeutic applications, the goal is to produce a functional benefit that lasts beyond the application of the stimulation itself. The question is arising, how FES can produce a “carryover” effect. FES, particularly when applied through surface electrodes, activates both motor and sensory nerve fibers. Repetitive movement therapy mediated by FES has the potential to facilitate motor relearning via cortical mechanisms. It was demonstrated that repetitive electrical stimulation of the peroneal nerve in able-bodied participants can lead to a long term increase in the contralateral motor evoked potentials of the tibialis anterior muscle [26]. The motor response of the tibialis anterior muscle was elicited by focal magnetic stimulation of the motor cortex. These results suggest that motor cortex excitability of the target muscle has increased. However, the authors are claiming that the increased motor evoked potentials cannot be explained exclusively by changes in the motor cortex cell excitability, but also by changes in subcortical neural structures involved in the excitation of spinal motoneurons. The same authors also demonstrated that the effect of FES on motor cortical excitability can be enhanced by the concurrent voluntary drive of an agonist muscle [27]. FES and the voluntary drive of the target muscle acting together and complementing the effects of each other may be beneficial for optimizing the therapeutic effects.

Regardless of spinal or cortical mechanisms, the experimental and theoretical considerations suggest that the necessary prerequisites for FES mediated relearning include repetition, novelty of activity, concurrent volitional effort, and high functional content [15]. Biofeedback mediated FES training, requiring greater cognitive investment, may result in greater therapeutic benefits.
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