

Rehabilitation with Functional Electrical Stimulation in Stroke Patients

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Abstract

In recent years, our understanding of motor learning, neuroplasticity and functional recovery after the occurrence of brain lesion has grown significantly. New findings in basic neuroscience have provided an impetus for research in motor rehabilitation. Several prospective studies have shown that repeated motor practice and motor activity in a real world environment have a favorable effect on motor recovery in stroke patients. Electrical stimulation can be applied in a variety of ways to the hemiparetic upper extremity following a stroke. In particular, electromyography (EMG)-triggered electrical muscle stimulation improves the motor function of the hemiparetic arm and hand. Triggered electrical stimulation is reported to be more effective than non-triggered electrical stimulation in facilitating upper extremity motor recovery after stroke. EMG-controlled functional electrical stimulation (FES) induces greater muscle contraction by electrical stimulation that is in proportion to voluntary integrated EMG signals. EMG-controlled FES and motor point block for antagonist muscles have been applied as a new hybrid FES therapy in an outpatient rehabilitation clinic for patients with stroke with good result. Daily EMG-controlled FES home-program therapy with novel equipment has been shown to effectively improve wrist, finger extension, and shoulder flexion. Combined modulation of voluntary movement, proprioceptive sensory feedback, and electrical stimulation might play an important role in improving impaired sensory-motor integration by EMG-controlled FES therapy. A multi-channel near-infrared spectroscopy (NIRS) studies in which the hemoglobin levels in the brain were non-invasively and dynamically measured during functional activity found that the cerebral blood flow in the injured sensory-motor cortex area is greater during a EMG-controlled FES session than during simple active movement or simple electrical stimulation. Nevertheless, evidence-based strategies for FES rehabilitation are more and more available, particularly for patients suffering from hemiparesis.

Keywords: Stroke; Functional electrical stimulation; Rehabilitation

Introduction

Upper extremity hemiplegia is the primary impairment underlying stroke-induced disability. Reducing chronic hemiplegic upper extremity impairment is generally difficult, and is the impairment most frequently treated by therapists [1]. Even 3 months after stroke only 20% of the stroke survivors, however, have normal upper extremity function [2]. Whereas motor practice improves motor skill learning [3], commonly used rehabilitation protocols have been found to be ineffective [4]. A number of promising therapeutic advances are emerging in the field of stroke rehabilitation at acute and/or chronic phase. None of these is yet universally accepted for enhancing outcome after stroke. Most of the approaches are currently being studied at the preclinical or early-phase human clinical trial stage.

In the upper extremities of patients who have had a stroke, a common course of hemiparetic recovery reveals the development of uncontrolled flexion synergy. This pathological synergy is induced in the hemiparetic limb during efforts to use it for a specific task. Often the individual is able to close the fingers into a fist, which is part of the flexion synergy, but is unable to open the fingers. Patients who continue to recover may regain the ability to produce movements outside of synergy patterns and, finally, to make isolated movements. Abnormal synergies constitute significant impairment that needs to be addressed by rehabilitation.

Stroke patients are often unable to perform important activities with their affected arms due to diminished active distal movement. Few motor therapies are available for patients exhibiting minimal movement in the affected arms, and no home-based therapies have shown efficacy for such patients. Stroke patients with unilateral upper extremity paralysis rarely improve arm and hand functions to the point of effective use in activities of daily living (ADL). Established occupational therapy and physiotherapy, which are commonly applied to rehabilitate these patients, seldom facilitate significant improvements in reaching, grasping and releasing functions. As a result, these patients frequently exhibit a "no-use pattern" and are

often released to home with a paralyzed arm. Chronic stroke motor problems that begin in the first year after stroke may lead to learned nonuse as individuals stop trying to voluntarily move the affected upper extremity. Especially, constrained induced movement therapy (CIMT) has recently been developed specifically for rehabilitation of upper-extremity function [5]. A 2-week program of CIMT for chronic stroke patients who maintain some hand and wrist movement can improve upper extremity function for more than a year. However, only a small percentage of individuals with hemiparesis display sufficient voluntary hand-opening to qualify for CIMT.

Another approach is based on functional electrical stimulation (FES) of muscles to augment hand function [6]. FES of upper limb muscles has been receiving increasing attention as a therapeutic modality in post-stroke rehabilitation. A meta-analysis of controlled studies supported the conclusion that FES promotes the recovery of muscle strength after stroke, with a reasonable likelihood of clinically significant results [7]. FES has been used for many years in clinical settings to help facilitate function of upper extremities among stroke patients, but research regarding its benefit had not been convincing. Recently, electrical stimulation of the upper limb has been receiving increasing attention as a therapeutic modality in post-stroke rehabilitation. A meta-analysis of controlled studies supported the conclusion that FES promotes the recovery of muscle strength after cerebrovascular accident, with a reasonable likelihood of clinically

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significant results [7]. Some recent FES modalities are overviewed with the discussion of their effectiveness and mechanism for improvement in this paper. We conducted a representative review of the literature, which included classic publications as well as more recent key publications. Due to the nature of the intervention, evaluations of FES therapy are not easily amenable to classic double-blinded, randomized clinical trials (RCT) designs.

FES prosthesis

Devices that provide FES are also referred to as neuroprosthesis. NESS Handmaster [8]” or “Bioness H-200 [9,10]” is a neuroprosthesis which combines a wrist-hand orthosis to provide stabilization with muscle activation of the paralyzed forearm and hand via integrated surface electrodes. The control unit is attached via a cable to the splint and allows the user to select between 3 exercise and 3 functional modes. The exercise modes provide stimulation to the targeted finger and thumb extensor and flex or muscles. The functional modes provide sequential key grip or palmer grasp and release patterns. The design of the Handmaster provides reproducible, accurate electro depositioning by the patient. The spiral design allows for wrist stabilization and maintains the wrist in a functional position of 10 to 20 degrees of extension. Subjects were issued a progressive home exercise program and were required to follow a conditioning paradigm using the system’s exercise modes. Once fitted into the orthosis, the electrodes remain in position for all subsequent applications and allow consistent replication of the grasp, hold, and release hand function. A case report describes a task-specific training protocol incorporating FES neuroprosthesis (Ness H-200) for a person who had chronic stroke and who initially exhibited no active wrist or finger movement [11]. Page et al. [9] reported that subjects administered 120 minutes per day of repetitive task-specific practice augmented with FES neuroprosthesis (Ness H-200) exhibit large, consistent upper extremity motor changes, even years after their strokes. However, chronic stroke subjects exhibited no changes in the various functional tests, indicating that changes in paretic upper extremity movement realized through repetitive task-specific practice using FES neuroprosthesis appear to be retained 3 months after the intervention [10]. Furthermore, the Ness H200 does not extend to the upper arm for elbow extension, limiting its use for ADL to those subjects who have functioning elbow extension. A study by Chae and Hart [12] showed that muscle activity from attempted movements in the paretic limb could be recorded by percutaneous intramuscular electrodes, which, in turn, triggered selective stimulation to similar electrodes implanted at selected motor point sites for functional movements in hemiparetic patients. They reported that there were no failures in the implanted radiofrequency microstimulator electronics and no infections in the adjacent tissues, and targeted and stimulated nerves appeared to be unharmed. This stimulator system was programmed to produce effective personalized functional muscle activity with little to no discomfort [13].

Contralaterally Controlled Functional Electrical Stimulation (CCFES)

CCFES is a new treatment aimed at improving recovery of volitional hand function in patients with hemiplegic stroke [14]. CCFES stimulates the paretic finger and thumb extensors with intensity in proportional to the degree of volitional opening of the contralateral unimpaired hand. The unimpaired hand wears an instrumented glove that detects the degree of hand opening [14]. The device enables patients with hemiplegia to open their paretic hand and practice using it in functional tasks (Figure 1). Surface electrodes were positioned on the forearm and hand. The muscles targeted for activation of functional



Figure 1: Contralaterally controlled functional electrical stimulation system (CCFES) [15].

Volitional opening of the unaffected hand produces a proportional intensity of stimulation to the paretic handextensors. The system enables patients with hemiplegia to practice tasks.

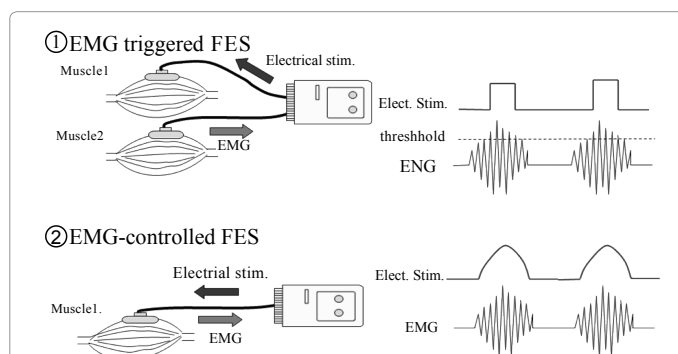


Figure 2: Schema of EMG-triggered FES and EMG-controlled FES

In EMG-triggered FES (①), EMG signal is picked up from muscle 2 and electrical stimulation is applied for muscle1. Surface electrodes pick up the EMG signal at the target muscles and simultaneously stimulate same muscles in proportion to the picked-up integrated EMG signal by the same surface electrodes in EMG-controlled FES (②) with enabling more delicate stimulation of muscles compared to EMG-triggered neuromuscular electrical stimulation. Because EMG-controlled FES device steadily records voluntary EMG only from the stimulated muscles, contraction of the wrong muscle can be avoided.

hand opening were the extensor digitorum communis and extensor pollicis longs. No more than 3 independent monopolar channels (using a common anode) of stimulation were used. The stimulator was programmed to modulate the pulse duration from each stimulation channel from minimum to maximum in proportion to the amount of opening of an instrumented glove worn on the non-paretic hand. The glove consisted of an assembly of 3 bend sensors in cloth sheaths attached to the dorsal side of the index, middle, and ring fingers. Proportional impedance changes in the sensors modulated an analog voltage input to the stimulator. CCFES produced larger improvements than cyclic neuromuscular electrical stimulation on upper extremity impairment and activity limitation in patients ≤ 6 months post stroke in every clinical measure [15].

EMG triggered FES

NM 900 [16] (Stroke Recovery Systems Inc., Littleton, CO, USA) is an electromyography monitored neuromuscular electrical stimulation

device approved by the federal Food and Drug Administration (FDA) for use by stroke survivors. The NM 900 uses three reusable, self-adhering, round surface electrodes (one ground over a bony protrusion; two active electrodes over the motor point of the targeted muscle). One active electrode is placed on the motor points of wrist or finger extensor muscle, while the other is placed approximately one inch below the first active electrode. The ground electrode is placed anywhere on the forearm as long as it is at least three inch away from either active electrode. The best position of the electrodes is to detect electromyography in the affected muscles, and to provide stimulation to them. A computer inside the device evaluates the amount of activity present in the muscle, and determines whether the patient's muscle activity meets or exceeds a preset threshold (Figure 2). If the subject attains the threshold, the NM 900 activates the muscle with its own biphasic waveform with pulse width ranging between 100 and 400 ms. A home-based electromyography triggered neuromuscular stimulation program is twice every weekday in 35-min increments during an eight-week period. The NM 900's safety and efficacy have been repeatedly demonstrated with no side-effects. Cauraough [17] and Chae [18] have reported that EMG-triggered neuromuscular electrical stimulation treatment is useful for rehabilitating wrist and finger extension movements in hemiparetic individuals.

EMG-controlled FES

A novel EMG-controlled FES system (Integrated Volitional Control Electrical Stimulator (IVES): OG GIKEN, Okayama, Japan) is a portable, 2-channel neuromuscular stimulator which works to promote wrist, finger extension or shoulder flexion movement during coordinate movement, but will not work when target muscles have no muscle contraction. This device induces greater muscle contraction by electrical stimulation in proportion to the voluntary integrated EMG signal picked up. The system comprises 2 instruments: a setting and input system and a stimulator (Figure 3). The portable stimulator is powered by very small batteries. Individual FES settings are saved in the portable FES stimulator device for home use via the setting and input system. The device can be set to pick up EMG signal sensitivities between 1000- and 10,000-times by a sensitivity controller and can be set for an electrical stimulation range with voltage (0~160V) by a stimulation range controller. Controlled by the clinician, the device delivers a train

of biphasic rectangular electric impulses via surface electrodes with a pulse width of 50 μ s. Details of the specifications and a performance test are given elsewhere [19]. The EMG-controlled FES device uses 3 reusable, self-adhering, round surface electrodes (1 reference electrode; 2 active electrodes over the motor point of the targeted muscles). Channel 1 has 1 reference and 1 active surface electrodes and channel 2 has 1 active surface electrode. Surface electrodes pick up the EMG signal at the target muscles and simultaneously stimulate these same muscles in proportion to the picked-up integrated EMG signal by the same surface electrodes. In particular, as this novel FES device steadily records from the stimulated muscles, contraction of the wrong muscle can be avoided. A computer inside the device evaluates the amount of activity present in the muscle, and determines whether stimulation intensity is proportional to muscle activity. The stimulator will not work when target muscles display no muscle contraction at all. This novel EMG-controlled FES device has the specific function for setting parameter memory compared to the former version one. Two experimental trials by the EMG-controlled FES were applied for stroke patients to improve arm and hand function [20,21].

Hybrid EMG-controlled FES

Antagonist muscle spasticity often disturbs agonist muscle activity; therefore, it is important to reduce finger and wrist flexor spasticity to improve hemiparetic hand function. FES is believed to inhibit antagonist muscle activity [22], but the effect sometimes is insufficient to control antagonist spasticity. Nerve or motor point block with phenol, in combination with FES, is useful for improving hemiparetic hand function. It is used clinically to improve the balance of activity at a joint, to improve motor control, or to increase tolerance to splinting and passive stretching. The rationale for using both modalities is to reduce the neurogenic component of finger flexor spasticity by means of a motor point block with the FES as adjunct therapy to improve hand function. EMG-controlled FES and motor point block for antagonist muscles have been applied as a hybrid FES therapy in an outpatient rehabilitation clinic for patients with stroke [20]. Chronic stroke patients who had spastic upper-extremity impairments more than 1 year after stroke were recruited in this trial. Patients underwent hybrid FES therapy on their extensor carpi radialis longus and brevis (ECRL & B), extensor digitorum communis (EDC), and extensor indicis proprius (EIP) muscles once or twice a week for 4 months after motor point blocks at the spastic finger flexor muscles. The movement, spasticity, and coordination function showed marked improvement in all outpatients with the hybrid treatment consisted of the FES and the motor point block as compared to the controls. This hybrid therapy consisting of a motor point block decreasing negative factor (antagonist muscle spasticity) and the EMG-controlled FES increasing positive factor (agonist muscle strength) has the potential to effectively improve hemiparetic hand function. Now we are using botulinumtoxin. A injection instead of motor point block as this hybrid therapy after its injection therapy had been supported by health insurance.

A home-based rehabilitation program

Targets on the hemiparetic side were the wrist and finger extensors for one group, comprising the ECRL & B, EDC and EIP muscles. For another patients group, the targets were the anterior portion of deltoid muscle and triceps brachii muscle. Subjects and family members or attendants learned how to operate the FES device (including electrode positions) from a physician at the hospital following completion of initial assessment. Electrode positioning and intensity of stimulation were individualized for each patient to provide active movement throughout the available ROM. Patients were given a protocol for

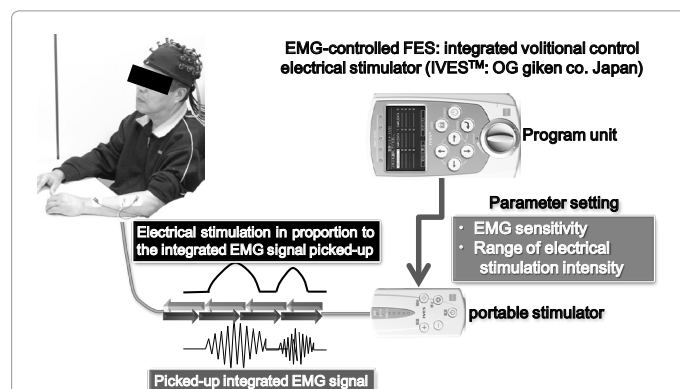


Figure 3: EMG-controlled FES instrumentation

A surface electrode picks up the EMG signal and stimulates the target muscle in proportion to the integrated signal. The EMG signal sensitivity is obtained and the electrical stimulation range is set. This device induces greater muscle contraction because electrical stimulation is proportional to the EMG signal. The EMG-controlled FES unit is an auto-driven system without an on-off switch; therefore, no more operation was required after it had been initially set.

daily home electrical stimulation. Specific affected limb exercises in the home exercise program included: supination/pronation exercises; flexion and extension of individual fingers; wrist extension and flexion exercises; elbow flexion and extension exercises; and shoulder adduction and abduction exercises. The instrumental tasks consisted of reaching, grasping, moving (e.g., pulling, rotating) and releasing an object on a desk using the hemiparetic upper extremity. Objects were chosen on the basis of the ability to grasp the object with FES assistance at the beginning of the training period. ADL training such as washing, drying dishes and folding cloths was also performed using an EMG-controlled FES device according to individual ability. Electrodes and lead wires were covered under the clothes and the portable stimulator was held in a small waist bag. As the EMG-controlled FES is portable and light, patients could perform ADL exercises with the hemiparetic hand and arm FES inside or outside the house. A 30-min FES program session was started at home about 5 days/week at first. During the first 10 days, stimulation time was gradually increased to a maximum of 1 h/session. Some patients could continue to perform ADL training with home FES as long as possible. In one way, this home FES program may offer the same effects as CIMT from that point of view. Since the FES unit is a closed-loop system without on-off switch, no operation of the FES device was required after initially setting the FES system. Patients were seen in follow-up visits to ensure proper use of the equipment and to supervise progression in the protocol. Most patients were able to use the device after the first session, and all were independent in operating it by the second or third visit. The physician checked the settings of the FES device and modified parameter settings for individuals as needed during follow-up visits. Safety and efficacy of the EMG-controlled FES device have been repeatedly demonstrated with no adverse effects. The stroke patients with the EMG-controlled FES displayed significantly greater improvements in active ROM, spasticity, EMG root mean square and motor performance tests and were able to smoothly perform ADL using the hemiparetic upper extremities. Some patients also revealed decreased lower extremity spasticity with improvements to severe spasticity of the upper extremity. Daily EMG-controlled FES home program therapy can effectively improve wrist, finger extension and shoulder flexion. Home-based EMG-controlled FES made hemiparetic patients to increase the chance of regaining use of the hemiparetic arm in ADLs [21].

Daily session, exercise dose and regulation of FES

Gritsenko et al. [23] reported that the use of FES-assisted exercise therapy in conjunction with an instrumented workstation was associated with improvements in hand function in a group of hemiplegic people whose level of motor function would have excluded them from CIMT. The eventual goal of this research is to provide workstations for home use that will allow people with hemiplegia to engage in regular tele-therapy sessions to improve upper-extremity function. But this equipment was too large to be set up at home. Daily electrical afferent stimulation applied via a mesh-glove reportedly modifies altered motor control and improves voluntary wrist extension movement in stroke patients with chronic neurological deficits [24].

Smith et al. [25] demonstrated a dose-response relationship between FES to the lower extremity and brain-activation in sensory and motor regions contralateral to the stimulation. Other studies have also examined whether daily home use of an upper limb FES device can change the physical status and functional abilities in patients with chronic hemiparesis who are already receiving long-term physical therapy [26,27]. Lourencao et al. [28] reported that at least 6 months is necessary for FES use to generate a significant improvement in grip speed in hemiplegic patients. They hypothesized that an effective home

FES program would need such a long time as five or six months to improve upper extremity function. For long-term daily use as a home-based FES system, the device should be easy and safe to operate. As The EMG-controlled FES system device is portable, easy and safe to operate, rehabilitation training is easily performed at home every day compared with other FES devices.

Some studies analyzing FES describing relief of spasticity and opening of the hemiplegic hand have attributed this finding to the mechanism of reciprocal inhibition of the finger flexor muscles, at the moment when the extensor muscles in hemiplegic patients are stimulated [27-30]. Not only reciprocal inhibition of antagonist muscle electrical stimulation, but simultaneous voluntary muscle contraction could also decrease antagonist muscle tone. This represents another merit of EMG-controlled FES.

Triggered electrical stimulation may be more effective than non-triggered electrical stimulation in facilitating upper extremity motor recovery following stroke [31]. Repetitive movement therapy where the subject is cognitively involved in generating the movement is more likely to be important and meaningful than therapy where the subject is not cognitively involved [30]. EMG-controlled FES device stimulates hemiparetic muscles in proportion to the integrated EMG signal picked up from the target muscles, enabling more delicate stimulation of muscles compared to EMG-triggered neuromuscular electrical stimulation, and thus has potential for use in such rehabilitation training methods as muscle relaxation and task-oriented exercise [21]. It appears that the specific stimulus parameters may not be crucial in determining the effect of electrical stimulation [31].

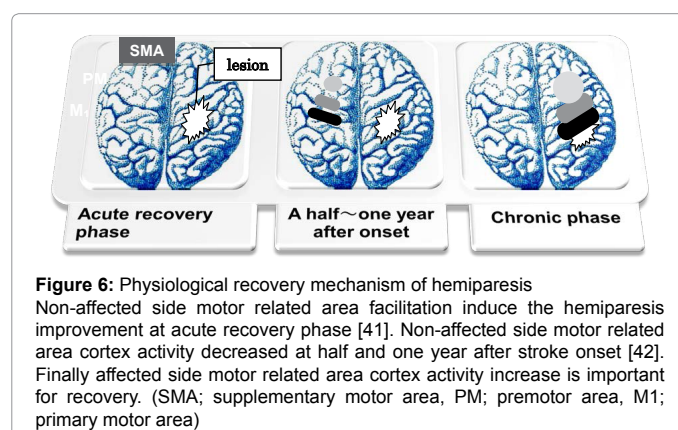
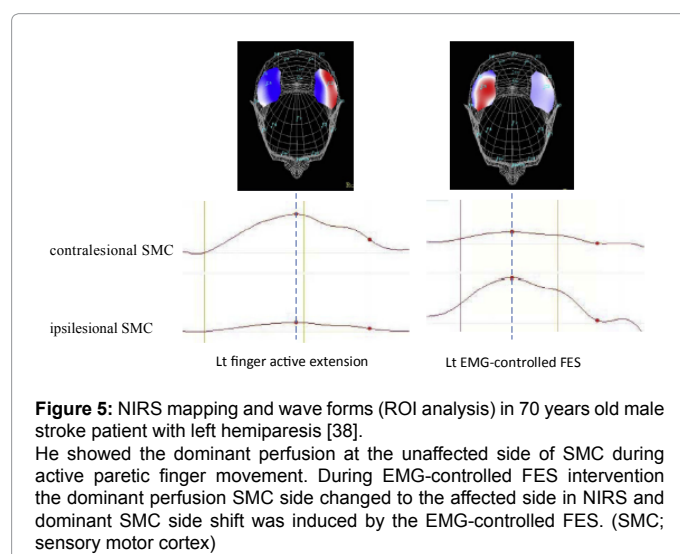
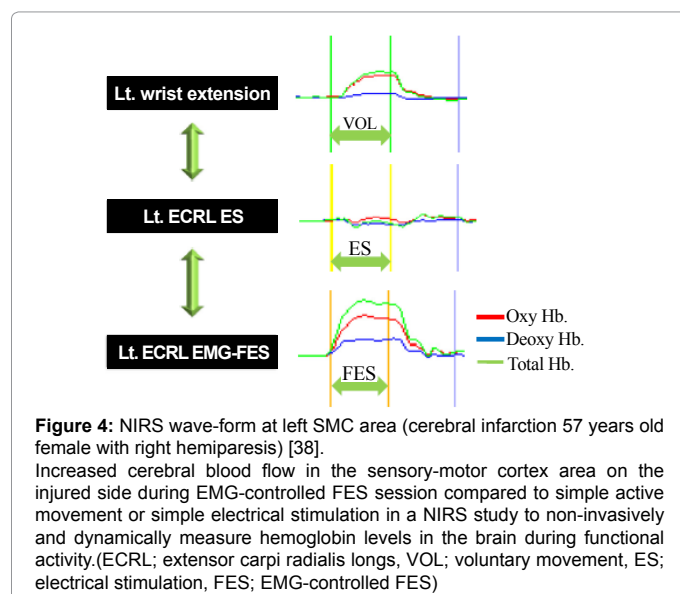
Mechanism of FES Effects

It has been reported that stroke survivors with lower sensorimotor function have a decreased potential for recovery than those who are less severely affected [32]. The sensory components of large afferent fiber activation, proprioceptive input and increased cognitive sensory attention are all weighted in the direction of spasticity reduction, and are thus helpful in the return of voluntary movement and increased function [33]. Nudo et al. [34] suggest that afferent input associated with repetitive movements facilitates improvement of motor function. For this reason, motor movement stimulation might be more effective in improving motor control than simple sensory stimulation. This is likely since electrical stimulation that provokes motor activation is associated with cutaneous, muscle and joint proprioceptive afferent feedback. In another way, the mechanism underlying the EMG-controlled FES therapy is that alternative motor pathways are recruited and activated to assist impaired efferent pathways [33]. This explanation is based on the sensory-motor integration theory that sensory input from movement of an affected limb directly influences subsequent motor output [35].

Iftime-Nielsen et al. [36] reported that neuromuscular stimulation combined with voluntary activation produces more activation of the cerebellum and less activation of secondary somatosensory cortex than dose neuromuscular stimulation alone in normal subjects. Neuroimaging studies of FES-evoked (FES delivered in the absence of voluntary activation) and FES-assisted (FES delivered to augment voluntary activation) movements have suggested bilateral secondary somatosensory cortex (S2) activation is related to the application of therapeutic FES [36]. Another study suggested FES-related S2 activation is mainly a sensory phenomenon and does not reflect integration of sensory signals with motor commands [37]. Those neuroimaging studies about combined FES and voluntary activation were investigated among normal subjects. We investigated increased cerebral blood flow in the sensory-motor cortex area on the injured

side during EMG-controlled FES session compared to simple active movement or simple electrical stimulation in a multi-channels Near Infrared Spectroscopy (NIRS) study to non-invasively and dynamically measure hemoglobin levels in the brain during functional activity (Figure 4) [38]. Figure 5 shows NIRS mapping and waveforms from a 70-year-old male stroke patient with left hemiparesis. He showed dominant perfusion in the contralesional sensory motor cortex (SMC) during the voluntary movement condition and in the ipsilesional SMC during the EMG-controlled FES condition. A shift in dominant perfusion from the contralesional to the ipsilesional SMC was therefore induced by EMG-controlled FES. This experiment suggests combined voluntary intension and electrical components as a possible mechanism for motor improvement due to brain functional reorganization.

Increase in somatosensory stimulation applied to a hemiparetic limb can benefit performance in functional tests for patients with chronic stroke [39]. This result supports the proposal that electrical sensory stimulation in combination with training protocols may enhance the benefits of standard neuro-rehabilitative treatments, and may also facilitate motor learning [40]. The sensory motor integration



that occurs during the EMG-controlled FES increased perfusion of the ipsilesional SMC and resulted in functional improvement in the hemiparetic upper extremity in chronic stroke patients. A5-month treatment intervention of EMG-controlled FES and motorlearning produced cortical reorganization correlated with functional gains as shift of the brain perfusion from the contralesional to the ipsilesional hemisphere [38]. Figure 6 shows physiological recovery mechanism schema of hemiparetic stroke. Non-affected side motor related area facilitation induces the hemiparesis improvement at acute recovery phase [41]. Non-affected side motor related area cortex activity decreased at half and one year after stroke onset [42]. Finally affected side motor related area cortex activity increase is important for recovery. The patterns of cortical activity in chronic stroke patients support the view that recovery from hemiparetic stroke depends on the recruitment of alternative systems even in the affected hemisphere [43]. From a point of view about this recovery mechanism, the FES increasing the activity of affected side SMC possibly induces brain reorganization to recover hemiparetic impairment in chronic stage.

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