—Review—

Neurorehabilitation with New Functional Electrical Stimulation for Hemiparetic Upper Extremity 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 stimulated research in motor rehabilitation. Repeated motor practice and motor activity in a real-world environment have been identified in several prospective studies as favorable for motor recovery in stroke patients. Electrical stimulation can be applied in a variety of ways to the hemiparetic upper extremity following stroke. In this paper, an overview of current research into clinical and therapeutic applications of functional electrical stimulation (FES) is presented. In particular, electromyography (EMG)-initiated electrical muscle stimulation—but not electrical muscle stimulation alone—improves the motor function of the hemiparetic arm and hand. Triggered electrical stimulation is reported to be more effective than untriggered electrical stimulation in facilitating upper extremity motor recovery following stroke. Power-assisted FES induces greater muscle contraction by electrical stimulation in proportion to the voluntary integrated EMG signal picked up, which is regulated by a closed-loop control system. Power-assisted FES and motor point block for antagonist muscles have been applied with good results as a new hybrid FES therapy in an outpatient rehabilitation clinic for patients with stroke. Furthermore, a daily home program therapy with power-assisted FES using new equipment has been able to effectively improve wrist and finger extension and shoulder flexion. Proprioceptive sensory feedback might play an important role in power-assisted FES therapy. Although many physiotherapeutic modalities have been established, conclusive proof of their benefit and physiological models of their effects on neuronal structures and processes are still missing. A multichannel near-infrared spectroscopy study to noninvasively and dynamically measure hemoglobin levels in the brain during functional activity has shown that cerebral blood flow in the sensory-motor cortex on the injured side is higher during a power-assisted FES session than during simple active movement or simple electrical stimulation. Nevertheless, evidence-based strategies for motor rehabilitation are more easily available, particularly for patients with hemiparesis.
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Key words: stroke, electrical stimulation, rehabilitation, home program

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Introduction

Upper extremity hemiparesis is considered the primary impairment underlying stroke-induced disability and is the impairment most frequently treated by therapists[1]. Even 3 months after stroke only 20% of survivors, however, have normal upper extremity function[2]. Although motor practice improves motor-skill learning[3], commonly used rehabilitation protocols have been found to be ineffective[4].

Several promising therapeutic approaches have emerged in the field of stroke rehabilitation. Some of these therapies are intended for the acute phase and others for the chronic phase. Examples of restorative therapies include cell-based approaches[5], selective serotonin reuptake inhibitors[6], catecholaminergics[7], brain stimulation[8], robotic and other device-based interventions[9], mental-imagery-based protocols[10], and constraint-induced movement therapy (CIMT) plus other intensive physical therapy regimens[11]. None of these therapies has been universally accepted for enhancing outcomes after central nervous system injury, such as stroke. Most approaches are now being studied in preclinical trials or early-phase human trials.

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 particular task. Often the individual can 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 a 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 to be effective for such patients. Stroke patients with unilateral upper extremity paralysis rarely show improvements in arm and hand functions to the point of effective use in activities of daily living (ADLs). Occupational therapy and physiotherapy, which are commonly used in the rehabilitation of these patients, seldom lead to significant improvements in reaching, grasping, or releasing functions. As a result, these patients frequently exhibit a "no-use pattern" and are often discharged to home with a paralyzed arm. Chronic 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. In particular, CIMT has recently been developed specifically for rehabilitation of upper-extremity function[12]. A 2-week program of CIMT for patients more than 1 year after stroke who retain some hand and wrist movement can achieve improvements in upper extremity function which persists for at least 1 year. However, only a small percentage of individuals with hemiparesis display sufficient voluntary hand-opening to qualify for CIMT.

Another approach is based on using functional electrical stimulation (FES) of muscles to augment hand function[13]. FES has been used for many years to facilitate functional recovery of upper extremity function in stroke patients, but research regarding the benefits of FES has not been persuasive. Recently, electrical stimulation of the upper limb has been receiving increasing attention as a therapeutic modality in poststroke rehabilitation. A meta-analysis of controlled studies has supported the conclusion that FES promotes the recovery of muscle strength after cerebrovascular accident, with a reasonable likelihood of clinically significant results[14]. In this paper some recent FES modalities are described and their effectiveness and mechanisms for improvement are discussed.

Recent FES Modalities for Stroke

NESS Handmaster[15]: The Handmaster neuroprosthesis (NESS Ltd., Ra'anana, Israel) **(Fig. 1)** combines a wrist-hand orthosis to provide stabilization with muscle activation of the paralyzed

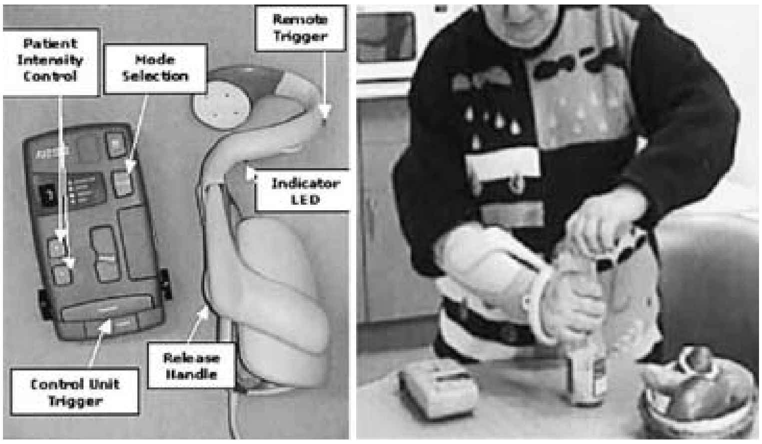

Fig. 1 Left: The NESS Handmaster Neuroprosthesis; right: opening a bottle as a selected ADL.

forearm and hand via integrated surface electrodes. The control unit is attached via a cable to the splint and allows the user to select from among 3 exercise modes and 3 functional modes. The exercise modes provide stimulation to the targeted finger and thumb extensor and flexor muscles. The functional modes provide sequential keygrip or palmar grasp and release patterns. The design of the Handmaster permits reproducible, accurate electrode positioning by the patient. The spiral design allows wrist stabilization and maintains the wrist in a functional position of 10 to 20 degrees of extension. Subjects are issued a progressive home exercise program and are required to follow a conditioning paradigm using the system's exercise modes. Training periods start at 10 minutes twice daily and gradually increase to 45 minutes 2 times a day. 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 functions.

The Neuromove 900[16]: The Neuromove 900 (Stroke Recovery Systems Inc., Littleton, CO, USA) is an electromyography (EMG)-monitored neuromuscular electrical stimulation device approved by the United States Food and Drug Administration for use by stroke survivors. The Neuromove 900 uses 3 reusable, self-adhering round surface electrodes (1 ground electrode over a bony protrusion and 2 active electrodes over the motor point of the targeted muscle). One active electrode is placed on the posterior forearm (on the extensor group) 1 inch (2.54 cm) from the elbow crease, while the other is placed approximately 1 inch below the first active electrode. The ground electrode is placed anywhere on the forearm as long as it is at least 3 inches (7.62 cm) away from either active electrode. The role of the electrodes is to detect EMG signals in the affected muscles and to stimulate 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. If the subject reaches the threshold, the Neuromove 900 activates the muscle with its own biphasic waveform with pulse widths ranging from 100 to 400 ms. A home-based EMG-triggered neuromuscular stimulation (ETMS) program is used twice every weekday in 35-minute increments during an 8-week period. The safety and efficacy of the Neuromove 900 have been repeatedly demonstrated with no side effects.

Power-assisted FES: We applied a new FES therapy for patients with chronic stroke hemiparesis as a new rehabilitation modality. Two experimental trials were performed with stroke patients to improve arm and hand function.

1. Hybrid Power-Assisted 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[7], but the effect is sometimes insufficient to control antagonist spasticity. Nerve or motor point block with phenol, in combination with

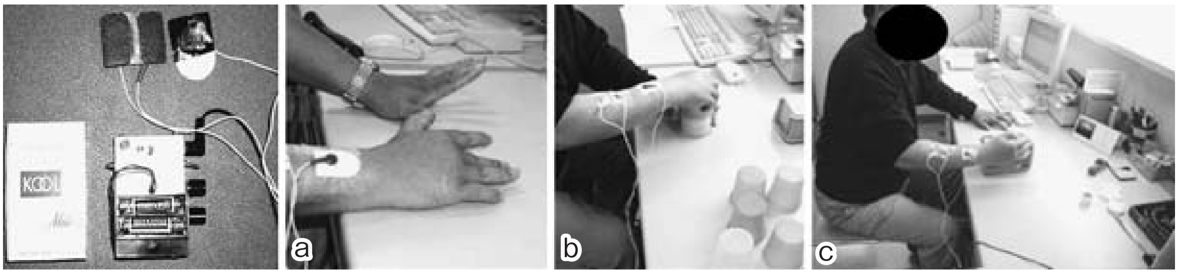

Fig. 2 Left: Power-assisted FES device; A surface electrode picks up the EMG signal and stimulates the target muscle in proportion to the integrated signal. The EMG signal sensitivity is obtained, and the electrical stimulation range is set. This device induces greater muscle contraction because electrical stimulation is proportional to the EMG signal. Outpatient FES training: **a**, Bilateral movement training involving mirror movements of the unimpaired wrist and fingers. **b**, Cup grasping, moving, and release training with FES. **c**, The full fingers-open position was necessary to hold the box. Patients were trained to rotate the box 90° while holding it. Box size: 14×10×8 cm.

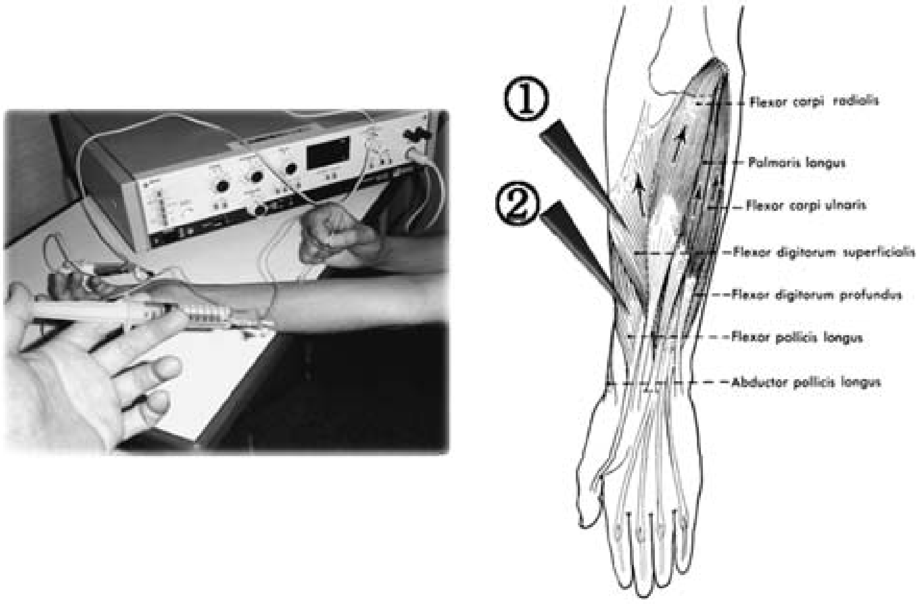

Fig. 3 Motor point block with 5% phenol was applied for the ① flexor digtitorum superficialis and ② flexor pollicis longus muscles.

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. Power-assisted FES **(Fig. 2)** and motor point block for antagonist muscles **(Fig. 3)** have been applied as a new hybrid FES therapy in an outpatient rehabilitation clinic for patients with stroke[17]. Sixteen consecutive patients who had had spastic upper-extremity impairments for more than 1 year after stroke were recruited for a nonblinded, randomized, controlled trial. Patients underwent hybrid FES therapy on the extensor carpi radialis longus and brevis (ECRL and ECRB), 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. Surface electrodes picked up the EMG signals and stimulated those muscles in proportion to the integrated EMG signal obtained by the FES device. All outpatients receiving the hybrid treatment consisting of the FES and the motor point

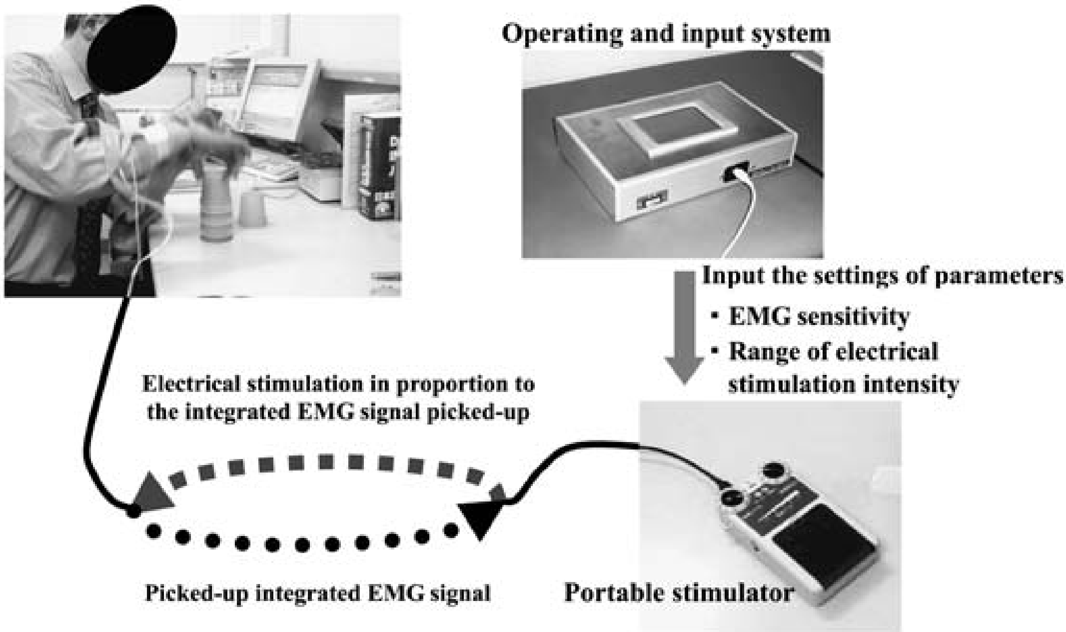

Fig. 4 Power-assisted FES system for home-based rehabilitation: This system comprised 2 instruments, a setting and input system and a stimulator. Individual FES settings are saved in the portable FES stimulator device for home use via the setting and input system. A surface electrode picks up the EMG signal and stimulates the target muscle in proportion to the integrated signal. This device induces greater muscle contraction because electrical stimulation is proportional to the EMG signal.

block showed greater improvement in movement, spasticity, and coordination function than did controls patients. This new hybrid therapy consisting of a motor point block decreasing a negative factor (antagonist muscle spasticity) and the power-assisted FES increasing a positive factor (agonist muscle strength) can effectively improve hemiparetic hand function.

2. A home-based rehabilitation program with power-assisted FES for the hemiplegic upper extremity: The effects of rehabilitation usually increase with the frequency and duration of rehabilitation. Whether daily power-assisted FES therapy at home would result in enhanced recovery for patients with partial hand or shoulder motion at the start of the study was examined. The problem may be compounded by a lack of familiarity with the course of improvement following the use of electrical stimulation and unrealistic expectations on the parts of both clinicians and patients. Difficulties in smooth voluntarily initiation and control of extension movements of the wrist and fingers or flexion movements of the shoulder were seen.

New power-assisted FES system: This new power-assisted FES system (OG Giken, Okayama, Japan) is a portable, 2-channel neuromuscular stimulator that promotes wrist or finger extension or shoulder flexion movement during coordinate movement but will not work when target muscles cannot contract. 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 (**Fig. 4**). The portable stimulator is powered by 4 1.5-V dry 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 from 1,000- to 10,000-times by a sensitivity controller and can be set for an electrical stimulation range with voltage (0～160 Vp-p) 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 μs. Details of the specifications and a performance test have been

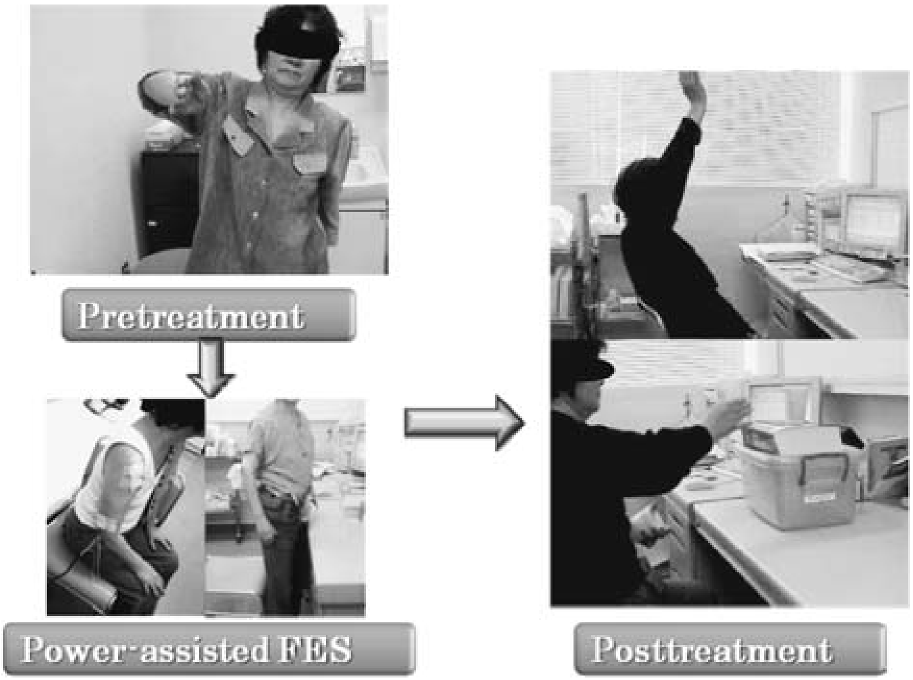

Fig. 5 Power-assisted FES effect after training at home: The patient places the surface electrodes on the deltoid and triceps muscles. Electrodes and lead wires are covered by clothing, and the portable stimulator is held in a waist pouch. Because the power-assisted FES is hidden and light, the patient can walk around inside or outside the house and perform ADL exercises with the hemiparetic hand and arm.

described elsewhere[18]. The power-assisted FES device uses 3 reusable, self-adhering, square surface electrodes (1 reference electrode and 2 active electrodes over the motor point of the targeted muscles). Channel 1 has 2 surface electrodes ([30 mm × 20 mm] × 2; 5 mm apart; 1 reference electrode and 1 active electrode), and channel 2 has 1 active surface electrode (30 mm × 30 mm). Electrodes comprise soft carbon mounted with a conductive gel sheet. Surface electrodes pick up the EMG signal at the target muscles and simultaneously stimulate the same muscles in proportion to the integrated EMG signal picked up. In particular, as the new 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. Unlike an earlier version, this new power-assisted FES device has a specific function for setting parameter memory.

A home-based rehabilitation program[19]: Targets on the hemiparetic side for 1 group of patients were the wrist and finger extensors, comprising the ECRL, ECRB, EDC, and EIP muscles. For another group of patients, the targets were the anterior potions of the deltoid muscle and the triceps brachii muscle (**Fig. 5**). 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 the intensity of stimulation were set for each patient to provide active movement throughout the available range of motion. Patients were given a protocol for 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,

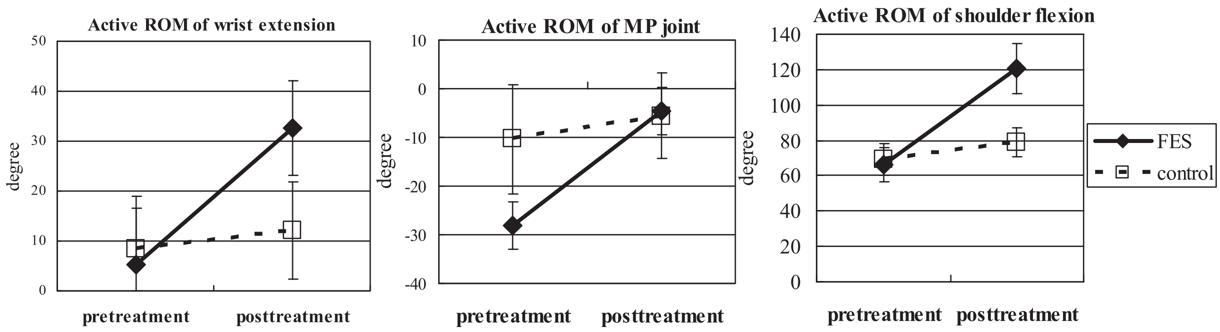

Fig. 6 Active range of motion at the wrist and metacarpopharangeal and shoulder joints. (FES group: n = 5, control group: n = 5)

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 patient's ability to grasp the object with FES assistance at the beginning of the training period. Training for ADLs, such as washing, drying dishes, and folding clothes, was also performed using a power-assisted FES device according to individual ability. Electrodes and lead wires were covered by clothes, and the portable stimulator was held in a small waist bag. Because the power-assisted FES is portable and light, patients could perform ADL exercises with the hemiparetic hand and arm FES inside or outside the house. At the start, the 30-minute FES program session was performed at home about 5 days per week. During the first 10 days, stimulation time was gradually increased to a maximum of 1 hour per session. Some patients could continue to perform ADL training with home FES as long as possible. Because the FES unit is a closed-loop system without an on-off switch, no operation of the FES device was required after the FES system was initially set. Patients were seen at 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 patients were independent in operating the device 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. The safety and efficacy of the power-assisted FES device have been repeatedly demonstrated with no adverse effects.

The stroke patients who used the FES displayed significantly greater improvements in active range of motion (**Fig. 6**), the modified Ashworth scale, root mean square (**Fig. 7**), and motor performance and were able to smoothly perform ADLs using the hemiparetic upper extremities. Some patients also showed decreased lower-extremity spasticity and improvements to severe spasticity of the upper extremity. Daily power-assisted FES home program therapy can effectively improve wrist and finger extension and shoulder flexion. Home-based power-assisted FES increased the likelihood that patients with hemiparesis would regain the use of a hemiparetic arm for ADLs.

Effectiveness of FES Modalities

Cauraough[20] and Chae[21] have reported that EMG-triggered neuromuscular electrical stimulation treatment is useful for rehabilitating wrist and finger extension movements in patients with hemiparesis. Gritsenko et al[22] have reported that the use of FES-assisted exercise therapy in conjunction with an instrumented workstation is associated with improvements in hand function in patients with hemipleiga whose level of motor function would have excluded them from CIMT. Although the eventual goal of this research is to provide workstations for home use that will allow people with hemiplegia to engage in regular teletherapy sessions to improve upper-extremity function, the equipment is now 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

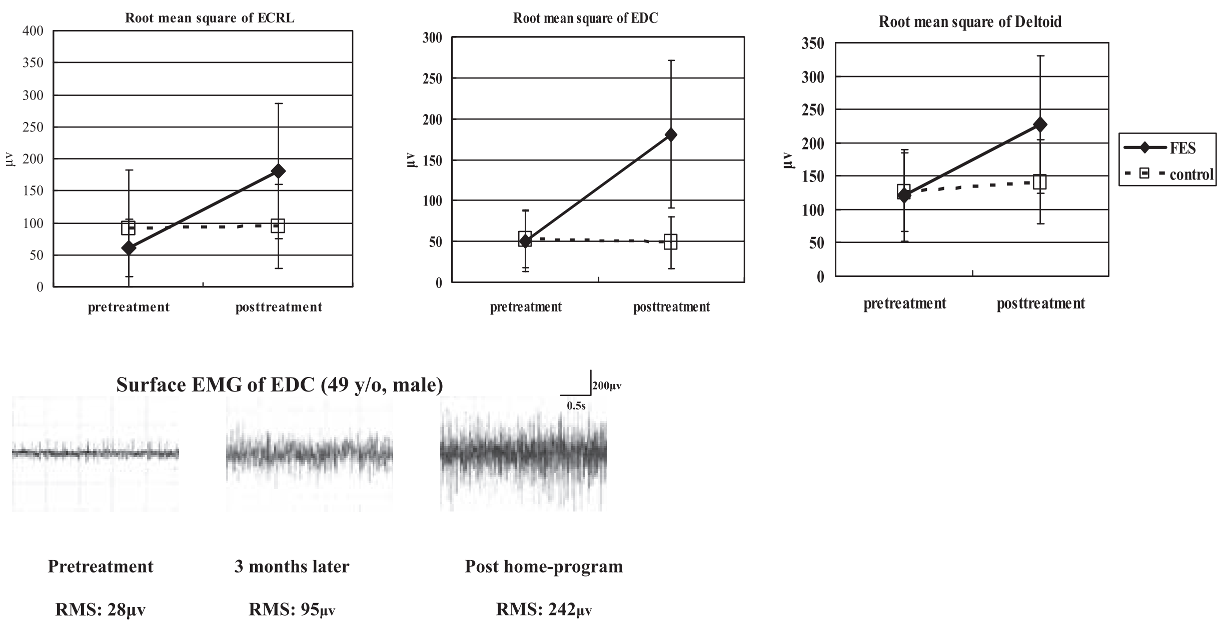

Fig. 7 Root mean squares of the ECRL, EDC and Del EMGs and sample EMGs (FES group: n = 5, control group: n = 5): Graphs; Root mean squares of all experimental-group patients were increased significantly after using the power-assisted FES home program for 5 months compared with the control group.
EMGs; Surface EMGs of EDC muscle in a 43-year-old patient with left hemiparesis at maximum effort before and after an FES training session. Compared with that before FES training, the EMG activity of the ECRL after FES training was significantly increased.

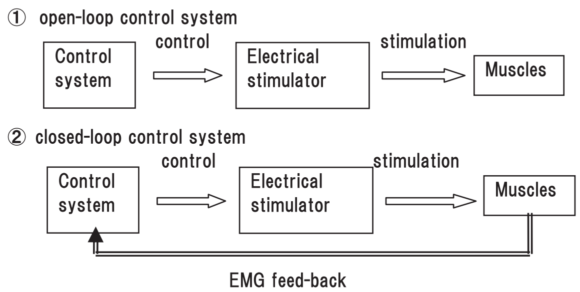

Fig. 8 FES control system

movements in patients with chronic neurological deficits after stroke[23].

Smith et al[24] have 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 (the Handmaster) can change the physical status and functional abilities in patients with chronic hemiparesis who are already receiving long-term physical therapy[25,26]. Lourencao et al[27] have reported that 6 months of FES is necessary for a significant improvement in grip speed in patients with hemiplegia, and it was hypothesized that as 5 months would be necessary for an effective home FES program 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.

The power-assisted FES system offers several specific advantages over previously described FES instruments. One advantage is that the new FES device continuously records signals from the stimulated muscles via an electrode working simultaneously as both EMG recorder and electrical stimulator, allowing contraction of the wrong muscle to be avoided. Another advantage is that the system is a closed-loop control FES system (**Fig. 8-2**). Most previous FES devices have used an open-loop switch control system that requires a manual on-off switch control (**Fig. 8-1**). It is tiresome to manipulate the switch in the open-loop control system with unaffected upper limb during FES intervention. The power-assisted FES device uses a closed-loop control system without a manual switch control after the proper parameters for EMG sensitivity and electrical stimulation have been set according to the condition of the patient. Because further adjustments are not

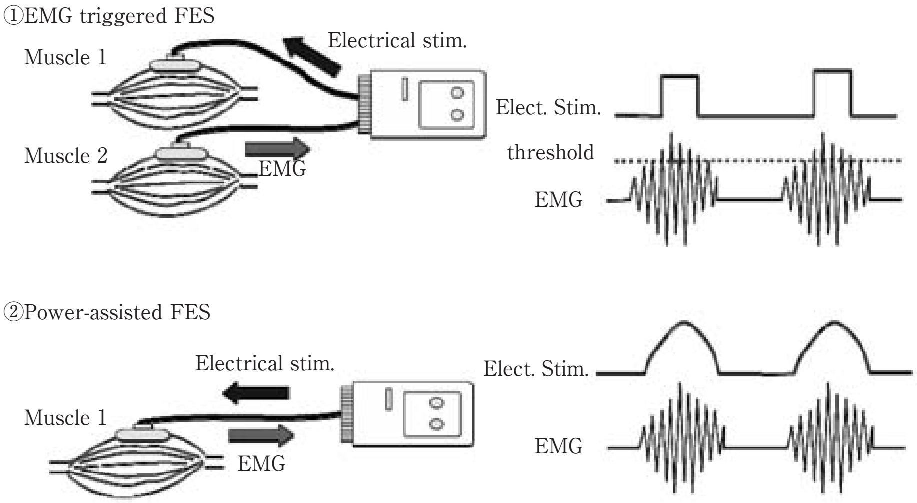

Fig. 9 In EMG-triggered FES (①), the EMG signal is picked up from muscle 2 and electrical stimulation is applied to muscle 1. Surface electrodes pick up the EMG signal at the target muscles and simultaneously stimulate the same muscles in proportion to the picked up integrated EMG signal by the same surface electrodes in power-assisted FES (②), which enables more delicate stimulation of muscles compared with EMG-triggered neuromuscular electrical stimulation. Because the power-assisted FES device steadily records voluntary EMG only from the stimulated muscles, contraction of the wrong muscle can be avoided.

required after initial set-up, patients are able to manage the power-assisted FES device easily at home. Because the device is portable and easy and safe to operate, rehabilitation training is easily performed at home every day. Compared with outpatient rehabilitation sessions, this daily home-program FES resulted in better outcomes. In one way, this home FES program may offer the same effects as CIMT from that point of view.

Some studies that have described relief of spasticity and opening of the hemiplegic hand with FES have attributed this result to reciprocal inhibition of the finger flexor muscles when the extensor muscles in patients with hemiplegia are stimulated[26,28,29]. Antagonist muscle tone can be decreased by simultaneous voluntary muscle contraction as well as by reciprocal inhibition of antagonist muscle electrical stimulation. This represents another advantage of power-assisted FES.

Triggered electrical stimulation may be more effective than nontriggered electrical stimulation in facilitating upper extremity motor recovery following stroke[30]. Repetitive movement therapy, in which the subject is cognitively involved in generating the movement, is more likely to be important and meaningful than therapy in which the subject is not cognitively involved[30]. Power-assisted FES devices stimulate hemiparetic muscles in proportion to the integrated EMG signal picked up from the target muscles, enabling more delicate stimulation of muscles compared with EMG-triggered neuromuscular electrical stimulation **(Fig. 9)** and, thus, has might be used in such rehabilitation training methods as cup transfer and box rotation[17]. It appears that the specific stimulus parameters may not be crucial for determining the effects of electrical stimulation[30].

Mechanism of FES Effects in Stroke Patients

It has been reported that stroke survivors with lower sensorimotor function have a decreased potential for recovery than do patients who are less severely affected[31]. 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[32]. Nudo et al[33] have

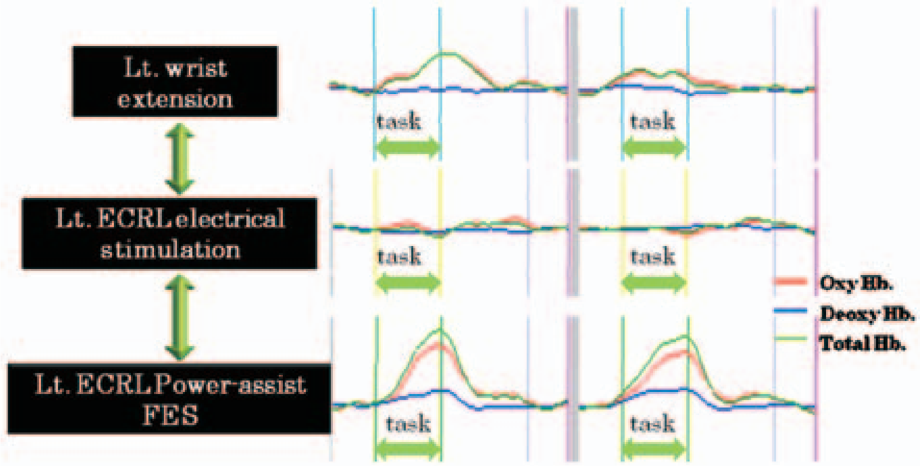

Fig. 10 Increased cerebral blood flow in the sensory-motor cortex area on the injured side during power-assisted FES session compared to simple active movement or simple electrical stimulation in a multichannel near-infrared spectroscopy study to noninvasively and dynamically measure.

suggested that afferent input associated with repetitive movements facilitates improvement of motor function. For this reason, motor stimulation might be more effective in improving motor control than sensory stimulation would be. This increased effectiveness is likely due to electrical stimulation that provokes motor activation being associated with cutaneous, muscle, and joint proprioceptive afferent feedback. In another way, the mechanism underlying power-assisted FES therapy is that alternative motor pathways are recruited and activated to assist impaired efferent pathways[32]. This explanation is based on the sensory-motor integration theory that sensory input from movement of an affected limb directly influences subsequent motor output[34]. As patients voluntarily attempt to extend the affected wrist and fingers, power-assisted FES induces movement, and full extension is obtained. We recognized that cerebral blood flow in the sensory-motor cortex area on the injured side was increased during the power-assisted FES session compared with simple active movement or simple electrical stimulation in a multichannel near-infrared spectroscopy study to noninvasively and dynamically measure hemoglobin levels in the brain during functional activity (**Fig. 10**). This also suggests sensory components as a possible mechanism for motor improvement with FES.

An increase in somatosensory stimulation applied to a hemiparetic limb can benefit performance on functional tests for patients with chronic stroke[35]. This result supports the proposal that electrical sensory stimulation in combination with training protocols may enhance the benefits of standard neurorehabilitative treatments and may also facilitate motor learning[36]. Patients receiving motor, proprioceptive, and cognitive inputs through the daily use of power-assisted FES may demonstrate significantly greater improvements in voluntary movement and functional use of the hand and arm.

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