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The effects of EMG-triggered functional electrical stimulation on upper extremity function in stroke patients

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Objective: The aim of this review is to explore the latest intervention trends and effects of EMG-triggered functional electrical stimulation on the upper extremity functions in stroke patients.
Design: Systematic review on clinical trials.
Methods: A systematic literature search was performed to identify clinical trials evaluating the effects of EMG-triggered functional electrical stimulation (EMG-FES) and task-oriented EMG-triggered FES on the hand functions in stroke patients. Literature review was conducted with the following key words: hand function, functional electrical stimulation, task-oriented, stroke.
Results: Ten clinical trials were included; 8 of them were randomized controlled trial, 1 was block-randomized, and 1 was a pre-post comparison study. A positive effect of electrical stimulation was reported in the patient groups that were treated with functional electrical stimulation combined with specific tasks, and volitional muscle contraction-triggered stimulation that was synchronized with tasks. Motor capabilities of the hand and arm were improved after the rehabilitation.
Conclusions: EMG-triggered electrical stimulation may be more effective than non-triggered electrical stimulation in facilitating the hand functions in stroke patients in terms of muscle strength and voluntary muscle contraction of the paretic hand and arm. Triggered electrical stimulation can be even more effective when it is combined with specific tasks.

Key Words: Electrical stimulation, Hand, Stroke, Task

Introduction

Of all stroke-induced impairments, arm hemiparesis may be the most disabling, considering its impact on the ability to perform activities of daily living (ADL) [1]. Recovery of upper extremity function is most rapid during the first months after stroke, but only 20% of the stroke survivors who are 3 months post stroke have normal upper extremity function [2,3].

There is growing evidence that electrical stimulation (ES) has a positive effect on upper extremity motor recovery following stroke [4-6]. ES might be a useful therapy in the rehabilitation of patients with stroke, but research reports demonstrate a wide variety of stimulation paradigms in terms of stimulation parameters, method of stimulations, and duration of treatment. This raises the question of how ES should be applied in order to achieve the optimum outcome.

Various devices are available for the application of ES, and different adjustments of stimulation parameters including amplitude, pulse duration, and pulse frequency are provided. With regard to motor stimulation, several methods of application have been reported [6]. Cyclic neuromuscular electrical stimulation (NMES) or functional electrical stimulation (FES) is applied by a pre-programmed scheme, which causes repetitive muscle contraction without active participation of the patient [5]. This passive neuromuscular stimulation has been reported to produce increased muscle strength, but the evidence is less convincing for more com-

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plicated hand manipulation tasks [7-9]. In contrast, electromyogram (EMG)-triggered functional electrical stimulation stimulation (EMG-FES) involves initiating a voluntary contraction for a specific movement until the muscle activity reaches a pre-set threshold level, and then an assisting electrical stimulus begins [7,10-12]. Compared to passive ES, voluntary initiating motor actions is known to be more effective in strengthening the muscles. Moreover, EMG-FES requires cognitive involvement by the motor cortex; improvement following EMG-FES was reported to be accompanied by changes in somatosensory cortex activation as measured by functional magnetic resonance imaging (fMRI) [13]. Other rehabilitative methods such as task-oriented training, bilateral movement training, and intensive tracking were associated with changes in size and location of motor output areas [10,14-17]. Therefore, task-oriented EMG-triggered FES can be a beneficial therapeutic intervention for hand function recovery in stroke patients.

The purpose of the present systematic review was to investigate the effects of task-oriented EMG-triggered FES on the arm/hand functions of stroke patients; mainly the wrist and finger extensors, which are known to be essential in regaining functional movement of the upper limb for ADL [18].

Methods

A computer-aided literature search up to March 2013 was performed in the following electronic databases: Pubmed (MEDLINE), Cochrane Central register of Controlled Trials, and CINAHL. The following medical subject headings and key words were used: stroke, hemiplegia, upper extremity, wrist extensors, hand function, task oriented, neuromuscular stimulation, EMG-triggered, and FES. References in relevant studies were examined, and the ones that were published after the year 2000 were included in this review.

Inclusion criteria for the present review were as follows. First, the studies involved patients diagnosed with a stroke. Second, the study investigated the effects of EMG-NMES or EMG-triggered FES by means of surface electrodes as the experimental intervention. Third, the EMG-NMES applied was targeted to activating the extensor muscles of the forearm. Fourth, the study was classified as a randomized controlled trial, involving at least one test treatment and one control treatment. Fifth, the application of EMG-NMES was the experimental treatment in the randomized controlled trial, not the control treatment. Sixth, the study analyzed the functional measures for the hemiparetic arm/hand functions. Case studies, animal studies, methodological, and theoretical discussions were exempted (Table 1).

Table 1. List of inclusion and exclusion details

Area	Contents
Inclusion details	
Study type	Randomized controlled trials, pre-post comparison, intervention study
Subjects	Stroke patients
Intervention	EMG-triggered FES, FES combined with tasks for arm/hand function
Outcomes	Arm/hand function improvement
Exclusion details	
	Case studies, animal studies, methodological, theoretical, or discussion papers

EMG: electromyogram, FES: functional electrical stimulation.

Results

After searching the latest EMG-triggered NMES research studies, 10 clinical intervention studies were selected for review on the efficacy of the intervention. Clinical characteristics and results of the included studies are summarized in Table 2 and 3. Among the 10 studies, 8 of them were randomized controlled studies. One study was block-randomized [19], and one other study was a pre-post comparison study [20]. Except 2 studies [21], chronic stroke patients were recruited for the research.

For outcome measures, clinical tests, kinematic measures, and electromyographic measures were used. As a clinical test, Box and Block test was the most commonly used measure, and then the upper-extremity portion of the Fugl-Meyer assessment was the second most commonly used measure.

Four studies by Cauraugh and Kim [10,11] and Cauraugh *et al*. [22,23] were included in this study. The results of their studies showed significantly decreased motor dysfunction and improved motor capabilities of the wrist and finger extensors after intervention. When different durations of stimulation was applied, longer active stimulation decreased residual motor dysfunctions more than the shorter stimulation duration (10 s > 5 s > 0 s). Longer stimulation group (10 s) displayed improvements on all outcome measures compared to the control group. The two coupled motor recovery

Table 2. Clinical characteristics of included trials

Study	Design	N	Subjects	Age (yr)
von Lewinski *et al*., 2009 [20]	Pre-post comparison	9	Chronic stroke	18-80
Hara *et al*., 2008 [25]	RCT	20	Chronic stroke	-
Alon *et al*., 2007 [19]	Block-randomized trial	15	Subacute stroke	20-90
Page *et al*., 2012 [24]	RCT	32	Chronic stroke	57.6
Kowalczewski *et al*., 2007 [21]	RCT	19	Subacute stroke	60.6
Kimberley *et al*., 2004 [13]	RCT	16	Chronic stroke	60.1
Cauraugh *et al*., 2000 [23]	RCT	11	Chronic stroke	61.6
Cauraugh and Kim, 2002 [10]	RCT	15	Chronic stroke	63.7
Cauraugh *et al*., 2005 [22]	RCT	26	Chronic stroke	54.48-69.37
Cauraugh and Kim, 2003 [11]	RCT	26	Chronic stroke	66.4

RCT: randomized controlled trial.

protocols increased movement capabilities in patients with stroke. The coupled bilateral protocol involved concurrent wrist/finger movements on the unimpaired limb that were coupled with active stimulation on the impaired limb. The group that was treated with unilateral EMG-FES on the impaired wrist/fingers exceeded the control group in Box & Block test and rapid onset of muscle contraction.

Kimberley *et al*. [13] compared the EMG-FES training group and the sham group in the aspect of arm and hand functions. Significant improvements were found in Box and Block test, isometric finger-extension strength, motor activity log (MAL), Jebsen-Taylor hand function test (JTHFT) for small objects, stacking, and heavy ans. The sham group improved isometric finger-extension strength, but no other test.

Kowalczewski *et al*. [21] used the scores from sensor readings on the workstation, which was used for task-oriented training for the high-intensity FES group. Kinematic scores were obtained from the 3 tasks given to each subject, and the maximal displacement was divided by the time taken. This score was normalized to that of control subjects, and the mean of 3 normalized task scores was calculated. This is called combined kinematic score (CKS). The CKS provided quantitative information on improvement in motor performance of the specific tasks on the workstation. The high-intensity group had more than tripled CKS, significantly increased Wolf motor function test, MAL (amount of use) and MAL (quality of movement) ($p < 0.05$) whereas the low-intensity group only increased about 20% in CKS.

Page *et al*. [24] compared different durations of task-oriented FES, and analyzed the effects on improving hand functions of stroke patients. Tasks were tailored for each subject based on their lifestyle and preference, but mainly included grasping, releasing, and pinching actions for ADL-related movements. The 'repetitive task-specific practice + FES 120 minute' group, which repetitively performed specific tasks with FES for 120 minutes a day, exhibited the most consistent pattern of motor change, and the largest number of significant changes of all of the groups, on the assessments. The Fugl-Meyer assessment subsets showed the most increase in shoulder/forearm and wrist, although hand and coordination/speed was increased. The group significantly increased functional movement ability on the arm motor ability test functional ability scale, and exhibited significantly increased quality of movement ($p < 0.05$).

Alon *et al*. [19] applied a microprocessor based FES to concurrently synchronize ES with specific tasks. The Box and Block test and JTHFT quantified the recovery of upper extremity function. The mean number of blocks transferred increased more in the FES group compared to the control, and JTHFT task was 6.7±2.9 seconds faster that the 11.8±5.4 seconds of the control group. Mean Fugl-Meyer score at 12 weeks was 49.3±5.1 points out of 54 compared to the control group that scored 40.6±8.2 points ($p < 0.05$). All patients regained hand function.

Hara *et al*. [25] also used instrumental tasks that were consisted of reaching, grasping, moving (pulling, rotating) and releasing an object using the hemiplegic upper extremity. Objects were chosen on the basis of each patient's ability to grasp the object with FES assistance at the beginning of the training period. ADL activity was also trained, and it included washing, drying dishes, and folding clothes according to individual ability. All of the tasks were performed with power-assisted FES. The stimulator induces greater muscle contraction by ES in proportion to the integrated EMG signal picked up from the target muscles as they ac-

Table 3. Outcome measures, intervention, and results of the studies included

Study	Outcome measures	Intervention (E/C)	Results
von Lewinski *et al*., 2009 [20]	Box & Block ARAT fMRI (motor area) TMS (functional testing)	E1 task-oriented EMG-FES Pre-post	No significance
Hara *et al*., 2008 [25]	AROM (UE) MAS (spasticity) EMG (RMS) 10-CMT 9-HPT	E1 power-assisted task-oriented EMG-FES C task without FES	AROM: E1＞C ($p<0.05$) RMS: E1＞C ($p<0.05$) 10-CMT: E1＞C ($p<0.01$) 9-HPT: E1＞C ($p<0.01$)
Alon *et al*., 2007 [19]	Box & Block JTHFT (light object lift) Fugl-Meyer (UE)	E1 task with EMG-FES orthosis C task only	Box & Block: E1＞C (p=0.049) JTHFT: E1＞C (p=0.049) Fugl-Meyer: E1＞C (p=0.042)
Page *et al*., 2012 [24]	Fugl-Meyer (UE) AMAT ARAT Box & block	E1 30 min RTP＋ESN orthosis E2 60 min RTP＋ESN orthosis E3 120 min RTP＋ESN orthosis C home exercise	E3 group: Fugl-Meyer (UE), AMAT (functional ability & movement quality), ARAT pre＜post ($p<0.05$) E2 group: ARAT pre＜post ($p<0.05$)
Kowalczewski *et al*., 2007 [21]	WMFT MAL Fugl-Meyer (UE) CKS (workstation)	E1 high-intensity task-oriented FES-assisted exercise C low-intensity task-oriented FES-assisted exercise	CKS: E1＞C ($p<0.05$)
Kimberley *et al*., 2004 [13]	Box & Block MAL JTHFT Isometric strength Finger tracking fMRI	E EMG-FES C sham	E group: Box & Block, strength, MAL, JTHFT (small objects, stacking, heavy cans) pre＜post ($p<0.05$) C group: strength pre＜post (p=0.01)
Cauraugh *et al*., 2000 [23]	Reaction time Sustained contraction (wrist extensor) MAS (hand, wrist, fingers) Fugl-Meyer (UE) Box & Block	E EMG-FES C no treatment	No significance
Cauraugh and Kim, 2002 [10]	Reaction time Sustained contraction (wrist extensor) Box & Block	E1 EMG-FES/bilat E2 EMG-FES C no treatment	Box & Block: E1 & E2 ＞C -test session ($p<0.001$)
Cauraugh *et al*., 2005 [22]	Reaction time Movement time Peak velocity Deceleration time	E1 EMG-FES/bilat E2 EMG-FES C no protocol	Deceleration time: E1＜E2 & C ($p<0.05$)
Cauraugh and Kim, 2003 [11]	Box & Block Reaction time Sustained contraction. (wrist extensor)	E1 10 s EMG-FES/bilat E2 5 s EMG-FES/bilat C 0 s EMG-FES/bilat	Box & Block: E1＞E2 & C -test session (p=0.001) Reaction time: E1 & E2＜C -stimulation duration (p=0.016) -test session (p=0.001) Sustained contraction: E1 & E2＞C

E: experimental group, C: control group, EMG: electromyogram, EMG-FES: EMG-triggered functional electrical stimulation, bilat: bilateral, MAS (hand, wrist, fingers): motor assessment scale, UE: upper extremity, MAL: motor activity log, JTHFT: Jebsen-Taylor hand function test, fMRI: functional MRI, WMFT: Wolf motor function test, CKS: combined kinematic score from the workstation, RTP＋ESN: repetitive task-specific practice (RTP) combined with functional electrical stimulation neuroprosthesis (ESN), FM: Fugl-Meyer assessment, AMAT: arm motor ability test, ARAT: action research arm test, AROM: active range of motion, MAS (spasticity): modified Ashworth scale, RMS: root mean square, ROM: range of motion, 10-CMT: ten-cup-moving test, 9-HPT: nine-hole-peg test, TMS: transcranial magnetic stimulation.

tively contract. The electrodes detect electromyography in the affected muscles, and then provide amplified stimulation to these muscles. A computer inside the device evaluates the amount of activity present in the muscle, and the stimulator does not work when there is no volitional muscle contraction detected. After participating in the FES program, subjects exhibited improved active range of motion, spasticity, hand performance according to ten-cup-moving test (F=18.72, $p < 0.01$) and nine-hole-peg test (F=12.27, $p < 0.01$) compared to the control group. The subjects in FES group also exhibited a significantly increased root mean square (RMS) of target muscle EMG, with values of 102.8±78.9 μv in extensor carpi radialis longus, 111.2±95.2 μv in extensor digitorum communis and 120.0±81.2 μv in deltoid compared to preintervention levels ($p < 0.05$).

von Lewinski *et al*. [20] studied the effects of task-oriented EMG-triggered FES training, and analyzed the activation patterns in the motor areas of the brain by using fMRI and transcranial magnetic stimulation. The subjects were asked to put plastic cups of different sizes into each other, and voluntary activity in at least one UE muscle group triggered the FES. fMRI showed an increase in the spatial extent of activation in the sensorimotor cortex (SMC) in 4 of 7 patients after EMG-FES therapy. The findings supported the notion that intensified EMG-FES may improve the arm function in individual chronic stroke patients but not in more severely impaired individuals. Functional improvements were paralleled by increased ipsilesional SMC activation and intracortical facilitation, supporting neuroplasticity.

Discussion

The present review was conducted to evaluate the effects of EMG-triggered FES on the arm/hand function after stroke. The important finding of this study was that EMG-FES, when performed in an intensive manner with higher voluntary muscle contraction, produced significant improvements in functional activities in the patients who were in the experimental groups. The control groups, or the sham treatment groups only showed gains in strength without functional improvements from pre-test to post-test.

The application of EMG-triggered FES was proved to be effective in post stroke hand function recovery in terms of grasping, releasing, and pinching; degree of improvements depending on the severity of impairment.

In this review, the studies that conducted various functional tests that would focus on finger and wrist movements for the hand function were included in order to understand the effective and accurate outcome measures for the hand function tests after EMG-FES training. Most of the studies used Box and Block and some JTHFT for dexterity function assessment. The changes in EMG amplitudes were analyzed by using the mean increase in RMS of target muscles during sustained contraction and for rapid onset of the target muscles [10,11,22,23,25]. The improved results were reflected on enhanced muscle strength and motor performance.

Most of the studies in this review were conducted with chronic stroke patients, but according to Meilink *et al*. [26], the return of finger extension is critical for improvement of dexterity after stroke, and because the return of dexterity is not fully defined within the initial five weeks post stroke, the effects of EMG-FES should be applied within this critical time window. More studies need to be conducted to find the effects of EMG-FES on the hand function recovery in subacute stroke patients.

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