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The effects of electromyography-controlled functional electrical stimulation on upper extremity function and cortical perfusion in stroke patients

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HIGHLIGHTS

- Near-infrared spectroscopy (NIRS) is feasible in measuring brain activity during the electrical stimulation which is not available with fMRI.
- With analysis of brain cortical perfusion (BCP) using NIRS during rehabilitative training of a paretic upper extremity, the relationship between EMG-controlled FES (EMG-FES) therapy and ipsilesional BCP was revealed.
- This is the first article describing the brain perfusion change during EMG-FES stimulation and its treatment benefits for the hemiparetic patients in rehabilitation course.

ABSTRACT

Objective: The relation was investigated between hemiparetic arm function improvement and brain cortical perfusion (BCP) change during voluntary muscle contraction (VOL), EMG-controlled FES (EMG-FES) and simple electrical muscle stimulation (ES) before and after EMG-FES therapy in chronic stroke patients.
Methods: Sixteen chronic stroke patients with moderate residual hemiparesis underwent 5 months of task-orientated EMG-FES therapy of the paretic arm once or twice a week. Before and after treatment, arm function was clinically evaluated and BCP during VOL, ES and EMG-FES were assessed using multi-channel near-infrared spectroscopy.
Results: BCP in the ipsilesional sensory-motor cortex (SMC) was greater during EMG-FES than during VOL or ES; therefore, EMG-FES caused a shift in the dominant BCP from the contralesional to ipsilesional SMC. After EMG-FES therapy, arm function improved in most patients, with some individual variability, and there was significant improvement in Fugl–Meyer (FM) score and maximal grip strength (GS). Clinical improvement was accompanied by an increase in ipsilesional SMC activation during VOL and EMG-FES condition.
Conclusion: The EMG-FES may have more influence on ipsilesional BCP than VOL or ES alone.
Significance: The sensory motor integration during EMG-FES therapy might facilitate BCP of the ipsilesional SMC and result in functional improvement of hemiparetic upper extremity.

1. Introduction

Upper extremity hemiplegia is the primary impairment underlying stroke-induced disability. Reducing chronic hemiplegic upper extremity impairment is generally difficult. One approach is based on functional electrical stimulation (FES) of muscles to augment hand function (Baker et al., 1979). FES of upper limb muscles has been receiving increasing attention as a therapeutic modality in

Abbreviations: EMG, electromyography; FES, functional electrical stimulation; fMRI, functional magnetic resonance imaging; NIRS, near-infrared spectroscopy; CBF, cerebral blood flow; SIAS, Stroke Impairment Assessment Set; VOL, voluntary muscle contraction; ES, simple electrical muscle stimulation; EMG-FES, electromyography-controlled functional electrical stimulation; SMC, sensory motor cortex.

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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 (Granz et al., 1996). Electromyography (EMG)-triggered FES may improve the motor performance of the affected limb of hemiparetic stroke patients even in the chronic stage. EMG-triggered FES treatment was reported as a useful intervention for rehabilitating wrist and finger extension movements in hemiplegic individuals (Cauraugh et al., 2000; Chae et al., 2001). We have applied EMG-controlled FES which induces greater muscle contraction by electrical stimulation in proportion to the integrated EMG signal picked up and motor point block for antagonist muscles as a novel hybrid EMG-controlled FES therapy in an outpatient rehabilitation clinic for patients with stroke (Hara et al., 2006), and have achieved good results using this novel FES therapy as an outpatient rehabilitation service. Daily EMG-controlled FES home therapy can also effectively improve wrist and finger extension and shoulder flexion compared to the conventional rehabilitation therapy in RCT study (Hara et al., 2008). Proprioceptional sensory feedback might play an important role in the effects of EMG-FES therapy.

There has been no study of brain activity during a therapeutic FES intervention because electrical stimulation obstructs assessment of brain activity via functional magnetic resonance imaging (fMRI), single-photon emission computed tomography, and positron emission tomography and a usual FES intervention is difficult under those functional neuroimaging condition. However, near-infrared spectroscopy (NIRS) is a recently developed neuroimaging methodology that is not influenced by electrical stimulation, and thus can be used to assess brain activity during FES in the rehabilitation room. The advantages of NIRS include its noninvasiveness, portability, the natural setting of the examination, low running cost and high sensitivity. NIRS measures changes in oxygenated and deoxygenated hemoglobin concentration that have been shown to correspond to regional cerebral blood flow (CBF) (Toronov et al., 2001) and are thus interpreted as reflecting cortical activation.

The objective of the present study was to examine the effect of EMG-FES therapy on cortical activity in stroke patients with partial hand or shoulder motion. In addition, we aimed to quantify the relation between EMG-FES therapy effects on cortical activity and functional improvement in the hemiparetic limb. This is the first report to show the cortical activity and functional impairment status during and after a therapeutic FES intervention.

2. Methods

2.1. Subjects

Subjects were more than 1 year post-stroke, by which time the recovery of upper-extremity function is thought have plateaued. Only subjects who met the following selection were enrolled in the trial: (1) first stroke; (2) stroke in only one hemisphere; (3) no known history of other neuromuscular disorders; (4) upper extremity (U/E) Stroke Impairment Assessment Set (SIAS, see Appendix A) (Chino et al., 1996) motor function score 2–4; (5) finger (F) SIAS motor function score 1a–2; (6) plateau in motor recovery after conventional neuro-rehabilitation; (7) the ability to voluntarily extend the metacarpophalangeal joint of the third finger >20° against gravity from a 90° flexed position; (8) modified Ashworth grade <2; (9) sufficient cognitive function to understand and follow instructions; and (10) passive range of motion in the affected wrist of extension to 45° from neutral, and in the affected shoulder joint of flexion to 140°, as measured by goniometry. All subjects had difficulties in the initiation and control of smooth voluntarily finger extension, wrist extension, and shoulder flexion movements. The following exclusion criteria were also used: (1) inability of EMG-FES to open the impaired hand; (2) intolerance of FES by the subject; (3) no voluntary movements of the wrist, finger or shoulder; (4) serious cognitive deficit (Mini-Mental State Examination score <20); (5) visual hemineglect; (6) severe depression; (7) other serious medical conditions; (8) pacemaker or other implanted stimulator; and (9) excessive pain in the affected upper limb, wrist or shoulder. All participants provided informed written consent prior to participation. All experimental procedures were approved by the Institutional Review Board and Ethics Committee of Nippon Medical School Chiba Hokusoh Hospital and the experiments were conducted in accordance with the Declaration of Helsinki.

2.2. EMG-FES apparatus and instrumentation

The EMG-FES system used (PAS System™ GD601: OG GIKEN Company, Okayama, Japan) is a novel EMG-controlled electrical stimulator called an integrated volitional control electrical stimulator (IVES) (Muraoka, 2001), which is portable, two-channel neuromuscular stimulator that can be used to elicit wrist and finger extension or shoulder flexion during coordinated movement. The system uses a three-electrode format to allow EMG-controlled electrical stimulation of muscles. Two self-adhesive electrodes (3-cm diameter, 3-cm inter-electrode distance) were placed over the belly of the wrist and finger extensor muscles, at the mid-point between the lateral epicondyle of the humerus and the dorsal tubercle of the radius. The stimulation promotes wrist and finger extension or shoulder flexion during coordinated movement, but will not work when muscles are quiescent; therefore, subjects were asked to initiate a voluntary contraction of the finger extensors. Surface electrodes detected the EMG signal at the target muscle and, through the same surface electrodes; the target muscle was electrically stimulated. The amplitude of stimulation was proportional to the amplitude of the integrated EMG signal detected, with the exception of the 25 ms after the stimulation pulse in which stimulus artifacts and M-waves are present. The EMG-FES device steadily records from the stimulated muscles; therefore, the contraction of the wrong muscle can be avoided. Details of this EMG-FES device are provided in reference (Hara et al., 2008).

2.3. EMG-FES training

Exercises of the hemiplegic upper extremity were performed, including supination and pronation, flexion and extension of individual fingers, flexion and extension of the wrist, flexion and extension of the elbow, and adduction and abduction of the shoulder. The tasks consisted of reaching, grasping, moving (e.g., pulling, rotating) and releasing an object on a desk using the hemiplegic upper extremity. The objects used were chosen on the basis that they could be grasped by the patient with EMG-FES assistance at the beginning of the training period. Training of activities of daily living, such as washing, drying dishes and folding clothes, was also performed using a EMG-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. The EMG-FES unit is an auto-driven system without an on-off switch; therefore, no operation of the EMG-FES system was required after it had been initially set. The physician checked the settings of the EMG-FES system and modified the parameters for individuals as needed during follow-up visits. Safety and efficacy of the EMG-FES system have been repeatedly demonstrated with no adverse effects (Hara et al., 2006, 2008). Each treatment session lasted approximately 40 min, and treatment sessions were performed once or twice a week for about 5 months.