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Original Article

Clinical usefulness of brain-computer interface-controlled functional electrical stimulation for improving brain activity in children with spastic cerebral palsy: a pilot randomized controlled trial

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Abstract. [Purpose] Evaluating the effect of brain-computer interface (BCI)-based functional electrical stimulation (FES) training on brain activity in children with spastic cerebral palsy (CP) was the aim of this study. [Subjects and Methods] Subjects were randomized into a BCI-FES group (n=9) and a functional electrical stimulation (FES) control group (n=9). Subjects in the BCI-FES group received wrist and hand extension training with FES for 30 minutes per day, 5 times per week for 6 weeks under the BCI-based program. The FES group received wrist and hand extension training with FES for the same amount of time. Sensorimotor rhythms (SMR) and middle beta waves (M-beta) were measured in frontopolar regions 1 and 2 (Fp1, Fp2) to determine the effects of BCI-FES training. [Results] Significant improvements in the SMR and M-beta of Fp1 and Fp2 were seen in the BCI-FES group. In contrast, significant improvement was only seen in the SMR and M-beta of Fp2 in the control group. [Conclusion] The results of the present study suggest that BCI-controlled FES training may be helpful in improving brain activity in patients with cerebral palsy and may be applied as effectively as traditional FES training.
Key words: Spastic cerebral palsy, Brain computer interface, Functional electrical stimulation

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INTRODUCTION

Functional Electrical Stimulation (FES) is a technique that can be used to treat muscles paralyzed because of upper motor neuron lesions such as those observed in cerebral palsy (CP) and hemiplegia[1]. FES therapeutically provokes contraction of denervated muscles by means of electric stimulation to create functional movements. FES is also used to treat foot drop in patients with hemiplegia (via electrical stimulation of the tibial nerve) and to rehabilitate paralyzed motor function in patients with other disorders of the central nervous system[2]. In addition, FES is particularly effective in treating muscle weakness due to brain injury, as symptoms commonly originate from type II muscle fibers[3]. The technique can also be used to stimulate muscle activation in patients with cerebral palsy, preventing weakness because of disuse, and helping to reeducate the patient. While FES is a passive technique with no required cognitive investment, researchers have discovered several benefits related to movement enhancement when paretic limbs are treated with active, goal-oriented repetitive movement training[4].

The brain-computer interface (BCI) is a method by which patients are able to directly control instruments (e.g., computer, virtual keyboard, virtual-reality environment)[5] using their own brains, enabling them to communicate and exercise control by focusing on the brain's electrical activity, as measured using electroencephalography (EEG)[6, 7]. In the initial phases

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of its use, BCI was approved for use in patients with severe motor dysfunction, such as amyotrophic lateral sclerosis, to enable communication and interaction with the external environment[8]. BCI was subsequently tested and utilized in research relevant to the rehabilitation of motor neurons in patients with quadriplegia as a result of spinal cord injury[9]. Research has also shown that direct control of ankle dorsiflexion is possible when FES is used with EEG signals, potentially allowing the brain direct access to control the movements of the four extremities[5].

In the present study, the changes in brain activity between children with CP and healthy controls following completion of a six-week BCI-FES training protocol were analyzed. The purpose of this study was to evaluate the therapeutic effectiveness of BCI-FES on brain activity in children with CP.

SUBJECTS AND METHODS

Twenty children with CP were recruited to participate in this study. The inclusion criteria were as follows: (1) diagnosis of spastic CP; (2) 4 to 9 years of age; (3) level III/IV on the Gross Motor Function Classification System [GMFCS]; and (4) no history of orthopedic surgery or spasticity-reduction intervention in the previous six months. Patients with a high degree of spasticity or poorly controlled epilepsy, and children taking medication for the treatment of stiffness were excluded from the study. All children who were recruited participated in the intervention at a rehabilitation hospital for children. The present study was approved by the Sahmyook University Institutional Review Board (SYUIRB2014-094). The objective of the study and its requirements were explained to the subjects, and all participants provided written parental consent, in accordance with the ethical principles of the Declaration of Helsinki.

Sensorimotor rhythms (SMR) and middle beta waves (M-beta) were evaluated prior to the intervention. Participants were randomized into a BCI-FES group (n=10) and an FES control group (n=10). Subjects in both groups trained for 30 minutes per session, five times per week for six weeks. In addition, the participants were offered conventional physical therapy for 30 minutes per session, five times per week for six weeks. Each group had one dropout due to personal reasons. The BCI-FES group contained six males and three females; their mean age, height, and weight were 6.33 ± 1.41 years, 120.49 ± 17.23 cm, and 26.33 ± 8.17 kg, respectively. Of these nine participants, six were right-handed, while three were left-handed. The FES group consisted of five males and four females; their mean age, height, and weight were 5.44 ± 1.50 years, 115.60 ± 13.94 cm, and 21.80 ± 5.76 kg, respectively. Of these nine participants, five were right-handed and four were left-handed. There were no significant differences in primary outcome measures such as SMR or M-beta between the groups prior to training.

In the BCI-FES group, FES was applied as patients concentrated on finger extension, wrist extension, wrist abduction, and wrist circumduction while holding a wrist bar. The equipment consisted of a monitor screen facing the subjects, EEG sensors (Brainwave-sensing headset, Neurosky, 2011) for retrieval of brainwave information, a laptop to record and process brain wave signals, a USB output board to link brain wave signals to FES when concentration occurred, and FES and EEG sensors to receive brain wave information when concentration was high[10–12]. When the measured level of concentration surpassed the threshold of the concentration index, this information was transferred to the USB output board, activating the FES (EMG FES 1000-Walking Man II, Cybermedic Inc., Korea, 2009). EEG patterns during concentration were subsequently used to trigger FES of the extensor carpi radialis, extensor carpi ulnaris, and extensor digitorum longus to achieve wrist extension. In order to avoid muscle fatigue due to electrical stimulation, the off-time was set to last 5 seconds, pulse frequency was 35 Hz, pulse width was 150 μs, and current was 10–20 mA[12].

Participants in the FES group underwent (EMG FES 1000-Walking Man II, Cybermedic Inc., Korea, 2009) 30 minutes of FES. Participants in the BCI-FES group were studied using the previously defined parameters.

Poly G-I (Laxtha Inc., Daejeon, Korea) was used to measure brain wave activity. Brain waves were measured in a separate space where patients were left undisturbed[13, 14]. The EEGs were based on the International 10–20 electrode system, and measurement positions were taken on the left side of frontopolar area 1 (Fp1) and the right side of frontopolar area 2 (Fp2). Quantitative analysis of EEG data was performed using Telescan 2.98 (Laxtha Inc., Daejeon, South Korea). With regard to the overall raw EEG data, 70 seconds of each measurement were analyzed after exclusion of the first and last ten seconds. Raw EEG data were converted into frequencies using a fast Fourier transformation. Brain waves were categorized according to convention into sensorimotor rhythm (12–15 Hz), and mid-beta (15–20 Hz). The attention index was defined as the ratio of theta waves to SMR and mid-beta waves[10].

The SPSS 20.0 program (SPSS, Chicago, IL, USA) was used for all statistical analyses. The Shapiro-Wilk test was used to determine the distribution of general participant characteristics and outcome measures. Paired t-tests were used to compare the changes in pre-test and post-test brain wave measurements within each group, and an independent t-test was performed to compare the two groups. A p-value<0.05 was considered significant.

RESULTS

Analysis of EEG data for the BCI-FES group revealed significant increases in the SMR of Fp1 (9.8×10^{-3} at baseline to 19.4×10^{-3} post-intervention; p<0.01), the SMR of Fp2 (1.5×10^{-3} at baseline to 30.8×10^{-3} post-intervention; p<0.01), the M-beta of Fp1 (8.3×10^{-3} at baseline to 15.3×10^{-3} post-intervention; p<0.01), the M-beta of Fp2 (1.3×10^{-3} at baseline to 26.9×10^{-3} post-intervention; p<0.01). Analysis of EEG data for the control group revealed significant increases in the SMR

Table 1. Comparison of brain activation within groups and between groups (N=18)

Parameters	Values				Change values	
	BCI-FES (n=9)		FES (n=9)		BCI-FES (n=9)	FES (n=9)
	Before	After	Before	After	Before-after	Before-after
Fp1 SMR	9.8×10^{-3} (4.7×10^{-3})	19.4×10^{-3} $(9.4 \times 10^{-3})^{**}$	10.1×10^{-3} (3.7×10^{-3})	13.4×10^{-3} (7.1×10^{-3})	-9.6×10^{-3} (7.9×10^{-3})	-3.2×10^{-3} (6.0×10^{-3})
M-beta	8.3×10^{-3} (2.4×10^{-3})	15.3×10^{-3} $(4.2 \times 10^{-3})^{**}$	7.9×10^{-3} (2.2×10^{-3})	10.9×10^{-3} (6.9×10^{-3})	6.9×10^{-3} (5.3×10^{-3})	2.9×10^{-3} (7.7×10^{-3})
Fp2 SMR	1.5×10^{-3} (6.4×10^{-3})	30.8×10^{-3} $(13.2 \times 10^{-3})^{**}$	15.4×10^{-3} (4.1×10^{-3})	24.0×10^{-3} $(6.9 \times 10^{-3})^{*}$	-15.5×10^{-3} (11.9×10^{-3})	-8.6×10^{-3} (8.7×10^{-3})
M-beta	1.3×10^{-3} (4.1×10^{-3})	26.9×10^{-3} $(8.1 \times 10^{-3})^{**}$	13.1×10^{-3} (4.2×10^{-3})	20.4×10^{-3} $(7.3 \times 10^{-3})^{*}$	14.0×10^{-3} (9.8×10^{-3})	7.3×10^{-3} (7.1×10^{-3})

Values are displayed as means (SD). *$p<0.05$, **$p<0.01$: significant difference within group, BCI-FES: Brain Computer Interface-based Functional Electrical Stimulation; FES: Functional Electrical Stimulation; Fp1: frontopolar 1; Fp2: frontopolar 2; SMR: Sensory Motor Rhythm; M-beta: Middle beta

of Fp2 (15.4×10^{-3} at baseline to 24.0×10^{-3} post-intervention; $p<0.05$) and the M-beta of Fp2 (13.1×10^{-3} at baseline to 20.4×10^{-3} post-intervention; $p<0.05$) (Table 1).

DISCUSSION

Brain-computer interfaces (BCI) are a relatively novel technology that enables a patient to interact with his or her environment through brain signals and restores motor function by inducing activity-dependent brain plasticity[12, 15]. BCI feedback training is also used in the rehabilitation of stroke patients. For instance, electroencephalography (EEG)-based BCI detects event-related synchronization in the oscillatory rhythms of sensorimotor activity associated with motor imagery or action observation, which in turn drives the BCI. Recent research has focused on combining BCI and FES to exercise control over output devices[16]. Additionally, BCI offers insight into the visuospatial patterns of such phenomena as event-related desynchronization, event-related synchronization and sensorimotor rhythms through motor imagery, motor observation, and movement execution[9].

In the present study, the results indicated a concentration index for FES with respect to the six types of movement of the fingers/wrist after observation of the recordings. The SMR concentration index in Fp1 increased from 9.8×10^{-3} to 19.4×10^{-3} ($p<0.05$) in the BCI-FES group and the SMR concentration index in Fp2 increased from 1.5×10^{-3} to 30.8×10^{-3} ($p<0.05$). In addition, the M-beta concentration index in Fp1 M-beta increased 8.3×10^{-3} to 15.3×10^{-3} ($p<0.05$), and from 1.3×10^{-3} to 26.9×10^{-3} ($p<0.05$) in Fp2 in the BCI-FES group. Chung et al.[10] utilized BCI-FES in post-stroke patients, and found that the attention index was significantly increased in Fp1 and Fp2, and activation index was significantly increased in Fp1. Lee et al. [13] used virtual reality-based bilateral upper-extremity training, and found significant increases in concentration in Fp2 and Fp4 and brain activity in Fp1 and F3. In this study, the results demonstrated significant increases in the SMR and M-beta concentration index. A potential reason for this improvement is that the children with CP received visual stimuli. As a result, event-related synchronization was shown while they were concentrated on finger extension, wrist extension, wrist abduction, and wrist circumduction while holding a wrist bar. After synchronization, brain activity was necessary for motor imagery, specifying the details from motor observation, and then finally the movement execution stage.

Mid-beta waves are related to logical thinking, problem solving, and attentiveness to external stimuli. When such waves are present, improvements in problem solving, simple concentration, general cognitive ability, and self-awareness with respect to bodily position and muscular stability, have been observed[17]. It has also been shown that subjects in this state are able to concentrate without tension and perform appropriately[18]. Educated self-control, through training designed to increase the sensorimotor rhythm, can in turn increase memory ability, attentive concentration, sensory perception, and language cognition[18]. In addition, sensorimotor rhythms are observed when stable vigilance and attentive concentration are maintained. Involuntary movements are reduced as motor activity declines and sensorimotor rhythm activity is increased. Sensorimotor rhythm (12–15 Hz) and beta (15–18 Hz) activation can consistently improve concentration and reaction time[17]. The results indicated that BCI-controlled FES increases brain activity in children with cerebral palsy and that the relative difference between pre- and post-intervention measures corresponds with improved wrist movement through visual stimuli, concentration, and muscle contraction from FES. These increases in concentration, improvement of wrist movement from muscle contraction, and joint ROM increase might have resulted in the improvements in upper extremity function. Researchers have also observed activation in the somatosensory and contralateral premotor areas—regions associated with knowledge acquisition and learning—when patients attend to movements on the BCI screen[19]. Brain activity in the frontal lobe while attending to and focusing on movement may therefore be regarded as a process of practice by which movement can be acquired.

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