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Original Article

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The Effects of Action Observation with Functional Electrical Stimulation on Corticomuscular Coherence

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Objective: To investigate the action observation effects of functional electrical stimulation (FES) on the communication between motor cortex and muscle through corticomuscular coherence (CMC) analysis.
Methods: Electroencephalogram (EEG) and electromyogram (EMG) of 27 healthy, nonathlete subjects were measured during action observation, FES, and action observation with FES, which lasted for 7sper session for 10 times. All trials were repeated for 30 times. Simultaneously measured EEG raw data and rectified EMG signals were used to calculate CMC. Only confidence limit values above 0.0306 were used for analysis. CMC was divided into three frequency domains, andthe grand average coherence and peak coherence were computed. Repeated ANOVA was performed to analyze the coherence value difference for each condition's frequency band.
Results: CMC showed significant differences in peak coherence and average coherence between the conditions ($p < 0.05$). Action observation application with FES in all frequency band showed the highest peak and average coherence value.
Conclusions: The results of this study are assumed to be the combination of increased eccentric information transfer from the sensory-motor cortex by action observation and an increased in concentric sensory input from the peripheral by the FES, suggesting that these are reflecting the sensorimotor integration process.

Keywords: Electroencephalography, Observation, Electromyography, Electric stimulation therapy, Coherence

INTRODUCTION

Central nervous system damage can cause disability, such as walking impairment, postural control, and muscle strength decreased sensory-motor performance.[1,2] Therefore motor function recovery, especially the upper extremity function recovery, which is important for independent daily life, is an important goal of the central nervous system rehabilitation.[3] The adult brain can adapt to environmental challenges, such as learning new skills, and to dysfunction caused by lesions on the central nervous system.[4] It is driven by cortex activation, resulting in muscle activation with feedback from sensory receptors activated by movements.[4] Recently, action observation has been studied as an intervention method for cognitive aspect supplementation, which is suggested to promote functional recovery after central nervous system injury.[5,6] Until now, several studies reported that sensory-motor cortex activated during action execution can cause the same pattern of action observation change.[7-11]

Functional electrical stimulation (FES) was introduced as a method, which artificially activates the sensory-motor system after a central nervous system injury,[2] provide selectrical stimulation to the muscle or nerve for functional improvement, and has been reported to increase upper and lower limb functions.[3,12-15] FES restores functional abilities and may also cause cortical excitability or brain plasticity changes.[2,16] However, according to some studies, achieving motor function improvement using electrical stimulation alone in patients who lack active movement is difficult, though could be strengthened when cognitive and physical factors are properly provided.[3]

In recent years, several studies tried to investigate the correlation between brain waves and movements[17-20] through the electrophysiological changes associated with motor control found in the central and peripheral nervous system levels by electroencephalogram (EEG) and electromyo-

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gram (EMG), or in the form of corticomuscular coherence (CMC).[21] CMC is the amplitude change of motor cortex oscillations during movement. Frequency coupling between brain oscillation and muscle rhythm has been observed during muscle activation,[22] CMC measures the degree of synchronisation between the oscillatory activity of the sensorimotor cortex and muscle.[21] Although the physiological basis of CMC is not clear, it is now generally accepted that it reflects the communication between the motor cortex and motor units,[23-25] showing that CMC reflects the connection and relationship between the central and peripheral activity.[26]

Combined physical and cognitive interventions facilitate motor recovery.[3,4,27] Unfortunately, however, several studies separately used action observation and FES to activate damaged motor cortex,[4,16,20,28,29] few studies have analyzed neurophysiological changes by combining action observation and FES. Therefore, in the present study, we tried to investigate the effects of action observation with FES on the communication between motor cortex and muscle through CMC analysis.

METHODS

1. Subjects

A total of twenty-seven healthy, nonathlete subjects participated in the study. The mean age ± standard deviation was 25 ± 3 years. They are all right-handed based on the Edinburgh Handedness Inventory, had normal or corrected normal vision, had no neurological diseases, had not taken medicine for therapeutic purposes. All the experiments were conducted in a private laboratory with quiet rooms. All subjects gave informed written consent, and participated according to the Declaration of Helsinki, conducted after receiving an IRB deliberation from Daegu Catholic University, approval number is CUIRB-2016-0038.

2. Experimental methods

1) EMG

Surface electrodes (Delsys Trigno Wireless EMG system, Delsys Inc., Boston, MA, USA) were used to stimulate and record EMG activity and were attached at the proximal part at 2 cm away from the muscle belly of the wrist extensor and parallel to the running direction of the muscle fiber. The EMG signals were sampled at 2,000 Hz, bandpass filtered at 10–500 Hz, resampled at 200 Hz, stored on a personal computer for offline analysis, and rectified before coherence analysis. There were 1,000 data collected every 5 seconds, with a total of 60–70 segments used for the analysis.

2) EEG

Scalp EEG was recorded using a multichannel recorder (Neurofax EEG-1,200, Nihon Kohden, Tokyo, Japan). Ag/AgCl ring electrodes filled with electroconductive gel were attached according to the international 10–20 electrode system. In this study, it was attached to Nz, A1, A2, Fp1, Fp2, Cz, C4, and C3 and to the peripheral electrodes C1, C5, FC3, and PC3 of C3 (Figure 1). Because analysis was performed only for the right hand in this study, only data from the C3 region were used. The EEG was calculated by taking the difference between the potentials at the C3 electrode and the mean of the four nearest neighbor electrodes (C1, C5, FC3, PC3) by a Laplacian algorithm.[19,28,30] EEG recording was initiated when stable EEG was sustained without the artifacts, initiating all stimuli after 60 seconds. Electrode impedance was kept below 10 kΩ. The lower and upper filters were set at 0.53 Hz and 60 Hz, respectively, with a 200 Hz sampling rate, while notch filter was kept at 60 Hz, avoiding power line interferences. All signals were A/D digitized and transferred using biosignal amplifier (NeuropackMEB-2200, Nihon-Koden, Japan) onto a PC for analysis. All segmented EEG data were inspected visually. Trials with eye blinks or other signal artifacts were excluded. The raw data was extracted every 5 seconds except for the first 1 second and the last 1 second.

3) FES

FES was performed with a Microstim (MedelGmBH, Berlin, Germany). Two electrodes were located on the forearm near the motor points of the extensor muscles of the wrist, with stimulation frequency at 30 Hz using a 300 ms biphasic constant current pulse with individual stimulation.[28] The

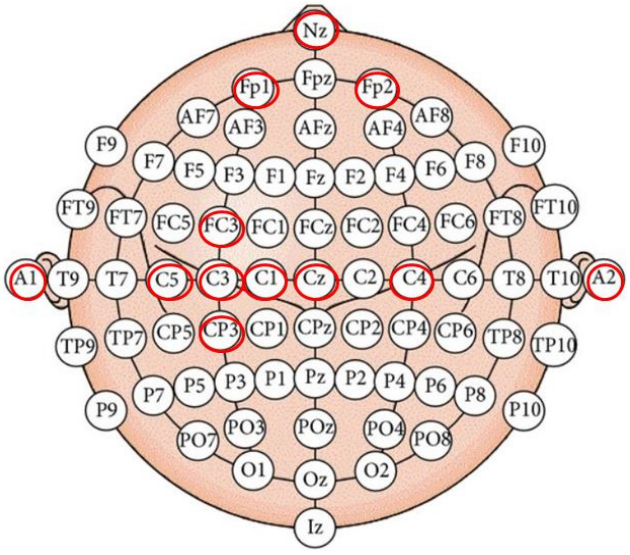

Figure 1. Attachment site of electrode.

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intensity was between 12 mA and 20 mA, which was similar to the wrist extension angle at which the subject performed a comfortable motion by pretest.

4) Action observation

A 27-inch monitor approximately 100 cm in front of the subject featuring a cup being grabbed set at a slower speed than the actual movement provided the visual stimuli. During observation under FES condition, they were instructed to imagine the wrist movement, especially focusing on wrist extension for grabbing the cup and provided only white cross on black background and instructed not to imagine.

5) Experimental paradigm

In a dimly lit room, all subjects were seated in a comfortable chair with one's hand on the desk with elbow joint flexion and forearm pronation. They were leaning on the chair to get the most comfortable position, preventing unnecessary movements other than wrist movements. EEG and EMG were measured during action observation, FES, and action observation with FES for 7 seconds each session for 10 times. All randomized controlled trials were repeated for 30 times.

6) Data analysis

Simultaneously measured EEG raw data and rectified EMG signals were used to calculate cortical-muscular coherence, analyzing every 1,000 data collected using MATLAB software (MathWorks, US). The calculation procedures of coherence between two signals have been described in accordance to Halliday et al.[5,25,31]

$$cohxy(f) = |Rxy(f)|^2 = \frac{|Pxy(f)|^2}{Pxx(f)Pyy(f)}$$

where Pxy is the cross power spectrum for the EEG signal (x) and the rectified EMG signal (y) at a given frequency bin (f) and Pxx and Pyy are the respective power spectrums for the EEG and EMG signals at the same frequency.[31]Coherence greater than the 95% confidence limit (CL) was considered significant and computed as follows.[24] In this study, only values above the calculated CL of 0.0306were used for the statistical analysis.

$$CL(\alpha = 0.95) = \frac{1-(1-\alpha)1}{(L-1)}$$

where α is the 95%significance level and L is the number of windows used for spectral estimation. CMC were divided into three frequency domains (alpha 8–13 Hz, beta 14–30 Hz, and gamma 31–50 Hz), and the grand average coherence and peak coherence were computed. Repeated ANOVA was performed to analyze the difference in coherence values for each frequency band flowed by each condition. All analyses used the statistical analysis program SPSS for Windows 18.0, the bonferroni test was used as a post test, having a statistical significance level p of 0.05.

RESULTS

Alpha, beta, and gamma CMCs showed significant differences in peak coherence and average coherence between the conditions ($p < 0.05$)(Table 1). Post hoc test using the Bonferroni method showed significant difference in action observation conditions only, FES only, and action observa-

Table 1. Comparison of each band average coherence and peak coherence according to conditions (N=27)

	Ave CMC	f	p	Post.hoc	Peak CMC	f	p	Post.hoc
Alpha								
OBS	0.00±0.00	13.116	<0.001	a/b/c	0.01±0.01	16.622	<0.001	a/b/c
FES	0.01±0.01				0.03±0.03			
OBSFES	0.03±0.03				0.05±0.05			
Beta								
OBS	0.01±0.01	27.237	<0.001	a/b/c	0.03±0.03	24.060	<0.001	a/b/c
FES	0.01±0.01				0.06±0.04			
OBSFES	0.03±0.02				0.15±0.12			
Gamma								
OBS	0.01±0.00	66.322	<0.001	a/b/c	0.03±0.04	64.736	<0.001	a/b/c
FES	0.03±0.02				0.15±0.09			
OBSFES	0.06±0.03				0.22±0.08			

mean±standard deviation.
Ave CMC: average corticomuscular coherence, Peak CMC: peak corticomuscular coherence, OBS: only action observation condition, FES: only FES condition, OBSFES: action observation with FES condition.

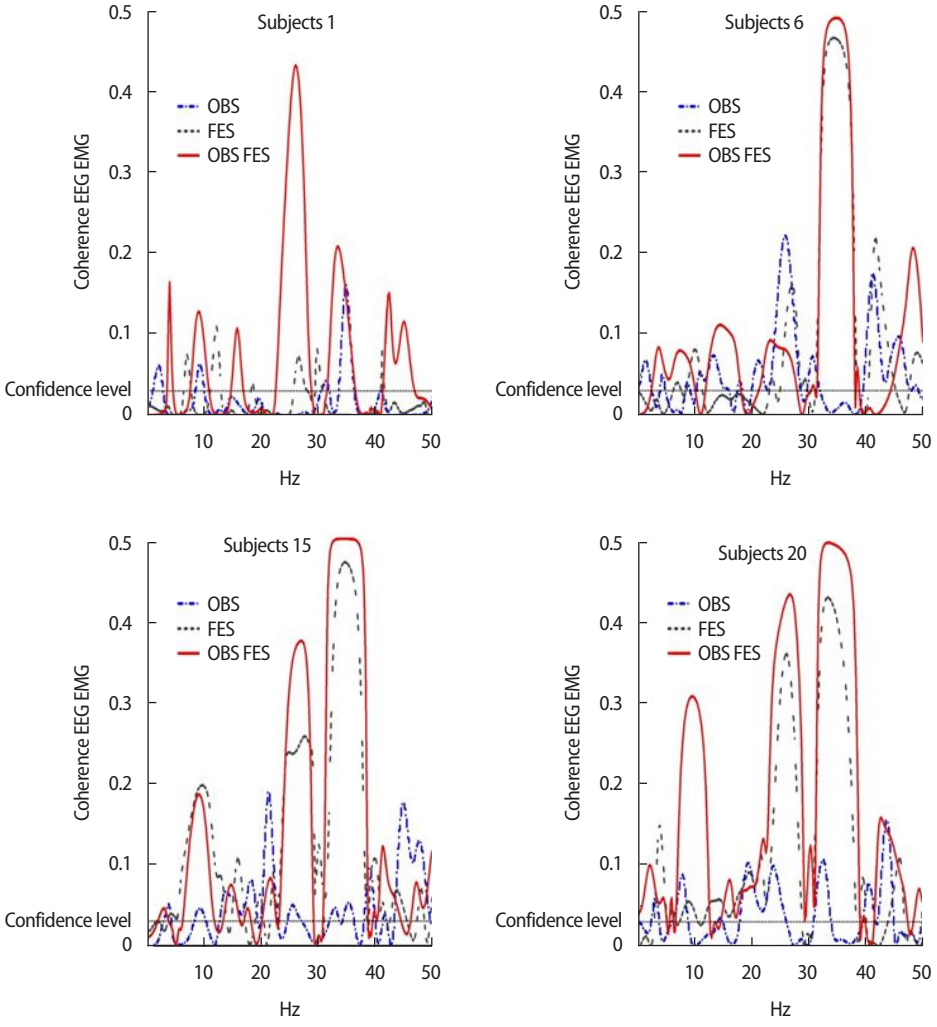

Figure 2. Changes of Corticomuscular coherence each condition.

tion with FES. The highest average and peak coherence values in alpha, beta, and gamma band were showed when action observation with FES is applied (Figure 2).

DISCUSSION

A number of studies tried to improve brain plasticity and induce functional improvements through various conditions. The purpose of this study was to investigate the effects of increased sensory input provided by FES on CMC during action observation. We analyzed the differences between providing action observation or FES alone and providing combination with FES during action observation. Dividing the highest and average CMC into frequency domain, each analysis result shows significant increase in all frequency domains when action observation with functional electric stimulation was applied simultaneously ($p < 0.05$). Especially, the largest coherence was shown in the gamma band. We assumed that this result was a combination of the increased eccentric output from the sensorimotor cortex by action observation and increased concentric input from the peripheral muscle by the FES.

CMC represents an independent efferent phase adjustment process, working in parallel with cardinal motor control processing,[21] related to the attention required to perform.[32] McClelland et al.[32] suggested that the CMC frequency and magnitude may depend on motor cortex output and the afferent peripheral feedback. Junichi Ushiyama et al.[33] suggested that the CMC mechanism may be a complex process involving feedback from the contracting muscle and sensorimotor cortex activity. Increased CMC in our study may be the result of overlapping from perceptual processing and motor control processing. In the study of Schoffelen et al.[34] MagnetoEncephaloGrams (MEG) and EMG of the extensor carpi radialis muscle during wrist extension showed a spatial maximum CMC in the motor

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cortex contralateral to the muscle. Petersen et al.[35] found that significant coupling between EEG and EMG during treadmill walking suggested a direct contribution of the motor cortex and corticospinal tract to muscle activity. Divekar and John[21] tracked the recovery of the CMC. They found a significant decrease during hand and wrist immobilization and a significant increase when returned to pre-immobilization levels following recovery time. Moreover, Fang et al.[26] found that functional corticomuscular connection is weakened during reaching after stroke.

In our knowledge, the study of alpha range CMC is few. Fang et al.[26] and Mehrkanoon et al.[36] suggested that alphaband coherence is considered to indicate communication between the brain and muscle, exposing the feedback and feedforward interactions associated with movement. Mat Safri et al.[37] found that enhanced alpha waves in EEG recordings of subjects maintaining the same isometric contraction suggested to be associated with attentional motor processes. Petersen et al.[35] found that alphaband coherence dominance during normal walking condition may reflect the afferent information inflow to the cortical network.

Beta range CMC is known to play an important role in sensorimotor integration,[32] related to demand toward the motor task and attention,[37] and associated with mechanism of maintaining the current sensorimotor state.[36] Since numerous studies showed beta band oscillatory activity involved in motor control,[21,23,32,34,38] we assumed that beta CMC increase is due to the communication between the sensory-motor cortex and the contralateral muscles. Yang et al.[23] and David et al.[17] reported a significant EEG-EMG coherence at beta frequency band during voluntary motor performance in healthy subjects. Monica et al.[39] showed that a voluntary contraction controlled by one hemisphere can influence beta coherence contralaterally during the hand grip. Mat Safri et al.[37] suggested that increased motor task by the visual stimuli can enhance CMC between the motor cortex and muscle. In Perez et al.[25] study, a significant increase in beta coherence during visuomotor skill training is shown supposing that it reflects sensorimotor integration processes between the cortex and muscle. McClelland et al.[32] showed that electrical or mechanical peripheral stimuli produced the B-band CMC pattern modulation. Moreover, Jacobs et al.[38] suggested that significant beta CMC is evident during human standing balance and responsive to mechanical changes. Divekar and John[21] assumed that beta CMC has higher motor output stability functional roles through improved sensorimotor integration, though it weakened during moderate isometric contractions[21] and eventually disappeared during movement.[36]

Various studies reported that gamma band coherence can be altered by preparatory movements and cognitive factors while maintaining maximum contraction and dynamic voluntary movements, such as reaching for a target.[23,26,37,40] Fang et al.[26] suggested that gamma band muscle activities linearly correlate with focal activity in the contralateral motor cortex, which could be a fundamental feature of the motor system to organize voluntary movements. Gwin and Ferris[24] and Mehrkanoon et al.[36] suggested that gamma band coherence has been linked to the dynamic force output during movement preparation, which was found to be significantly greater for isotonic exercises than for isometric exercises.[24] The highest gamma CMC in this study is assumed to be due to the cognitive factors by action observation and wrist movement induced by FES. Attention is known to increase gamma band activity in the somatosensory cortex.36 Gwin and Ferris[24] suggested that the required integration of visual and somatosensory information may increase gamma coherence. Muthukumaraswamy[22] showed that gamma coherence may occur during the production of dynamic movements, while gamma oscillations are mostly linked to movement production. Moreover, a previous study found that reduced gamma CMC in stroke patients compared to normal adults during reaching task suggested a poor brain-muscle communication or poor integration of the gamma band CMC, reflecting the mechanism of movement defects after stroke.[26]

The results of this study showed that the simultaneous action observation with FES can increase CMC compared to action observation or FES alone, which is assumed to be the result of the combination of increased eccentric information transfer from the sensorimotor cortex by action observation and an increased concentric sensory input from the peripheral by the FES and may reflect the process of sensorimotor integration. The combination of action observation and FES in areas of neural rehabilitation will promote brain plasticity and affect the reorganization with the corresponding segment muscle, which will have a positive effect on the functional improvement of the subject.

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