

# Effects of brain-computer interface-based functional electrical stimulation on balance and gait function in patients with stroke: preliminary results

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**Abstract.** [Purpose] The purpose of this study was to determine the effects of brain-computer interface (BCI)-based functional electrical stimulation (FES) on balance and gait function in patients with stroke. [Subjects] Subjects were randomly allocated to a BCI-FES group (n=5) and a FES group (n=5). [Methods] The BCI-FES group received ankle dorsiflexion training with FES according to a BCI-based program for 30 minutes per day for 5 days. The FES group received ankle dorsiflexion training with FES for the same duration. [Results] Following the intervention, the BCI-FES group showed significant differences in Timed Up and Go test value, cadence, and step length on the affected side. The FES group showed no significant differences after the intervention. However, there were no significant differences between the 2 groups after the intervention. [Conclusion] The results of this study suggest that BCI-based FES training is a more effective exercise for balance and gait function than FES training alone in patients with stroke.

**Key words:** Brain-computer interface, Functional electrical stimulation, Gait

*(This article was submitted Jul. 22, 2014, and was accepted Sep. 10, 2014)*

## INTRODUCTION

Stroke is a cerebrovascular disease in which the blood supply to the brain is blocked, or in which hemorrhages develop in the brain. Common features of the disorder are hemiplegia, motor impairment, sensory impairment, cognitive impairment, speech disorders, visual-perception disabilities, and dysphasia<sup>1)</sup>. Because less than 43% of body weight is supported by the affected lower extremity while standing and because of asymmetrical muscle strength, patients with stroke develop balance control problems due to an asymmetric posture. Thus, stroke patients develop an abnormal gait due to the weakened ability to bear weight on the affected side while walking and because of impaired balance control<sup>2)</sup>.

Foot drop is a common feature of the gait of stroke patients and implies a partial or complete loss of motor function, resulting in dorsiflexion. Patients with foot drop excessively lift their hip joints or adopt a circumduction

gait during the swing phase in order to prevent dragging the foot on the ground while walking<sup>3)</sup>. These gaits are not only dangerous but also require maximum energy consumption and cause patients to walk slower and suffer more falls<sup>4)</sup>.

Functional electrical stimulation (FES) uses electrical stimulation to induce muscle contraction, in order to induce functional actions of non-innervated muscles in patients with stroke, multiple sclerosis, or spinal damage. FES is applied on the tibialis anterior muscle to enhance coordination capability during a gait cycle, and to increase the angle range of the ankle joint and walking speed, thus improving the quality of gait in patients with foot drop<sup>5)</sup>.

The brain-computer interface (BCI) is one of the fields of human-computer interaction that concerns investigation of the interaction between a human and a computer. The BCI measures brainwave signals in a specific state to gain singularities or characteristics, and then classifies them. The classified components are then converted to common control signals to control computers and equipment. In other words, this technology analyzes brain waves, in real-time, as the brain attempts to control equipment<sup>6)</sup>.

Recently, BCI technology has been applied to rehabilitation training using FES, robots, and other assistance tools in BCI feedback training<sup>7)</sup>. In the present study, we aimed to assess the effects of BCI-based FES on balance ability and gait function, when applied to patients with stroke.

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## SUBJECTS AND METHODS

Ten subjects from S hospital in Seoul, Korea, all of whom had been diagnosed with chronic hemiparetic stroke, were enrolled in this study. The subjects were provided with a full explanation of the experimental procedure, and all subjects provided written consent signifying voluntary participation. This study was approved by the Sahmyook University Human Studies Committee (SYUIRB2012-010). The detailed inclusion criteria were as follows: (1) more than 6 months after clinical diagnosis of ischemic or hemorrhagic hemiparetic stroke, (2) more than 24 points on the Mini-Mental State Examination<sup>8)</sup>, and (3) able to walk independently for more than 10 m<sup>9)</sup>. The exclusion criteria were as follows: (1) severe hemineglect, (2) history or current diagnoses of other neurologic diseases or musculoskeletal conditions, and (3) allergic reaction to FES. The general characteristics of the subjects in the BCI-FES group were as follows: 4 men, mean age of 43.6 years, mean height of 173.1 cm, mean weight of 70.3 kg, stroke onset of 16.4 months, right-side hemiplegia in 2 patients, infarction-type stroke in 2 patients, and hemorrhagic-type stroke in 3 patients. The characteristics of the subjects in the FES group were as follows: 4 men, mean age of 50.2 years, mean height of 166.2 cm, mean weight of 65.6 kg, stroke onset of 8.4 months, right-side hemiplegia in 2 patients, infarction-type stroke in 1 patient, and hemorrhagic-type stroke in 4 patients. There were no significant differences between the groups.

The subjects in both the BCI-FES and FES groups participated in the program according to a designated schedule, and 1 research assistant for training and 2 research assistants for measuring were recruited for this study. They were educated and trained in the use of equipment, measurement methods, and training programs prior to the experiment, in order to minimize possible errors during the experiment. The BCI-FES group received ankle dorsiflexion training with FES as per the BCI-based program for 30 minutes per day, for 5 days. The FES group received ankle dorsiflexion training with FES for the same duration.

In the BCI-FES group, FES was applied to train the participants when they were concentrating on a dorsiflexing ankle on the monitor screen, and the (sensorimotor rhythm (SMR) + mid-Beta)/theta pattern was generated through brain waves. This equipment consists of a monitor screen for the subjects, a brain wave measurement tool PolyG-I (Laxtha, Inc., Daejeon, Republic of Korea), a laptop to record and process brain wave signals, a USB output board to link the brain wave signals to the FES when concentration occurred, FES and electroencephalogram (EEG) sensors to receive brain wave information when the concentration was high, and cables.

Since subjects are easily influenced by external environmental factors, such as temperature, location, intensity of illumination, noise, and smell, participants were provided with separate spaces without external factors. To measure brain waves, electrodes were attached to the frontopolar 1 (Fp1) and frontopolar 2 (Fp2) regions. A reference electrode was attached behind the right earlobe, and a ground electrode was attached behind the left earlobe. For FES training, an inactive electrode was attached to the proximal tibialis anterior

(5 cm from the lower portion of the fibular head), which is an antagonist of the plantarflexor muscles, while an active electrode was attached to the distal tibialis anterior (lateral and 5 cm from the upper portion of the fibula). The subjects sat comfortably on a chair with armrests and concentrated on moving their ankles by looking at a monitor screen displaying a dorsiflexing ankle. According to the neurophysiologic brain wave index, the degree of concentration was analyzed using the brain wave concentration index. For measuring brain waves, the concentration index was quantified as in the formula above. In a state of concentration, the theta rhythm decreases. On the other hand, the SMR (12–15 Hz) and mid-Beta rhythm (16–20 Hz) increase. The SMR denotes the unfocused attention ability to be cautious about one's surroundings, while mid-Beta rhythm denotes the focused attention ability to be cautious about one's surroundings. Therefore, the concentration index was quantified as a ratio between the SMR and mid-Beta rhythm over the theta rhythm as in the formula above.

Before beginning the experiment, the investigator passively modulated the stimulated current intensity frequency 35 Hz, and pulsed with 250  $\mu$ s from 1 mA to 50 mA according to the response from the subject's ankle joint. To gauge the focused threshold of the subjects, 10 rounds of focused inspections were implemented before the training to obtain and input the average concentration index threshold into the computer. Subsequently, the subjects were instructed to focus on the movement of the ankle on the monitor screen. When the concentration index value exceeded the threshold, this information was transferred to the USB output board, and the FES equipment was turned on. However, when the concentration index value did not exceed the threshold, this information was transferred to the USB output board, and the FES equipment was turned off, which resulted in FES as per the degree of concentration of the subject. When the concentration index value exceeded the threshold to turn on the FES equipment, FES based on concentration was set to last 5 seconds in order to avoid causing muscle fatigue.

Microstim (Medel GmbH, Inc., Germany) is a BCI-FES-based system that can be used for FES training. This equipment has an adjustable frequency, contraction time, relaxation time, and pulse width, and consists of a 1-foot switch, a pair of surface electrodes (50  $\times$  50 mm), and a stimulator. An inactive electrode was attached to the proximal tibialis anterior (5 cm from the lower portion of the fibular head), which is an antagonist of the plantar flexor muscles, while an active electrode was attached to the distal tibialis anterior (lateral and 5 cm from the upper portion of the fibula). The waveform was rectangular biphasic, and the therapeutic exercise was adjusted in order to avoid exceeding 50 mA so that patients would endure as much dorsiflexion as possible. The ramp-up for maximum intensity was set to occur in 2 seconds, and the on-time for the stimulation duration was set to last 7 seconds. In order to avoid muscle fatigue due to electrical stimulation, the off-time was set to last 7 seconds, the pulse frequency was 35 Hz, and the pulse width was 250  $\mu$ s.

Balance ability was measured using the Timed Up and Go (TUG) test and the Berg Balance Scale (BBS). For the TUG test, subjects were seated in a chair with armrests and

**Table 1.** Comparison of balance and gait function within groups and between groups (N=10)

Parameters	Values				Change values	
	BCI-FES group (n=5)		FES group (n=5)		BCI-FES group (n=5)	FES group (n=5)
	Before	After	Before	After	Before-after	Before-after
<b>Balance functions</b>						
TUG (sec)	28.7 (12.6)	22.7 (11.4)*	27.0 (17.0)	23.6 (13.4)	-6.0 (3.3)	-3.5 (4.5)
BBS (score)	42.2 (4.9)	45.4 (3.3)	42.6 (4.9)	44.2 (5.9)	3.2 (2.4)	1.6 (1.8)
<b>Gait functions</b>						
Cadence (steps/min)	83.7 (23.6)	94.8 (18.2)*	77.2 (15.9)	89.5 (11.3)	11.0 (7.5)	12.3 (12.2)
Affected side step length (cm)	38.0 (11.2)	46.6 (12.8)*	33.4 (12.1)	41.8 (8.9)	8.6 (4.4)	8.3 (10.3)
Affected side stride length (cm)	82.1 (13.4)	88.0 (17.5)	64.4 (19.5)	71.2 (19.1)	6.0 (5.1)	6.8 (7.0)

Data are presented as means (SD). BBS: berg balance scale; BCI: brain-computer interface; FES: functional electrical stimulation; TUG: Timed Up and Go. \*p<0.05.

then instructed to stand (using the armrests, if desired) and walk as quickly and safely as possible for a distance of 3 m. The subjects then turned around, returned to the chair, and sat down. The time from the point at which their spine left the back of the chair until they returned to that same position was recorded using a stopwatch<sup>10</sup>. The BBS is a valid and reliable instrument for measuring both static and dynamic aspects of balance in elderly people with stroke. BBS scores range from 0 to 56 points, with higher scores indicating better balance<sup>11</sup>.

Gait function was measured using a GAITRite system (CIR Systems Inc., Havertown, PA, USA). The GAITRite system was used to measure spatiotemporal parameters, including gait velocity, cadence, step length, and stride length. The subjects were asked to walk at a comfortable speed, without the use of an assistive device, along a 10-m hallway<sup>12</sup>.

SPSS version 12.0 was used for all statistical analyses. Nonparametric statistical methods were used because the number of research subjects was 5. Wilcoxon's test was used to compare the pre- and posttest results within each group, while the Mann-Whitney U test was performed to compare the 2 groups before and after training. A p value of <0.05 was considered significant.

## RESULTS

Differences in balance ability and gait function after the intervention are shown in Table 1. The BCI-FES group showed significant differences in the TUG test, cadence, and step length on the affected side. The FES group showed no significant differences after the intervention. However, there were no significant differences between the 2 groups after the intervention.

## DISCUSSION

To enhance balance ability via postural control, the alignment of the pelvis, femoral region, and foot is essential. Since the lower extremity on the paralyzed side in stroke patients shows an abnormal state of alignment, normal alignment of this lower extremity is necessary. To achieve physi-

cal stability, alignment of the ankle joint is also important<sup>13</sup>. Bajd et al.<sup>14</sup> reported that correct postural alignment can be a precondition for alignment of not only the knee joint, but also the ankle joint. This is reported to be effective when combined with FES. In the present study, the BCI-FES group showed a significant difference in the TUG test value after the intervention (from 28.7 to 22.7 sec). However, there were no significant differences in TUG test value between the 2 groups after the intervention. We believe the experiment duration was too short to assess the full effect of FES on balance ability. As the FES component of BCI-FES is activated when the patient concentrates, the amount of FES activation varies depending on the patient given that the concentration index does not reach the threshold in patients who are not concentrating.

The cadence of a healthy person is approximately 101–122 steps/min when waking at an optimal speed<sup>15</sup>; Perry<sup>16</sup> reported that the cadence of normal people is 116 steps/min. Lau et al.<sup>17</sup> reported that speed-dependent treadmill training in patients with subacute stroke resulted in an increase in cadence (from 36.9 to 58.5 steps/min). However, there was no significant difference in cadence between the 2 groups. In the present study, the BCI-FES group showed a significant difference in cadence after the intervention (from 83.7 to 94.8 sec). Therefore, FES training may prevent foot drop in the swing phase by contributing to enhancement of ankle dorsiflexion and motor control ability and stimulation of proprioception in the ankle joint<sup>18</sup>. FES training also confers stability to the lower extremities upon initial contact, which influences the change in cadence. We speculate that cadence increased due to security of stability induced by a reduction in postural disturbance and enhancement of balance ability. In addition, FES training greatly influences partial recovery of the peripheral mechanism and plasticity of the cerebral cortex, which helps patients with stroke to control their posture due to neuroplasticity<sup>19</sup>.

Hebb et al.<sup>20</sup> reported that the enhancement of plasticity represents functional recovery via the improvements in afferent, and efferent neural activities. The effect of afferent neural activity in this recovery increased when rehabilitation treatment was combined with motor imagination with computer feedback<sup>21</sup>. The reason for the significant difference in

the BCI-FES group was as follows: since FES using the BCI system was activated when patients concentrated and tried to move on their own, there was a positive impact on gait ability due to improvements in afferent and efferent neural activities and voluntary movement.

There are 2 limitations to this study. First, due to the small sample size, it is difficult to make any generalizations. Second, this study was a pilot study, and the experiment duration was short (only 5 days). Further studies are required to investigate the long-term intervention effects of BCI-FES training. Our findings suggest that BCI-FES training increases balance and gait function in patients with stroke. We hope that future studies will further investigate BCI-FES training and its role in improving balance and gait.

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