

Original Article

Effects of virtual reality-based bilateral upper-extremity training on brain activity in post-stroke patients

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Abstract. [Purpose] This study investigated the therapeutic effects of virtual reality-based bilateral upper-extremity training on brain activity in patients with stroke. [Subjects and Methods] Eighteen chronic stroke patients were divided into two groups: the virtual reality-based bilateral upper-extremity training group ($n = 10$) and the bilateral upper-limb training group ($n = 8$). The virtual reality-based bilateral upper-extremity training group performed bilateral upper-extremity exercises in a virtual reality environment, while the bilateral upper-limb training group performed only bilateral upper-extremity exercise. All training was conducted 30 minutes per day, three times per week for six weeks, followed by brain activity evaluation. [Results] Electroencephalography showed significant increases in concentration in the frontopolar 2 and frontal 4 areas, and significant increases in brain activity in the frontopolar 1 and frontal 3 areas in the virtual reality-based bilateral upper-extremity training group. [Conclusion] Virtual reality-based bilateral upper-extremity training can improve the brain activity of stroke patients. Thus, virtual reality-based bilateral upper-extremity training is feasible and beneficial for improving brain activation in stroke patients.

Key words: Stroke, Virtual reality, Bilateral arm training

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INTRODUCTION

Virtual reality (VR) therapy has recently been demonstrated to improve upper-extremity motor function in stroke patients¹⁾. VR therapy has been used as an interactive intervention for motor retraining in children²⁾ as well as adults^{1,3)} because of the intensity of practice and sensory feedback.

Electroencephalography was the first brain imaging assessment tool used to demonstrate alterations of brain functions in patients with traumatic brain injury⁴⁾. The electrodes are used only to measure the brain's electrical activity. Brain wave activity is relayed from the scalp to a computer, where it is recorded and stored. All of this is performed while the patient is resting quietly with his or her eyes closed or sometimes while performing a cognitive task such as reading. Disturbed cortical functions, as evidenced by the abnormal wave size, are indicative of brain activity malfunction. These issues usually manifest as abnormal behaviors such as difficulty paying attention, distractibility, learning disabilities, and loss of memory, while many others cause attention

deficit disorders. The frontal lobes in particular are involved in motor function, problem solving, spontaneity, memory, language, initiation, judgment, impulse control, and social and sexual behaviors. Because of their location at the front of the cranium, proximity to the sphenoid wing, and large size, the frontal lobes are extremely vulnerable to injury. MRI studies show the frontal area is the most commonly damaged region following mild to moderate traumatic brain injury⁵⁾.

There are important differences in the symmetry of the frontal lobes: the left frontal lobe is involved in controlling language-related movement, whereas the right frontal lobe plays a role in nonverbal abilities. Some researchers emphasize that this rule is not absolute and that both lobes are involved in nearly all behaviors in many people. Motor function disturbances are typically characterized by a loss of fine movements and strength of the arms, hands, and fingers. Complex chains of motor movement also appear to be controlled by the frontal lobes⁶⁾.

The present study investigated virtual reality-based bilateral upper-extremity training (VRBT) for the rehabilitation of chronic stroke patients. We hypothesized that the training provides more appropriate sensory feedback than bilateral upper-limb training, which subsequently leads to improved brain activity and upper-extremity function in stroke patients.

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SUBJECTS AND METHODS

A total of 20 stroke patients were recruited from a general hospital. Stroke survivors were included if they met the following criteria: (1) hemi-paralytic, (2) able to follow verbal instructions, (3) at least 6 months post-stroke diagnosed by a physician, (4) able to communicate (i.e., Mini Mental State Examination language section score from 24–30), and (5) a Modified Ashworth Scale (MAS) score less than 2 for the upper extremities. Patients were excluded if they had diplegia or a visual field defect. This study was approved by the Sahmyook University Institutional Review Board. The purpose and requirements of the study were explained to all patients before the experiment began, and all patients signed a written informed consent form prior to participation.

Upper-extremity function, muscle strength, and brain waves were evaluated before the intervention. Twenty patients were randomly divided into the virtual reality-based bilateral upper-extremity training (VRBT, $n = 10$) group or the bilateral upper-limb training (BT, $n = 10$) group as controls; the latter performed the BT while watching an irrelevant video. The patients in both groups trained 30 minutes per session, three times per week for six weeks. In addition, the patients were offered conventional physical therapy for 30 minutes per session, five times per week for six weeks. Two physical therapists were randomly allocated to each group for training. The VRBT group had no dropouts, but two patients were excluded from the BT group because of poor participation (<80%)⁷. The VRBT group contained 5 men and women each; their mean \pm SD age, height, and weight were 69.2 ± 5.5 years, 163.5 ± 8.6 cm, and 59.4 ± 8.3 kg, respectively. Seven and three had right and left hemiplegia, respectively. The mean duration after stroke onset was 16.2 ± 6.5 months, and their mean MMSE score was 24.5 ± 0.7 . Meanwhile, the BT group consisted of 3 men and 5 women, with a mean age, height, and weight of 73.1 ± 8.9 years, 160.9 ± 9.5 cm, and 54.9 ± 10.7 kg, respectively; 3 and 5 had right and left hemiplegia, respectively. The mean duration after stroke was 17.0 ± 6.5 , and their mean MMSE score was 24.1 ± 0.4 . There were no significant differences between the groups.

A physical therapist who also was an expert in electroencephalography was recruited to measure brain wave activity at baseline and after the intervention. The electroencephalogram (EEG) is produced by synchronous postsynaptic potentials from cortical neurons recorded at the scalp. The raw EEG signal is amplified, digitized, plotted, and filtered to isolate narrow frequency bands (in Hz) that reflect specific brain sources and functions⁸. EEG neuro-feedback refers to the conversion of information regarding brain wave activity (i.e., the quantitative measurement of brain wave frequencies) into graph- or game-like displays as the patient learns to control and improve brain wave patterns.

The VRBT involved a visual expression technique using animations and provided cognitive information for feedback⁷. The animation consisted of symmetric and asymmetric upper-extremity training as well as symmetric and asymmetric upper-extremity training at 45° in a virtual reality environment. The patients performed each movement for 4 minutes and then rested for 1 minute to minimize fa-

igue. Depending on the severity of the deficits, the patient either grasped the handles or the affected hand was strapped to the handle⁹. An upper-extremity instrument (50 cm wide and 60 cm long) was used to control the inclination and width. A laptop (SVS13116FKP, Sony Vaio, Korea), webcam (QuickCam Orbit, QVR-1, Logitech, Korea), and monitor (M2352D-PN, LG, Korea) were used to create the virtual reality environment. The webcam had a resolution of $1,600 \times 1,200$ at a medium frame rate (30 frames/s) and recorded a patient's upper-extremity movement. One webcam was placed in front of the patient, and another was placed on the ceiling above. A monitor displayed the virtual reality program and simultaneously recorded the patient's bilateral upper-extremity movements. The monitor had a resolution of $1,920 \times 1,080$ and a diagonal measurement of 23 inches. Patients received real-time feedback through the monitor while training. The monitor simultaneously displayed an animation with the virtual reality training, and the patient's upper-extremity movement. The patients in the VRBT and BT groups were offered the same four upper-extremity training programs as well.

A QEEG-8 (Laxtha Inc., Daejeon, Korea) was used to measure brain wave activity¹⁰. An expert on brain wave measurement instructed an evaluator how to apply the analysis program and use the equipment, who was then trained to repeat the measurement process. Brain waves were measured in a separate space where patients were undisturbed. Measurements were performed after the baseline and post-intervention examinations. The patients' eyes were closed in order to block noise due to eye movement. The patients kept their eyes closed and remained in a comfortable position for brain wave measurement for 80 seconds. In order to decrease the incidence of artifacts, the patients were instructed not to speak or move during the process. Four electrodes were attached to the surface of the skull, and brain waves were measured using a monopolar derivation method. The EEGs were based on the International 10–20 electrode system, and measurement positions were on FP1, FP2, F3, and F4. In general, plate electrodes (7–10 mm) that consist of a silver electrode whose surface is covered with a thin film of argentic chloride are used for EEG measurement¹⁰. A Telescan 2.98 (Laxtha Inc., Daejeon, Korea) was used to analyze brain wave data. The measured brain wave patterns were evaluated to determine whether they were artifacts, and all raw data except for the first and last 10 seconds were analyzed. Sampling rates from 4–50 Hz were used. The relative power of each band (i.e., the percentage of the total power in each channel) is a measure of the percentage of the total power in a specific frequency band. Whereas the absolute power can sum to essentially any magnitude across the frequency spectrum, the relative power must add up to 100%, with the relative power in any given band representing some fraction of the total power. Evaluation of the relative power may improve the detection of subtle shifts in brain function over time according to the normalization of fluctuations in the total power observed among individuals or within one individual across several recordings.

All statistical analyses were performed using SPSS version 17.0. The Shapiro-Wilk test showed the data had a normal distribution. A paired t-test was performed to compare

changes before and after the intervention. An independent sample t-test was used to compare differences in the means between the two study groups. The level of significance was set at $p < 0.05$.

RESULTS

On the EEG in the VRBT group, the concentration of Fp2 increased significantly from 20.2 at baseline to 30.0 post-intervention ($p < 0.05$). In addition, in the VRBT group, the F4 concentration significantly increased from 13.5 at baseline to 19.5 post-intervention ($p < 0.05$). Regarding EEG brain activity, Fp1 increased significantly from 2.11 Hz at baseline to 3.13 Hz post-intervention in the VRBT group ($p < 0.05$); likewise, F3 increased significantly from 4.41 Hz at baseline to 8.30 Hz post-intervention ($p < 0.05$) (Table 1).

DISCUSSION

Cramer et al.¹¹⁾ applied finger movement training to hemiplegic stroke patients and investigated the active regions of the brain by using functional magnetic resonance imaging (fMRI). They found patients exhibited significantly more activity in the exercise neural networks near the damaged cortex area, complemented exercise area, and sensorimotor cortex than normal controls. In addition, they report reorganization and activation of the ipsilateral motor pathway and complemented movement area around the patients' damaged region.

Toyokura et al.¹²⁾ applied both simple and complex tasks to stroke patients and measured their sensorimotor cortex activation by using fMRI. Accordingly, the sensorimotor cortex area exhibited significantly greater activation during the complex task than the simple task. The simple task consisted of grasping and making a fist with one or both hands, while the complex task involved alternately opening and closing both hands simultaneously.

A beta wave from 12–35 Hz is a brain wave that affects concentration; it is increased by executing cognitive information processes or physical activities that require concentration. During such tasks, alpha waves decrease while beta waves increase¹³⁾. Strong beta waves (e.g., 20–35 Hz) indicate concentration, while lower-frequency theta waves indicate decreased concentration. In the present study, EEGs were based on the International 10–20 electrode system, but the measurement positions were only FP1, FP2, F3, and F4. Even though concentration (i.e., Fp2 and F4) and brain activity (i.e., Fp1 and F3) improved significantly after treatment in the VRBT group, the frontal lobes showed asymmetric activity. However, as only four electrodes were used, further studies should examine brain activity by EEG using more electrodes. Despite this limitation, the present results indicate virtual reality training with bilateral motor learning is promising for the neuro-rehabilitation of post-stroke motor deficits.

The virtual reality environment with repeated bilateral movement learning increased the efficiency of training by inciting the patient's interest, providing real-time feedback to modify the patient's movement, and improving behavioral understanding. On the other hand, the VRBT group exhibited

Table 1. Comparison of EEG variables between groups ($N = 18$)

Parameters	VRBT (n = 10)		BT (n = 8)	
	Pre	Post	Pre	Post
Concentration				
Fp1	24.3 (21.9)	29.3 (19.2)	23.9 (30.5)	33.0 (24.2)
Fp2	20.2 (18.1)	30.0 (23.1)**	23.2 (29.7)	37.1 (28.6)
F3	18.8 (–7.5)	22.3 (–8.7)	26.4 (30.9)	35.7 (26.1)
F4	13.5 (–5.2)	19.5 (–5.4)**	21.8 (27.9)	33.0 (21.1)
Brain activity				
Fp1	2.11 (1.33)	3.13 (2.23)*	1.76 (0.30)	2.23 (1.14)
Fp2	1.99 (1.28)	3.92 (4.05)	1.95 (0.85)	3.50 (2.08)
F3	4.41 (2.76)	8.30 (5.58)*	4.79 (5.02)	4.34 (3.55)
F4	4.01 (2.83)	5.08 (3.71)	4.41 (4.49)	4.05 (2.50)

Data are mean (SD). VRBT: virtual reality-based bilateral upper-limb training; BT: bilateral upper-limb training group; Fp1: frontopolar 1; Fp2: frontopolar 2; F3: frontal 3; F4: frontal 4; * $p < 0.05$, ** $p < 0.01$

improved concentration and brain activity compared with the BT group. This difference might be due to an external stimulus such as virtual reality that involves a direct multi-sensory system, thus inducing concentration and enhancing brain activity.

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