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Development of digital mirror therapy for stroke-severe patients

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Abstract— **Mirror therapy (MT), which is used in the existing stroke rehabilitation environment, has significant limitations for use with severe stroke patients. Since mirrors only reflect symmetrical movement, allowing a patient to observe precise asymmetrical movement is impossible. This study proposes a new MT system by developing a pyramid hologram technology that uses delayed motion to create realistic images. Significant differences, observed via electroencephalogram, were shown in all motor cortex channels immediately after the event in the delayed condition when compared to before the event (C3: $p < 0.001$; Cz: $p < 0.001$, C4: $p < 0.001$). The illusion of asymmetrical movement using the proposed system can be applied to severe stroke patients to increase the positive outcome of rehabilitation.**

I. Introduction

Approximately 85% of strokes cause hemiplegia, and sequelae occur in motor and sensory impairment [1]. In particular, it leads to upper limb damage resulting in abnormal muscle tension, which severely restricts activities of daily living (ADLs) [2, 3]. In functional recovery intervention for stroke, task training is mainly performed and it can be approached with simple ADLs method [4].

This method requires intervention that can be performed anywhere, not solely in a controlled environment, and mirror therapy (MT) is a representative example [5, 6]. MT is a method of inducing brain activation through the visual illusion that the paralyzed side is moving by placing a mirror on the patient's median plane and observing the mirrored movements of the unaffected side [7].

Rehabilitation necessary to improve cognitive function is conducted through a task-specific MT technique approach. However, MT can cause pain due to prolonged uncomfortable posture [8, 9]. To avoid this complication, virtual reality has been tested as an alternative method; however patients have reported experiencing dizziness, which then results in a return to the standard MT technique. A further limitation of MT is the inability to conduct delayed asymmetrical movement training, since mirrors can only display symmetric movements that move simultaneously [10].

In addition, serious stroke patients have severe contractures and have difficulty in moving the affected limb, which is the reality of rehabilitation treatment in which the basic principles of MT are limited. To overcome these limitations, an apparatus capable of active participation in treatment and the realization of realistic images through asymmetrical movement that can be utilized by patients with severe upper extremity paralysis is needed.

This study aims to overcome limitations to MT by developing a novel pyramid-hologram-based MT system. To evaluate the efficacy of this system, we propose a new MT protocol for rehabilitation treatment by acquiring mu rhythm signals in the motor area using electroencephalography (EEG) and analyzing the mechanism of immediate brain activation during asymmetrical training.

II. Methods

A. Participants

This study was approved by the Human Subjects Ethics Committee of Soonchunhyang University, in accordance with the ethical principles of the Declaration of Helsinki (Approval number:1040875-202202-SB-031). Fourteen healthy adults in their 20s were recruited, and the study was conducted after obtaining written informed consent. Participants with no prior EEG experience were recruited. They were then randomly classified into pyramid mirror therapy (PMT; n = 7) and pyramid delayed mirror therapy (PDMT; n = 7).

B. Sensorimotor cortex

All protocols were conducted by a researcher with a physical therapy license. In order to recreate the environment of MT, the upper limb was made in the shape of a pyramid, which can be expressed in 3D object imaging. This study was produced according to the appropriate size for a 24-inch monitor using the reflector required for the pyramid design. Among the EEG waveforms, alpha waves (8-12 hz) are generated by excitation and inhibition of the cerebral cortex. Alpha waves are activated at rest and decrease during action observation (AO) [11, 12]. This is also called mu rhythm inhibition, which greatly affects the sensorimotor cortex [13]. These are the necessary tools for MT training (Fig. 1). The EEG (Quick-20 system, Cognionics, USA) attachment sites were attached to C3, Cz, and C4 in the sensorimotor cortex [14, 15]. In addition, it was attached according to the International 10-20 system, and the reference was set to the left ear lobe (A1).

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C. Task protocol of activities of daily livings

In this study, a cup was used for simple ADLs. This study was built with a webcam using the Unity-based WebCamTexture function to display the affected hand on the monitor. OpenCV Python-based chroma key technology was used to remove noise in the background area to isolate the image of the hand. Asymmetrical movement was then implemented using the WaitForSecond function.

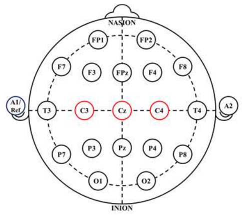

Figure 1. Electroencephalography (EEG) measurement of sensorimotor cortex.

D. EEG processing for mu rhythm signal

The EEG sampling rate was set to 1,000 hz and the electrode impedance was set to 5 kΩ. MATLAB (MathWorks, Inc., USA) was used for alpha processing of the acquired EEG. Following this, the re-reference was set to the Cz channel, and time averaging was performed with a 250 ms window to reduce baseline smoothing and variability in order to analyze 1,000 data points per epoch. Event-related desynchronization (ERD) was extracted to correct the electrical resistance due to the scalp condition of each individual of the treated mu rhythm signal.

$$\mathrm{ERD} = (\mathrm{A} - \mathrm{R}) / \mathrm{R} * 100 \quad (1)$$

A is the mu-rhythm signal and R is the reference level. The reference level indicates the PMT. In addition, Mu-rhythm extracts the lateralization index (LI), which enables immediate analysis of a specific area as a parameter of cortical reactivity through events.

$$\mathrm{LI} = \frac{(\mathrm{ERD_{left}} - \mathrm{ERD_{right}})}{|\mathrm{ERD_{left}}| + |\mathrm{ERD_{right}}|} \quad (2)$$

It is the average ERD of the primary motor cortex, and C3 is the left region and C4 is the right region.

E. Statistical analysis

All statistical analyzes were performed using SPSS 25.0 version (IBM, USA). An independent *t*-test was used to analyze the mean ERD. In addition, the ERD activity of the section was analyzed using one-way repeated measures analysis of variance ANOVA test. The post-hoc test was performed with Bonferroni correction. All statistically significant probabilities were analyzed at $p < 0.05$.

III. Results

A. Demographics of the participants

TABLE 1 compares the participants at baseline, and no significant differences were found ($p > 0.05$).

TABLE I. BASELINE OF PARTICIPANTS.

Baseline	**PMT (n = 7)**	**PDMT (n = 7)**
Age (years)	24.86 ± 0.90	26.14 ± 2.12
Height (cm)	169.43 ± 9.36	169.29 ± 9.25
Weight (kg)	67.31 ± 12.79	68.86 ± 14.96

PMT: Pyramid mirror therapy, PDMT: Pyramid delayed mirror therapy.

B. Mu rhythm with digital mirror therapy

This is a representative example of an MT system using a pyramid (Fig. 2). (a) PMT and (b) PDMT. After positioning the right hand in the appropriate position, the inverted image of the hand was illuminated on the pyramid. The proposed system can implement MT using only a simple projector light, providing visual feedback (VF) based on the basic theory that stimulates visual illusions.

In both conditions, it was found that the mu rhythm decreased in all channels from 0 to 2 s when the event occurred. In particular, the black arrow indicates that AO of asymmetrical movement further reduces the mu rhythm, and delayed training was proven possible with our system. This leads to a reduction in mu-power from motor imagery training related to the cognitive process of the upcoming AO. In other words, viewing still pictures of hand actions results in a greatly increased neural activation through the process of imagination training, which supports the results of this study [16].

C. Spectral edge frequency (SEF) evaluation

The spectral edge frequency (SEF) is a quantitative value for the entire high-frequency domain in the power spectrum distribution of the EEG (Fig. 3) [17]. In all channels, PDMT had a significantly higher SEF activity rate than PMT (C3, p = 0.021; Cz, p = 0.041; C4, p = 0.032).

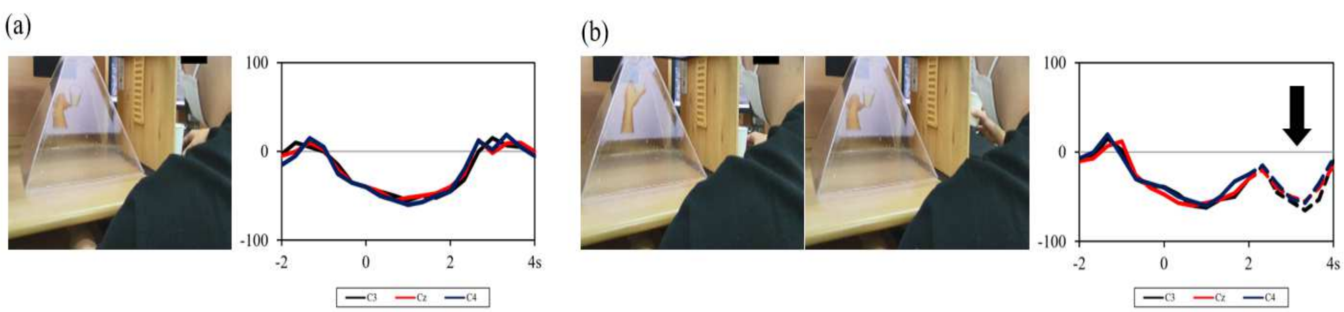

Figure 2. Proposed mirror therapy. (a) PMT, (b) PDMT.

Thus, the PDMT method can be used as a stroke rehabilitation treatment capable of neural activation.

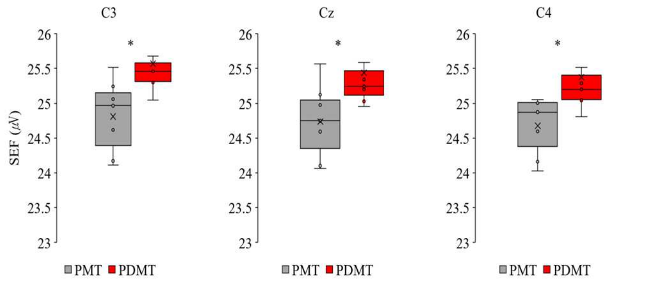

Figure 3. Pyramid hologram for SEF (μV). PMT (n = 7), PDMT (n = 7). $^{*}p < 0.05$.

D. Event-related desynchronization of pyramid hologram

Figure 4 illustrates the mu-rhythm evaluation for the ERD region under the two conditions. Observing asymmetrical movement, which is impossible in standard MT, was achieved using the system of this study. It was confirmed that ERD of the sensorimotor cortex was enhanced in the PDMT condition compared to the PMT condition. In all channels, the PDMT condition showed a significantly higher ERD (C3, $p = 0.011$; Cz, $p = 0.007$; C4, $p = 0.019$).

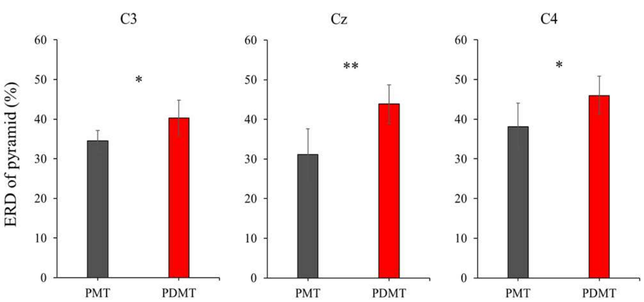

Figure 4. Event-related desynchronization (%). PMT (n = 7), PDMT (n = 7). $^{*}p < 0.05$, $^{**}p < 0.01$.

E. Separated section for mu rhythm with pyramid

The ERD wave was separated into a three-section time series (Fig. 5). S0 is -2 - 0s immediately before the event, S1 is the event time of 0 - 2s, and S2 is the time immediately after the event of 2 - 4s. In the ERD of the PMT section, the main effects showed significant differences (representatively, only the Cz channel was expressed, $F = 160.338$, $p < 0.001$, $\eta^2 = 0.964$). In particular, S1 showed a significant increase in all channels compared with S0 (C3, $p < 0.001$; Cz, $p < 0.001$; C4, $p < 0.001$).

In addition, there was a significant difference in the effect of the ERD section of PDMT (representatively, only the Cz channel was expressed, $F = 561.533$, $p < 0.001$, $\eta^2 = 0.989$). Post-hoc tests also showed that S1 had a significant increase in all channels compared to S0 (C3, $p < 0.001$; Cz, $p < 0.001$; C4, $p < 0.001$). Interestingly, S2 increased more than S0 did, showing significant differences in all channels (C3, $p < 0.001$; Cz, $p < 0.001$; C4, $p < 0.001$).

F. Cortex response of proposed system

Parameter analysis was performed to analyze neural activity using the proposed system (Fig. 6).

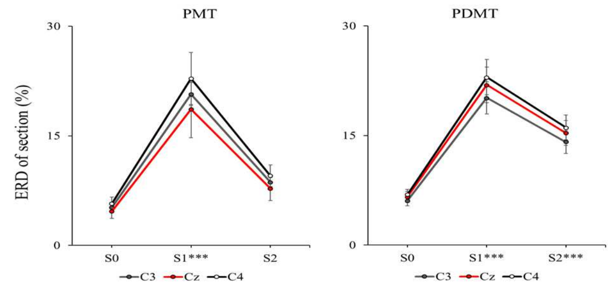

Figure 5. Section conditions of mu rhythm (%).PMT (n = 7), PDMT (n = 7). S0: -2 – 0s, S1: 0 – 2s, S2: 2 – 4s. $^{***}p < 0.001$, vs S0.

Motor skills were analyzed using channels C3 and C4 located in the primary motor cortex (M1). In the M1 area, motor activity was high in the condition where the delay was applied, and there was a significant difference ($p = 0.003$). In addition, the lateralization index of M1 was evaluated to determine the cortical reactivity of both conditions. The cortex of the dominance of ipsilateral (mirrored hand, pyramid hologram) was activated and showed a significant difference ($p = 0.009$).

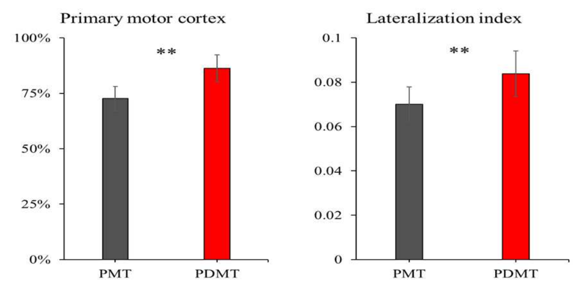

Figure 6. Paramters of primary motor cortex. PMT (n = 7), PDMT (n = 7). $^{**}p < 0.01$.

IV. DISCUSSION AND CONCLUSION

The degree of motor function in patients after stroke is an important evaluation index for prognostic status, but it leads to complex effects such as compensation by movement; thus, existing MT interventions have limitations. These limitations worsen the patient's prognosis, and further research on challenging intervention protocols for post-stroke rehabilitation treatment is required.

In this study, a new MT system was developed through the application of pyramid hologram technology. This system was able to overcome the problem of increasing neck tension in the subject's field of view, which is a limitation of standard MT. Based on the basic principles of MT [18], the proposed system is expected to enable the development of new MT protocols, as it can perform immediate mechanism analysis of the sensorimotor cortex. In addition, asymmetric training was possible by adding delayed movements, which resulted in greater stimulation of the sensorimotor cortex than with non-delayed PMT intervention.

It is characterized by the suppression of the mu rhythm and activation of the mirror nervous system (MNS) during AO and represents an activity index [19, 20]. AO provides stimulation through VF, in particular, upper limb rehabilitation should focus on task training to obtain the delicate movements required for ADLs and should aim to expand into independent activities. In other words, it is possible to induce neural activity through AO using an object that conveys a real sense of tactile sensation [21, 22]. These MNSs can influence the motor cortex through stimulation and performance of specific motor training tasks.

It was confirmed that voluntarily focusing on motor and sensory processes led to a decrease in the mu rhythm in the central posterior cortex during AO [23, 24]. Learning and observing the movement pattern according to the new training promotes activation of neural pathways related to the temporal lobe, occipital lobe, and parietal cortex, leading to regeneration through the promotion of sensory information in the MNS [25].

This system presents a treatment tool that overcomes the limitations of standard MT, which does not have objectified diagnosis and evaluation scales based on empirical therapeutic techniques. In addition, it is possible to provide individualized rehabilitation services based on the hand movements of stroke patient, and it is possible to promote a return to daily life by continuously observing the individual patient's recovery process. The developed system is not limited to stroke patients and can lead to further research to quantify the symptoms of dementia, cerebellar disease, and Parkinson's disease. It can serve as a basis for developing assessments that enable early diagnosis in these conditions. Therefore, the PDMT technology and novel approach can promote activation of the MNS through asymmetric training in a wide variety of patients with severe hand paralysis or patients with difficulty in producing symmetrical movement.

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