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The Effects of Motor Imagery Combined with Neuromuscular Electrical Stimulation on Using Transcranial Magnetic Stimulation in Stroke Patients

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The purpose of this study was to investigate the effect of motor imagery combined with neuromuscular electrical stimulation (MI-NMES) on cerebral cortex excitability in stroke patients. We examined the effect of MI-NMES on cerebral cortex excitability using transcranial magnetic stimulation (TMS) of motor evoked potential (MEP) amplitude and latency, quantitative electroencephalography (QEEG) of $\delta\alpha$ ratio (DAR) and power ratio index (PRI) assessments. This study was to evaluate 30 stroke patients who were satisfied the selection criteria of the study. Experiments were divided into MI-NMES group, motor imagery (MI) group. This study showed that there was a significant difference for all evaluations within the MI-NMES group, with significant differences in MEP amplitude and latency, QEEG DAR, and PRI index values in the comparison that those of the MI group. MI-NMES is suggested to be an effective approach for cerebral cortex excitability in stroke patients.

Keywords : motor imagery combined with neuromuscular electrical stimulation, motor imagery, motor evoked potential amplitude, motor evoked potential latency, quantitative electroencephalography

1. Introduction

Most strokes cause damage to the motor area, especially in the upper limb (U/L), and about 70 % of patients require neurorehabilitation. Reduction in U/L strength and impaired function are important issues for patients [1]. Neurorehabilitation generally focuses on improving independent functioning for various activities of daily livings (ADLs), and it may be effective if the patient's therapeutic movements and activities are transferred to an unemployed daily living environment [2]. Therapeutic approach for the recovery of the U/L function of stroke patients is accomplished through the reconstruction processes in the brain, and various approach such as neuromuscular rehabilitation and neuroplasticity based therapy are provided in various forms [3]. Studies show that various functional task activities and repetitive physical activities are effective [4]. However, depending on the degree of impairment of the patient, the effects may be limited. These interventions are effective when active movements are possible among stroke patients. In a study in monkeys, movement in the mirror was perceived as a self-motional movement and was activated in the premotor cortex area by what was referred to as a mirror neuron [5]. Subsequently, a study on human subjects showed that when observing or imagining various task movements, they were activated in the motor cortex area as in actual body movements [6]. Based on these theories, cognitive strategy interventions such as virtual reality, mirror therapy, action observation, and motor imagery (MI) have been used. The most representative is MI. It carries out cognitive activities that imagine movement or specific task performance without physical activity. MI contributes to brain activation through cognitive rehearsal of body movements without commands in the motor cortex area [7]. Some studies have reported neuroplasticity changes through repeated and intensive MI [5]. In results, the primary motor cortex, the premotor cortex, and the supplement motor area were activated. In another study, a limitation of MI was reported, whereby it was unable to produce an electrical signal causing substantial muscle

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contraction in the peripheral nerve. MI induces neurological changes in the central nervous system (CNS) due to the activation of cortical motor related areas and the corticospinal tract, but it has the drawback of not inducing functional movement because of the lack of sensory stimulation coming from the peripheral nerve [8]. Neuromuscular electrical stimulation (NMES) is a method that produces muscle contractions through peripheral sensory stimulation, which replaces these shortcomings. NMES induces muscle contraction using a short electrical signal passing through a pad attached to a specific muscle and is effective in enhancing functions such as reaching and grasping of the upper limbs. NMES can improve the movement of the U/L of an affected side unable to achieve movement due to damage to the CNS [9]. However, it is a controversial technique and questions about the effectiveness of the method have been raised. Persistence of the effect after the intervention, hardness impairment, and severely impaired patients [10]. In addition, regardless of the patient's motivation and attention intensity, periodic electrical stimulation stimulates peripheral nerves, resulting in muscle contraction. Therefore, the CNS effects are limited by the patient's concentration and willingness. Previous studies have attempted to determine the effect of MI combined with NMES (MI-NMES), which complements the shortcomings of MI and NMES alone. MI-NMES induces muscle contraction through electrical stimulation by producing microelectrical signals through MI rather than by actual muscle contraction. Once these signals reach the threshold value for producing electromyogram (EMG) information, they are recorded through the patches attached to muscles. Greater concentration and mental activity are needed to induce EMG signals only through the imagination of movement [11]. However, the number of subjects evaluated is limited, and assessment tools for effect validation are not objective. In this study, we propose clear and objective evidence for effect using a MI-NMES study and considering the limitations of previous studies. Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) are two of diagnostic tools for examining CNS changes in stroke patients. This test tool is useful as a quantitative index of CNS network and functional interaction changes. Nevertheless, it is limited in use because of the need for patient cooperation, and high economic costs [12]. Motor evoked potential (MEP) is an electrodiagnostic test that induces muscle contraction through the stimulation of the peripheral nerve by transcranial magnetic stimulation (TMS) of the cerebral motor cortex. It represents the degree of activation of the entire motor nerve system through motor neurons from the cerebral cortex to the muscles. In other words, the magnetic stimulation occurs in the spinal cord connected to the cerebral motor cortex by contracting the terminal muscle through the α motor neuron [13]. Therefore, the MEP is associated with the excitability of the cerebral cortex, and when the appropriate magnetic stimulation does not induce or induces the MEP, it indicates a high threshold level of motor neuron damage or motor neuron activation. MEP is a noninvasive technique applicable to hemiplegic patients after stroke and is used for the evaluation of clinical motor function and prediction of recovery [14]. It has been reported that there is a high correlation of recovery of U/L function as well as the degree of motor function impairment [15]. Another test tool is Quantitative electroencephalography (QEEG). QEEG is a valid alternative surrogate tool. Electroencephalography (EEG) is a non-invasive method of recording electrical activity associated with the activity of nerves using frequency based data obtained by electrodes placed on various parts of the scalp [16]. It is very sensitive to detecting brain frequency rhythm abnormalities of a stroke patient. Specific frequency activities are associated with brain function and can predict and presume the degree and extent of brain damage [17]. It is generally divided into δ, θ, α, and β waves according to the frequency of the EEG. In stroke patients, the activities of the δ and θ classified as abnormally slow waveforms are increased, and the activity of α, β, the latter classified as a rapid wave of the wave, are reduced [18]. Thus, the QEEG, an index that quantifies brain waves based on the brain activity relationship in the form of slow waves and fast waves, can confirm the functional status of the brain after stroke and predict changes [19]. In particular, the δ/α ratio (DAR) and $\delta+\theta/\alpha+\beta$ ratio defining the power ratio index (PRI) are used as important predictors of functional recovery and change in stroke patients. In this study, the amplitude and latency of the MEP, DAR and PRI of the QEEG index were used as a test tool to examine changes in cerebral cortex excitability after MI-NMES treatment in stroke patients.

2. Method

2.1. Subject

The study enrolled 30 stroke patients who understood the nature of the study and agreed to actively participate. The inclusion criteria and exclusion criteria for patients receiving physical therapy (PT) and occupational therapy (OT) at the K university hospital are described below. Subjects satisfying the following inclusion criteria were asked to participate in the study. Age over 19 years; hemiplegic and between 2 and 6 months after stroke; ability to

fully understand and accurately follow the instructions for the study, with a score of at least 24 points in mini mental state examination-korea; an average of 2.26 or less in vividness of movement imagery questionnaire test [10]. The following subjects were excluded. Those with an attached artificial pacemaker; subjects experiencing severe pain on the paralyzed U/L, visual analogue scale score of ≥ 5; subjects with an affected wrist extensor muscle having peripheral nerve damage, skin lesions, and electrical hypersensitivity and subjects with a metal implant in the brain.

2.2. Study procedure

The 30 subjects who participated in this study were divided into two groups by block randomization method. The group each of which consisted of two groups characterized by motor imagery combined with neuromuscular electric stimulation (MI-NMES group), motor imagery (the MI group). All subjects were assessed before intervention for amplitude and latency of the MEP, DAR and PRI of the QEEG index. Following the pretest, all subjects participating in the study were given traditional PT and OT for 30 minutes, 5 times weekly, and MI-NMES in the experimental group, MI in control group were carried out twice for 20 minutes per day, 5 days a week, for 6 weeks, followed by a posttest [10].

2.2.1. MI combined with MI- NMES

The MI-NMES used Mentamove (Mentamove, Munich, Germany). This tool combines motor imagery training with neuromuscular electrical stimulation by applying electric stimulation to the peripheral nerve with MI. It is easy to carry and easy to operate, and can be used indoors or outdoors. The attachment sites of the electrical stimulation were the active electrode and the reference electrode at the origin and insertion sites of the extensor pollicis brevis (EPB) and extensor pollicis longus (EPL), which comprised the wrist extension muscles used in a previous study [10]. In addition, the EMG electrode was attached to the medial side of the forearm between the two electrodes, and the pad attachment sites were marked using a pen before application (Fig. 1). Based on an electrical signal of up to 50 μV, which does not induce active muscle contraction, the EMG threshold value generated when imagining was set. Before the test was performed, the data within the error range was checked three times in order to confirm the reliability between the measurements. The device was programmed to automatically reset the threshold value in the tool to maximize the effect if the microcurrent generated through imagination during the treatment reached or failed to reach more than three consecutive threshold levels. The intensity of the

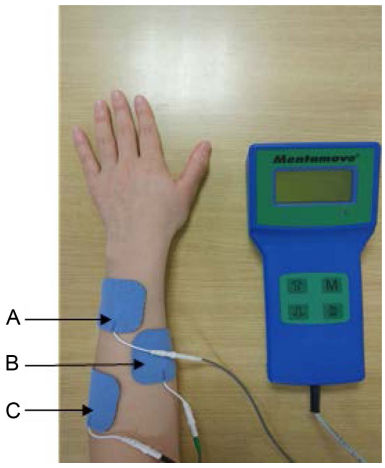

Fig. 1. (Color online) Attached surface electrodes of mentamove. A and C: active electrode and the reference electrode at the origin and insertion sites of the extensor pollicis brevis and extensor pollicis longus. B: EMG electrode.

electrical stimulation was set between 15 and 30 mA to allow adequate wrist extension as in previous studies [20]. MI-NMES consisted of three phases: mental rest, mental activation, and peripheral nerve stimulation.

2.2.2. Motor imagery program (MIP)

MIP selected 10 MI tasks as meaningful ADLs from the studies which were presented as effective MI tasks for stroke patients [21]. MIP is It consists of following, using chopsticks, using a pencil, using a computer mouse, hand washing, using a mobile phone, upper body dressing, drinking with a water bottle, grasping and release of tennis ball, handling of a credit card, combing hair. Ten MI tasks were conducted for about 2 minutes each, for a total of 20 minutes twice a day. The subject performed MI by sitting at a desk in a quiet independent space, checking ten task lists and timers. Imagery training was divided into visual motor imagery and kinematic motor imagery training. Kinematic motor imagery training was performed in this study, which involves the imagination of inner sensory information that is felt while performing the actual body movement. MIP is directed to imagine a sequence of movements by subdividing the ten task movements into a process of reaching with the arm, picking up tasks, and a manipulation process [21]. In the MI-NMES group, imagery training was performed using the same tasks and methods.

2.3. Assessment methods

2.3.1. MEP amplitude and MEP latency

MEP amplitude and MEP latency used in this study was the TMS: Nicolet Viasys Viking Select EMG EP System (San Diego, CA, USA) (Fig. 2). MEP is an electro-

Fig. 2. (Color online) TMS: Nicolet Viasys Viking Select EMG EP System (San Diego, CA, USA).

diagnostic test, which induces peripheral muscle reaction by directly inducing TMS to the cerebral motor cortex. MEP has been used to evaluate clinical motor function and to predict recovery in hemiplegic patients after stroke [14]. Magnetic stimulation was performed by placing the central part of the coil stimulator at the Cz position using the International Electroencephalograph 10-20 recording method. With the subject in a relaxed posture, the center of the coil was placed in contact with the cerebral hemispheres of the unaffected side. The abductor pollicis brevis (APB) is located at the motor cortex at an angle of 45 degrees from the centerline and the point where the maximum reaction occurred was determined by moving in small increments. The maximum magnetic field strength was 2.0 Tesla and the stimulation time was 0.1 millisecond [22]. The stimulus intensity was gradually increased from 80 % to 100 % and stimulation occurred several times. A silver to silver chloride electrode was attached to the APB on the affected side by a belly tendon method and the ground electrode was attached to the arm to measure the EMG values [23] (Fig. 3). The resting motor threshold was defined as the minimum stimuli intensity at which a MEP > 50 μV is recorded at least 5 times during 10 stimulations. The amplitude of the MEP was determined by measuring the amplitude 15 times after stimulation at 120 % [22]. Peak to peak amplitudes of the MEP evoked from the contralateral target muscle were obtained. The

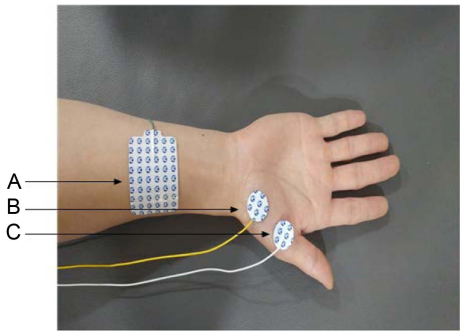

Fig. 3. (Color online) TMS attached surface electrodes. A: EMG electrode, B and C: active electrode and the reference electrode at the origin and insertion sites of the abductor pollicis brevis.

EMG values were recorded using mobile Viking Select software, and the signal was amplified to 100 ms/div and filtered from to 2 Hz to 10 KHz.

2.3.2. Quantitative electroencephalography (QEEG)

In this study, 64-channel digital EEG (64ch SynAmps2 Neuroscan System, Compumedics, Charlotte, NS, USA) was used to measure the EEG. Twenty-one channels were attached based on the International 1020 System and all electrodes were used as reference electrodes. An Ag-AgCl electrode was used, and the impedance was kept < 5 kΩ. The sampling rate of the signal was set to 1000 Hz, the high-pass filter was set at 0.5 Hz, and the low pass filter was set at 40 Hz. The measurement time was measured for 5 minutes, and the 1-minute value showing the most stable frequency rhythm was used. Independent component analysis (ICA) was performed to remove artifacts and noise [24]. For quantitative analysis, data was digitized by fast Fourier transformation, and power spectrum values of various bands were obtained. The relative power values obtained by comparing these frequencies with the normal database were used for the analysis by obtaining 21 channels. Neuroguide (Applied Neuroscience, Inc., St. Petersburg, FL, USA) was used in this study as a QEEG analysis tool. This is a software package that provides a standardized database that can be used to compare and analyze QEEG measurements. Relative power was summed across the δ (0.98-3.91 Hz), θ (4.39-7.32 Hz), α (7.81-12.21 Hz), and β (12.70-29.79 Hz) bands. The relative power values for each frequency band were calculated as the ratio of summed absolute band-power to total summed power across the 0.98-29.79 Hz range. All indices were initially calculated for each channel, and were then averaged across all electrodes [25]. The relative band-power values were used to calculate the following quantitative indices, DAR: defined as the ratio of δ to α absolute

power (DAR = Δ/α), PRI: the ratio of "slow" to "fast" activity defined as the ratio of $\delta+\theta$ to $\alpha+\beta$ absolute power (PRI = $\delta+\theta/\alpha+\beta$).

2.3. Statistical analysis

In this study, SPSS the statistical program for Windows, version 20.0 was used for statistical analyses. To evaluate the effects of intervention, a Wilcoxon signed-rank test was used to compare pre- and post-intervention results in each group. The Mann-Whitney *U* test was used to compare changes in outcome measures between the groups.

$\alpha = 0.05$ is significance level in statistical analyzes

3. Results

3.1. General characteristics of subjects

The general characteristics of the subjects are shown in Table 1.

3.2. Comparison of treatment results before and after the intervention within the MI-NMES group (NMESG)

The MEP amplitude increased to 111.70 μV and 165.00 μV, before and after the intervention in the MI-NMESG. There were significant differences ($p < 0.05$). And the MEP latency decreased to 29.70 ms and 27.59 ms, before and after intervention. There were also significant differences ($p < 0.05$). The QEEG DAR decreased to 3.63 % and 1.91 %, before and after the intervention in the MI-NMESG. There were significant differences ($p < 0.05$). And the QEEG PRI decreased to 3.36 % and 2.00 %, before and after intervention. There were also significant differences ($p < 0.05$) (Table 2).

3.3. Comparison on results before and after the intervention within the MI group (MIG)

The MEP amplitude increased to 120.20 μV and 125.00 μV, before and after the intervention in the MIG. There were significant differences ($p < 0.05$). And the MEP latency decreased to 29.62 ms and 29.07 ms, before and after intervention. There were also significant differences ($p < 0.05$). The QEEG DAR increased to 3.25 % and 3.26 %, before and after the intervention in the MIG. And the QEEG PRI decreased to 3.34 % and 3.24 %, before and after intervention. There were no statistically significant differences (Table 3).

Table 1. Characteristics of subjects.

Characteristics	MI-NMESG (N=15)	MIG (N=15)
Age (year)	63.82±6.96	61.74±8.14
Gender (male/female)	7/8	9/6
Type of stroke (Hemorrhage/Infarction)	5/10	8/7
Side of stroke (Right/Left)	6/9	7/8
Time since onset of stroke months	4.53±1.72	5.17±1.86

M±SD: mean ± standard deviation, MIT-NMESG: motor imagery training combined with neuromuscular electric stimulation group, MIG: motor imagery group

Table 2. Clinical Parameters before and after Treatment with MI-NMESG.

	MI-NMESG		*p*-value
	Pretest	Post test	
MEP amplitude (μV)	111.70(54.51)	165.00 (81.53)	<.001*
MEP latency (ms)	29.70(1.56)	27.59(1.57)	<.000*
QEEG DAR (%)	3.63(2.19)	1.91(1.53)	<.001*
QEEG PRI (%)	3.36(1.46)	2.00(1.81)	<.003*

The values are mean ± standard deviation, MIT-NMESG: motor imagery training combined with neuromuscular electric stimulation group, MEP: Motor evoked potential, QEEG DAR: Quantitative electroencephalography $\delta\alpha$ ratio, QEEG PRI: Quantitative electroencephalography power ratio index.
*$p < 0.05$

Table 3. Clinical Parameters before and after Treatment MIG.

	MIG		*p*-value
	Pretest	Post test	
MEP amplitude (μV)	120.20(49.88)	125.22(46.53)	<.018*
MEP latency (ms)	29.62(1.66)	29.07(1.83)	<.005*
QEEG DAR (%)	3.25(2.53)	3.26(2.35)	<.990
QEEG PRI (%)	3.34(2.06)	3.24(1.82)	<.501

The values are mean ± standard deviation, *$p < 0.05$
MIG: motor imagery group, MEP: Motor evoked potential, QEEG DAR: Quantitative electroencephalography $\delta\alpha$ ratio, QEEG PRI: Quantitative electroencephalography power ratio index.

3.4. Comparison of the difference in results between the two groups

Concerning the changes in MEP amplitude before and after the intervention, the MI-NMESG showed an increase of 53.29 μV, which was statistically greater than the

Table 4. Comparison of results between the two groups.

	Mean change		*p*-value
	MI-NMESG	MIG	
MEP amplitude (μV)	53.29(48.34)	5.01(7.22)	<.001†
MEP latency (ms)	-2.10(0.62)	-0.55(0.64)	<.000†
QEEG DAR (%)	-1.72(1.64)	0.01(0.81)	<.001†
QEEG PRI (%)	-1.36(1.43)	-0.59(0.55)	<.004†

The values are mean ± standard deviation, †$p < 0.05$ MIT-NMESG: motor imagery training combined with neuromuscular electric stimulation group, MIG: motor imagery group, MEP amplitude: Motor evoked potential amplitude, MEP latency: Motor evoked potential latency, QEEG DAR: Quantitative electroencephalography $\delta\alpha$ ratio, QEEG PRI: Quantitative electroencephalography power ratio index.

increase of 5.01 μV observed in the MIG ($p < .005$). The changes in MEP latency was -2.10 ms in the MI-NMESG, which indicates a more significant difference than -0.55 ms observed in the MIG ($p < .05$). Concerning the changes in QEEG DAR was -1.72 % in the MI-NMESG, which indicates a more significant difference than 0.01 % observed in the MIG ($p < .05$). The changes in QEEG PRI was -1.36 % in the MI-NMESG, which indicates a more significant difference than -0.59 % observed in the MIG ($p < .05$) (Table 4).

4. Discussion

Over time after the onset of stroke, the patient shows severe disability in the U/L. Although there have been no reports of intervention methods for the recovery of severely impaired U/L stroke patients, new neurorehabilitation have been attempted and many studies are under way. Hong *et al.* (2012) conducted a preliminary study using MIT-NMES in 14 chronic stroke patients and have reported the recovery of U/L function and activation of the cerebral cortex in the supplementary motor area, precentral gyrus, and postcentral gyrus [10]. Mrachacz-Kersting *et al.* (2012) reported an increase in corticospinal tract activation through a combination of imagery training and peripheral nerve electrical stimulation in a study of 21 healthy subjects [26]. In this study, MEP amplitude and latency, QEEG DAR and PRI indices were examined by evaluation of cerebral cortex activation. The MEP amplitude, latency was significantly difference in the MI-NMES group between the before and after assessments. Saito *et al.* (2013) studied changes in MEP amplitude and latency in 11 healthy adults [8]. One group was subjected to electrical stimulation in the thenar muscle while imagining the opposition movements of the thumb and index finger, and a second group was subjected to a voluntary opposition movement of the thumb and index finger combined with electrical stimulation. Thus, cerebral cortex excitability was further increased in the group undergoing MI training combined with electrical stimulation. This suggested that when active muscle contraction is applied together with electrical stimulation, this did not result in changes of primary motor cortex [27]. In addition, it has been reported that on voluntary muscle contraction and electrical stimulation occurred simultaneously in the stroke patients, abnormal activation of the agonist and antagonist muscles could be induced. Kaneko *et al.* (2014) studied the effect of corticospinal tract activation through MEP amplitude and latency in five states of relaxation state, MI, MI-NMES, NMES, and during voluntary muscle contraction [28]. The target muscle was FDI of the index finger, MI and voluntary movement performed resulted in abduction of the index finger. The results of the study showed that a significant difference in the MEP amplitude and latency was observed in the MI-NMESG and on voluntary muscle contraction. MEP amplitude activation of the corticospinal tract was similar for both groups. This suggested that MI-NMES might affect the activation of the cerebral motor cortex in stroke patients without requiring voluntary muscle contractions. The above mentioned previous studies support the results of this study. However, those studies were conducted on healthy subjects. In the present study, we provide evidence that MI-NMES activates the cerebral cortex motor area in stroke patients. As the results of this study show, MEP provide several critical pieces of information including integrity and excitability of the descending motor pathways that is particularly relevant for stroke by using TMS. For example, the presence of an MEP after stroke provides some indication that the descending motor tracts are intact, suggesting potential for recovery [27]. Furthermore, following stroke, excitability of the ipsilesional cerebral motor cortex is reduced and the magnitude of this reduction in excitability is correlated with motor impairment. As a result, ipsilesional excitability is frequently used as a marker of response to therapy, and has been the target of noninvasive brain stimulation. TMS have been studied to determine the extent of brain damage and to predict motor recovery in patients with stroke by MEP latency and amplitude. Evaluation of MEP in the acute phase of stroke showed a relationship between motor recovery and the degree of motor impairment, as attested by central motor conduction time, MEP latency and amplitude [29]. The QEEG DAR, PRI values were significantly lower in the MI-NMESG on before and after comparisons. There was no significant difference in the MIG. Comparisons between the two groups with regard to the QEEG DAR, PRI values showed that there were significant differences between the MI-NMESG and MIG. Many studies have shown that the QEEG DAR and PRI index are objective tests useful for identifying factors predictive of U/L function recovery and the level of functional activity in stroke patients [18]. Finnigan *et al.* (2016) evaluated the accuracy of the QEEG index as a grade of impairment by evaluating seven QEEG indices in 18 acute stroke patients and 28 healthy adults [30]. Among the seven indices, DAR was the most objective indicator, while the second was reported to be the PRI. A lower QEEG DAR and PRI index defines a higher residual functional level. In general, an index of $> 2\%$ indicates abnormality of brain function and an index of < 1 % suggests normal brain function. This is supported by the findings of the significant differences in

the QEEG DAR and PRI indices in the MI-NMESG of this study. It is also important to confirm the objectivity and accuracy of the results of MEP amplitude and latency evaluation. As a result of this study, it was more effective in a cerebral cortex activation when combined than when only MI or NMES was applied. The most important factor in neuroplasticity is the involvement of the active cognitive function of the patient, the motivation, and the repetitive activity through afferent stimulation [10]. A limitation of this study is that the outcome of cases were likely to be complicated by the effect of natural recovery of function as the study population targeted acute stroke patients. The number of subjects was relatively small, and thus, it is difficult to generalize the results to all stroke patients. This study demonstrated the effects of cerebral cortex activation but did not address the ultimate effect on ADLs, and thus, future research is necessary. A representative approach focused on neuroplasticity is MI-NMES and the MI-NMES effect of this study supports the results previous study. Therefore, we would like to suggest effective approach for patients with severe stroke who are undergoing limited intervention participation and recovery. In addition to the effect of short-term U/L function enhancement, it is expected to contribute to cerebral cortex activation in combination with action observation, mirror therapy, and various sensory stimulation in the long-term.

5. Conclusion

This study showed that there was a significant difference for all evaluations within the MI-NMESG, with significant differences in MEP amplitude and latency, QEEG DAR and PRI index values in the comparison that those of the MIG. The objectivity of the results was improved by a research design that took into consideration the limitations faced by the previous study. MI-NMES is suggested to be an effective intervention for cerebral cortex excitability in patients with severe stroke.

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