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Chapter 4

The Application of Motor Imagery to Neurorehabilitation

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Abstract

We investigated the influence of the imagined muscle contraction strength on the spinal motor neural excitability and sympathetic nerve activity by using the F-wave and heart rate variability analysis. Motor imagery of isometric thenar muscle activity increased the spinal motor neuron excitability and sympathetic nerve activity. The imagined muscle contraction strength did not affect changes of the spinal motor neuron excitability and sympathetic nerve activity. Therefore, Motor imagery at slight imagined muscle contraction strength can facilitate the spinal motor neuron excitability without physical load. Motor imagery-based Brain-machine interface is widely used for neurorehabilitation. To achieve better outcomes in neurorehabilitation used Brain-machine interface, performing trained motor imagery would be required, and the F-wave may be exploited an index of motor imagery training effect.

Keywords: motor imagery, F-wave, imagined muscle contraction strength, autonomic nervous system, neurorehabilitation

1. Introduction

Motor imagery (MI) is defined as an active process during which a specific motor action is reproduced within working memory without any overt movement [1]. MI is considered a potential tool for improvement of motor function in rehabilitation. Indeed, MI has been shown to improve various motor functions. Yue and Cole [2] reported that muscle strength of little finger abduction was significantly increased after MI training for 4 weeks. Additionally, muscle strength of ankle dorsiflexion was significantly increased after MI training for 4 weeks [3]. Also, Guillot et al. [4] reported that muscle flexibility was improved after MI of stretching for 5 weeks.

Immediate enrollment in rehabilitation programs for functional reorganization should be important to obtain better outcomes [5]. Specifically, Motor-evoked potentials (MEPs) amplitude, an index of corticospinal excitability, was decreased in post-stroke [6]. However, MEPs amplitude was increased in patients who have functional motor recovery [7]. Additionally, spinal motor neuron excitability was significantly reduced in the post-stroke acute phase [8]. Thus, facilitating the corticospinal excitability, including the spinal motor neuron excitability, should be needed for post-stroke patients whom have motor impairment.

Numerous neurophysiological studies using positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and near infrared spectroscopy (NIRS) have demonstrated that MI and motor execution activate similar brain activation patterns [9–13]. Specifically, primary motor cortex, supplementary motor area, premotor area, somatosensory area, prefrontal cortex, parietal lobule, cingulate area, cerebellum, and basal ganglia were activated during MI and motor execution. Thus, MI shares common neural substrates with motor execution. When transcranial magnetic stimulation (TMS) was delivered over the primary motor cortex during MI, MEPs amplitude obtained from corresponding muscle was significantly increased relative to rest level [14–16]. The increase of MEPs amplitude during MI indicates that MI facilitates corticospinal excitability. Thus, MI can facilitate the central neural function.

However, previous studies have shown various patterns in the spinal motor neuron excitability during MI using the F-wave and H-reflex as indices of spinal reflex excitability [17–19]. Taniguchi et al. [17] reported that the F-wave amplitude was significantly decreased after volitional relaxation for 3 h. When subjects did MI of thumb abduction during volitional relaxation simultaneously, the F-wave amplitude was maintained at before volitional relaxation level. Whereas, Kasai et al. [18] reported that the H-reflex amplitude was unchanged during MI of wrist flexion movement. Oishi et al. [19] also reported that there was decline of H-reflex amplitude during MI of speed skating. Our laboratory previously investigated the spinal motor neuron excitability during MI of isometric thenar muscle activity at 50% maximal voluntary contraction (MVC) for 1 min using the F-wave [20]. The F-wave is a compound action potential resulting from re-excitation ("backfiring") of an antidromic impulse following distal electrical stimulation of motor nerve fibers at the anterior horn cells [21–23]. The F-wave measured during MI at 50% MVC for 1 min was significantly increased than that at rest. Thus, we concluded that MI of isometric thenar muscle activity can increase the spinal motor neuron excitability.

We are aiming to find the way of MI obtained most beneficial effect. In order to do that, it is important to assess the spinal motor neuron excitability concurrent with the central nervous system. We think that facilitating the spinal motor neuron excitability will be required for improvement of motor function. Because, described above, the facilitation of the corticospinal excitability including the spinal motor neuron excitability is needed for recovery of motor function. In this chapter, we would like to introduce our previous works about the spinal motor neuron excitability during MI of isometric thenar muscle activity. In the first half of this chapter, we described about the spinal motor neuron excitability during MI of isometric thenar muscle activity at various imagined muscle contraction strengths. In the second half of this chapter, we described about the autonomic nervous system during MI. At the end of chapter, we discuss about how apply MI to neurorehabilitation using brain-machine interface (BMI).

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2. The spinal motor neuron excitability during MI at various imagined muscle contraction strengths

2.1. The spinal motor neuron excitability during MI at 10, 30, 50, and 70% MVC

2.1.1. Purpose

We previously reported that when the subject performed MI of isomeric thenar muscle activity at 50% MVC, the spinal motor neuron excitability was significantly increased than at rest [20]. In actual motion, Suzuki et al. [27] reported the spinal motor neuron excitability was increased linearly with muscle contraction strength. If MI and motor execution share common neural networks, the spinal motor neuron excitability will be increased linearly with imagined muscle contraction strength. Then, we investigated the spinal motor neuron excitability during MI at various imagined muscle contraction strengths. Specifically, we adopted the 10, 30, 50, and 70% MVC for imagined muscle contraction strength. In this research, we assessed the spinal motor neuron excitability during MI by using the F-wave [24–26].

2.1.2. Materials

Ten healthy volunteers were participated in this research (5 males, 5 females; mean age = 28.7 ± 4.5 years). All participants provided informed consent before the study commenced. This research was approved by the Research Ethics Committee at Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

2.1.3. F-wave recording procedure

Participants were in supine position on a bed and instructed to fix one's eye on a pinch meter (Digital indicator F304A, Unipulse Corp., Japan) display throughout the F-wave recording. A Viking Quest electromyography machine ver. 9.0 (Natus Medical Inc., USA) was used for the F-wave recordings. The room temperature was kept at 25°C. The skin was cleaned with an abrasive gel to keep impedance below 5 kΩ. F-waves were recorded from left thenar muscle after stimulating the left median nerve at the wrist. A pair of 10 mm silver EEG cup electrodes (Natus Medical Inc., USA) were placed over the ventral surface of the thumb and base of the first dorsal metacarpal bone. The simulating electrodes comprised a cathode placed over the left median nerve 3 cm proximal to the palmar crease and an anode was placed 2 cm more proximally. Before the F-wave recording, maximal intensity of electrical stimulation was determined by delivering 0.2-ms square-wave pulses of increasing intensity from 0 to 50 mA until eliciting the largest compound muscle action potential (M-wave). Supramaximal electrical stimuli (20% above maximal stimulus intensity) were delivered at 0.5 Hz in each trial. The sensitivity for the F-wave was set at 200 μV/division and a sweep of 5 ms/division. Filter bandwidth was ranged from 20 Hz to 3 kHz.

2.1.4. Experimental protocol

For the rest trial (rest), F-waves were recorded during relaxation for 1 min. Subsequently, for the motor task, participants learned the isometric thenar muscle activity at 50% MVC (i.e.,

participants press the sensor of pinch meter by left thumb and index finger at 50% MVC) for 1 min. They were instructed to keep the 50% MVC value (kgf) measured numerically on the display of pinch meter. For the MI trial, participants performed MI of isometric thenar muscle activity at 50% MVC for 1 min. F-waves were recorded during MI (50% MI). Immediately after 50% MI trial (post), F-waves were recorded during relaxation for 1 min. The above process was defined as the MI at 50% MVC condition (50% MI condition). This protocol was repeated for 10, 30, and 70% MI conditions. Each condition was performed randomly on different days.

2.1.5. F-wave data analysis

All recorded F-wave data were analyzed for the persistence, F/M amplitude ratio, and latency in each trial. The minimum of F-wave peak-to-peak amplitude was at least 20 μV [21]. The persistence was defined as the number of detected F-wave responses divided by 30 supramaximal electrical stimuli. The F/M amplitude ratio was defined as the mean amplitude of all responses divided by the M-wave amplitude. The amplitude measured individually for each F-wave and then the mean calculated. The latency was defined as the mean latency from the time of electrical stimulation to onset of detected F-waves. The persistence reflects the number of backfiring spinal anterior horn cells [22, 23]. The F/M amplitude ratio reflects the number of backfiring spinal anterior horn cells and the individual cells excitability [22, 23]. Thus, these parameters are considered the indices of the spinal motor neuron excitability.

2.1.6. Statistical analysis

The normality of F-wave data was not confirmed by using the Kolmogorov-Smirnov and Shapiro-Wilk tests. We used a nonparametric method in this research. The persistence, F/M amplitude ratio, and latency among three trials (rest, MI, post) under each MI conditions (10% MI, 30% MI, 50% MI, and 70% MI conditions) were compared using the Friedman test and Scheffe's post hoc test.

We also calculated the relative value obtained by dividing F-wave data during MI under four MI conditions by that at rest. The relative values among four MI conditions were compared using the Friedman test. We used SPSS statistics ver. 19 (IBM Corp., USA) for statistical analysis. The threshold for statistical significance was set to $p = 0.05$.

2.1.7. Results

The persistence during MI under all MI conditions was significantly greater than that at rest (10% MI vs. Rest, 70% MI vs. Rest, $^{**}p < 0.01$; 30% MI vs. Rest, 50% MI vs. Rest, $^{*}p < 0.05$) (**Tables 1–4**). The persistence immediately after MI under all MI conditions was reduced to rest level (**Tables 1–4**).

The F/M amplitude ratio during MI under 10, 30, and 50% MI conditions was significantly greater than that at rest (10% MI vs. Rest, 50% MI vs. Rest, $^{**}p < 0.01$; 30% MI vs. Rest, $^{*}p < 0.05$) (**Tables 1–3**). The F/M amplitude ratio during MI under 70% MI condition was tended to be increased than that at rest ($p \fallingdotseq 0.082$) (**Table 4**). The F/M amplitude ratio immediately after MI under all MI conditions was reduced to rest level (**Tables 1–4**).

	Rest	10% MI	post
Persistence (%)	61.8 ± 12.6	91.9 ± 9.70**	73.1 ± 20.7
F/M amplitude ratio (%)	0.90 ± 0.35	2.46 ± 2.61**	1.18 ± 0.67
Latency (ms)	25.3 ± 0.98	25.2 ± 1.25	25.5 ± 0.99

**$p < 0.01$; significant difference between rest and 10% MI trial.

Table 1. Changes in F-wave under 10% MI condition.

	Rest	30% MI	post
Persistence (%)	61.2 ± 19.5	88.0 ± 12.2**	60.0 ± 18.7
F/M amplitude ratio (%)	1.00 ± 0.94	2.92 ± 2.95**	1.11 ± 0.52
Latency (ms)	24.9 ± 1.16	24.6 ± 0.99	24.9 ± 1.14

**$p < 0.05$; significant difference between rest and 30% MI trial.

Table 2. Changes in F-wave under 30% MI condition.

	Rest	50% MI	post
Persistence (%)	62.7 ± 22.3	94.0 ± 9.40*	65.5 ± 27.0
F/M amplitude ratio (%)	1.08 ± 0.28	2.60 ± 2.30**	0.98 ± 0.40
Latency (ms)	24.5 ± 1.61	24.3 ± 1.82	24.5 ± 1.58

*$p < 0.05$; significant difference between rest and 50% MI trial.
**$p < 0.01$; significant difference between rest and 50% MI trial.

Table 3. Changes in F-wave under 50% MI condition.

	Rest	70% MI	post
Persistence (%)	55.9 ± 17.6	88.1 ± 10.8**	65.3 ± 19.9
F/M amplitude ratio (%)	0.94 ± 0.33	1.79 ± 1.23	1.11 ± 0.44
Latency (ms)	24.4 ± 1.37	24.1 ± 1.27	24.3 ± 1.15

**$p < 0.01$; significant difference between rest and 70% MI trial.

Table 4. Changes in F-wave under 70% MI condition.

No significantly differences in the latency were observed among three trials (rest, MI, post) under all MI conditions (**Tables 1–4**).

The relative values of the persistence, F/M amplitude ratio, and latency did not exhibit significant differences among all MI conditions (**Table 5**).

	10% MI condition	30% MI condition	50% MI condition	70% MI condition
Relative values of persistence	1.53 ± 0.31	1.58 ± 0.61	1.78 ± 0.93	1.69 ± 0.45
Relative values of F/M amplitude ratio	2.40 ± 1.38	3.31 ± 0.56	2.52 ± 1.96	2.10 ± 1.37
Relative values of latency	0.99 ± 0.02	0.99 ± 0.02	0.99 ± 0.03	0.99 ± 0.02

Table 5. Comparison of F-wave among 10% MI, 30% MI, 50% MI, and 70% MI condition.

2.2. The spinal motor neuron excitability during MI at 50 and 100% MVC

2.2.1. Purpose

Our previous works [24–26] suggested that MI of isometric thenar muscle activity at 10, 30, 50, and 70% MVC can facilitate the spinal motor neuron excitability. However, the imagined muscle contraction strength did not influence on change of the spinal motor neuron excitability. Whereas, Cowley et al. [29] previously reported that the amplitude of H-reflex during MI of ankle plantar flexion at 100% MVC was significantly greater than that at 50% MVC. Then, we hypothesized the MI of isometric thenar muscle activity at 100% MVC will be greater than that at 50% MVC. In this research, we compared the spinal motor neuron excitability between 50% MI and 100% MI condition [28].

2.2.2. Materials

Fifteen healthy volunteers were participated in this research (13 males, 2 females; mean age = 25.3 ± 5.0 years). All participants provided informed consent before the study commenced. This research was approved by the Research Ethics Committee at Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

2.2.3. F-wave recording procedure

The environment and F-wave recording condition was set as previous works [24, 25].

2.2.4. Experimental protocol

For the rest trial (rest), F-waves were recorded during relaxation for 1 min. Subsequently, for the motor task, participants learned the isometric thenar muscle activity at 50% MVC (i.e., participants press the sensor of pinch meter by left thumb and index finger at 50% MVC) for 1 min. They were instructed to keep the 50% MVC value (kgf) measured numerically on the display of pinch meter. For the MI trial, participants performed MI of isometric thenar muscle activity at 50% MVC for 1 min. F-waves were recorded during MI (50% MI) and immediately after 50% MI trial (post) for 1 min respectively. The above process was defined as the MI at 50% MVC condition (50% MI condition). F-wave recording under 100% MI condition was performed using the same protocol as 50% MI condition. These conditions were performed randomly on different days.

After all F-wave recordings, F-wave data was analyzed with respect to the persistence, F/M amplitude ratio, and latency.

2.2.5. Statistical analysis

The normality of F-wave data was not confirmed by using the Kolmogorov-Smirnov and Shapiro-Wilk tests. We used a nonparametric method in this research. The persistence, F/M amplitude ratio, and latency among three trials (rest, MI, post) under two MI conditions (50% MI and 100% MI conditions) were compared using the Friedman test and Scheffe's post hoc test.

We also calculated the relative value obtained by dividing F-wave data during MI under four MI conditions by that at rest. The relative values among two MI conditions were compared using the Wilcoxon signed rank test. We used SPSS statistics ver. 19 (IBM Corp., USA) for statistical analysis. The threshold for statistical significance was set to $p = 0.05$.

2.2.6. Results

The persistence during MI under two MI conditions was significantly greater than that at rest (50% MI vs. Rest, 100% MI vs. Rest, $^{**}p < 0.01$) (**Tables 6**, **7**). The persistence immediately after MI under two MI conditions was reduced to rest level (**Tables 6**, **7**).

The F/M amplitude ratio during MI under two MI conditions was significantly greater than that at rest (50% MI vs. Rest, 100% MI vs. Rest, $^{**}p < 0.01$) (**Tables 6**, **7**). The F/M amplitude ratio immediately after MI under two MI conditions was reduced to rest level (**Tables 6**, **7**).

No significantly differences in the latency were observed among three trials (rest, MI, post) under two MI conditions (**Tables 6**, **7**).

The relative values of the persistence, F/M amplitude ratio, and latency did not exhibit significant differences between two MI conditions (**Table 8**).

2.3. Discussion

2.3.1. The spinal motor neuron excitability during MI of isometric thenar muscle activity

From results of our previous works, it is suggested that MI of isometric thenar muscle activity at 10, 30, 50, 70, and 100% can facilitate the spinal motor neuron excitability. About this, it is considered to be influence of descending pathways corresponding to thenar muscle. Previous researches have demonstrated the activation of diverse brain area contribute to motor preparation and planning during MI [9–13]. The excitatory and inhibitory inputs modulate the spinal motor neuron excitability via the corticospinal and/or extrapyramidal tract [30]. Thus, it is plausibly that the activation of central nervous system contributes to motor preparation and planning during MI facilitated the spinal motor neuron excitability via the corticospinal and/or extrapyramidal tract.

Furthermore, all subjects participated in our previous works were instructed to perform MI with holding the sensor of a pinch meter. Mizuguchi et al. [31] reported that corticospinal excitability during MI utilizing an object was modulated by a combination of tactile and proprioceptive inputs while holding an object. We previously reported that the spinal motor neuron

	Rest	50% MI	post
Persistence (%)	50.8 ± 21.7	88.2 ± 13.2**	48.3 ± 19.9
F/M amplitude ratio (%)	1.71 ± 0.89	3.96 ± 4.56**	1.29 ± 0.56
Latency (ms)	25.5 ± 1.40	24.9 ± 1.91	25.3 ± 1.29

**$p < 0.01$; significant difference between rest and 50% MI trial.

Table 6. Changes in F-wave parameters under 50% MI condition.

	Rest	100% MI	post
Persistence (%)	60.8 ± 24.9	91.9 ± 7.58**	60.7 ± 21.5
F/M amplitude ratio (%)	1.32 ± 1.12	3.57 ± 4.67**	1.39 ± 1.25
Latency (ms)	25.2 ± 1.32	24.8 ± 1.31	25.2 ± 1.40

**$p < 0.01$; significant difference between rest and 100% MI trial.

Table 7. Changes in F-wave parameters under 100% MI condition.

	50% MI condition	100% MI condition
Relative values of persistence	2.04 ± 1.17	2.06 ± 1.71
Relative values of F/M amplitude ratio	2.75 ± 2.04	2.53 ± 1.76
Relative values of latency	0.98 ± 0.06	0.99 ± 0.03

Table 8. Comparison of F-wave parameters between 50% MI and 100% MI condition.

excitability during MI with holding the sensor of a pinch meter was significantly greater than that during MI without holding the sensor [20]. Consequently, it is suggested that tactile and proprioceptive perceptions during MI while holding the sensor facilitated the spinal motor neuron excitability cooperatively with MI-activated pathways.

2.3.2. Influence of the imagined muscle contraction strength on the spinal motor neuron excitability

In our previous works, the relative value of the persistence, F/M amplitude, and latency were similar among all MI conditions. It is suggested that the imagined muscle contraction strength may not affect the spinal motor neuron excitability. There are several previous researches investigated the spinal motor neuron excitability during MI at different imagined muscle contraction strengths. Bonnet et al. [32] reported that the amplitude of H-reflex was significantly greater during MI of ankle plantar flexion at 2 and 10% than that at rest. Additionally, the amplitude of H-reflex during MI was similar between 2% MI and 10% MI condition. Hale et al. [33] also reported that the amplitude of H-reflex during MI of ankle plantar flexion was similar among five (i.e., 20, 40, 60, 80, and 100% MVC) MI conditions.

Similarly, Aoyama and Kaneko [34] reported that the amplitude of H-reflex during MI was similar between 50% MI and 100% MI condition. In actual motion, the spinal motor neuron excitability was increased linearly with the muscle contraction strength [27]. Described in the introduction, MI is the mental rehearsal of a movement without any overt movement [1]. One possibility is the contribution of neural mechanism which inhibits actual movement and muscle contraction during MI. Park and Li [35] reported that the amplitude of MEPs during MI of finger flexion and extension at 10, 20, 30, 40, 50, and 60% MVC was significantly greater than that at rest. However, the amplitude of MEPs during MI was similar among all six MI conditions. Further, in an event-related potential study, the magnitude of primary motor cortex activity during MI did not correlate with the imagined muscle contraction strength, although activities of the supplementary motor and premotor area during MI were strongly correlated with it [36]. The supplementary motor and premotor area have crucial roles in larger force generation [37], motor planning, preparation, and inhibition [38, 39]. Thus, the supplementary motor and premotor area may inhibit the actual muscle activity depending on the muscle contraction strength. Because these areas also are connected directly to primary motor cortex, inhibitory inputs from the supplementary motor and premotor area may suppress any additional excitation of primary motor cortex conferred by MI with high imagined contraction strength. Furthermore, the spinal motor neuron excitability during MI is thought to be affected by central nervous system via the corticospinal and/or extrapyramidal tract. The degree of the spinal motor neuron excitability during MI at various imagined muscle contraction strengths may be modulated by both excitatory and inhibitory inputs from the central nervous system.

2.4. Conclusion

Our previous woks showed significant increase of the spinal motor neuron excitability during MI of isometric thenar muscle activity. However, the imagined muscle contraction strength was not involved in change of the spinal motor neuron excitability.

3. The autonomic nervous system during MI of isometric thenar muscle activity

3.1. The autonomic nervous system during MI of isometric thenar muscle activity at 10 and 50% MVC

3.1.1. Purpose

We previously suggested that MI can facilitate the spinal motor neuron excitability. Sympathetic nerve activity was increased during actual isometric muscle contraction [41]. If MI shares common neural substrates with motor execution, it would be expected to observe the similar pattern in autonomic nervous system (ANS) activity during MI would be observed. In previous research, the heart rate during MI was significantly increased than that at rest [42]. Thus, MI can regulate sympathetic nerve activity without any overt movement. However, whether the imagined muscle contraction strength affects the ANS activity is still unclear.

Then, this research aimed to investigate the ANS activity during MI of isometric thenar activity at 10 and 50% MVC [40].

3.1.2. Materials

Nine healthy volunteers were participated in this research (7 males, 2 females; mean age = 25.3 ± 5.3 years). All participants provided informed consent before the study commenced. This research was approved by the Research Ethics Committee at Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

3.1.3. The ANS activity recording procedure

The ANS activity was recorded using a heart rhythm scanner PE (Biocom Technologies, USA). The pulse wave from the photoplethysmography sensor attached on earlobe was measured. The low frequency/high frequency (LF/HF) ratio was calculated by analyzing measured the pulse wave. The LF/HF ratio is considered to be an index of the sympathetic nerve activity.

3.1.4. Experimental protocol

For the rest trial (rest), the ANS activity was recorded during relaxation for 5 min. The European Society of Cardiology and the North American Society of Pacing and Electrophysiology recommend 5 min recordings for heart rate variability analysis [43]. Subsequently, for the motor task, participants learned the isometric thenar muscle activity at 50% MVC (i.e., participants press the sensor of pinch meter by left thumb and index finger at 50% MVC) for 1 min. They were instructed to keep the 50% MVC value (kgf) measured numerically on the display of pinch meter. For the MI trial, participants performed MI of isometric thenar muscle activity at 10% MVC for 5 min. The ANS activity was recorded during MI (10% MI) and immediately after 10% MI trial (post) for 5 min respectively. The above process was defined as the MI at 10% MVC condition (10% MI condition). The ANS activity recording under 50% MI condition was performed using the same protocol as 10% MI condition. These conditions were performed randomly on different days.

3.1.5. Statistical analysis

The normality of the ANS activity data was not confirmed by using the Kolmogorov-Smirnov and Shapiro-Wilk tests. We used a nonparametric method in this research. The LF/HF ratio among three trials (rest, MI, post) under two MI conditions (10% MI and 50% MI conditions) were compared using the Friedman test and Scheffe's post hoc test.

We also calculated the relative value obtained by dividing the LF/HF ratio during MI under four MI conditions by that at rest. The relative values among two MI conditions were compared using the Wilcoxon signed rank test. We used SPSS statistics ver. 19 (IBM Corp., USA) for statistical analysis. The threshold for statistical significance was set to $p = 0.05$.

3.1.6. Results

The LF/HF ratio during MI under two MI conditions was greater than that at rest (50% MI vs. Rest, $*p < 0.05$) (**Tables 9**, **10**). The LF/HF ratio immediately after MI under two MI conditions was reduced to rest level (**Tables 9**, **10**).

	Rest	10% MI	post
LF/HF ratio (%)	1.23 ± 0.75	2.73 ± 3.68	1.54 ± 0.52

Table 9. Changes in ANS activity under 10% MI condition.

	Rest	50% MI	post
LF/HF ratio (%)	1.74 ± 1.16	2.92 ± 2.17*	2.07 ± 1.42

*$p < 0.05$; significant difference between rest and 50% MI trial.

Table 10. Changes in ANS activity under 50% MI condition.

The relative values of the LF/HF ratio did not exhibit significant differences between two MI conditions (**Table 11**).

3.2. The autonomic nervous system during MI of isometric thenar muscle activity at 50 and 100% MVC

Firstly, about purpose, the ANS recording procedure, experimental protocol, and statistical analysis, please refer to our previous research [40].

3.2.1. Materials

Ten healthy volunteers were participated in this research (8 males, 2 females; mean age = 25.3 ± 5.3 years). All participants provided informed consent before the study commenced. This research was approved by the Research Ethics Committee at Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

3.2.2. Results

The LF/HF ratio during MI under two MI conditions was significantly greater than that at rest (50% MI vs. Rest, 100% MI vs. Rest, *$p < 0.05$) (**Tables 12**, **13**). The LF/HF ratio immediately after MI under two MI conditions was reduced to rest level (**Tables 12**, **13**).

The relative values of the LF/HF ratio did not exhibit significant differences between two MI conditions (**Table 14**).

3.3. Discussion

Our previous works demonstrated significant increase of the LF/HF ratio during MI at various imagined muscle contraction strengths (i.e., 10% MVC, 50% MVC, and 100% MVC) [40, 44]. Thus, MI of isometric thenar muscle activity can increase the sympathetic nerve activity as with previous researches [42]. The central command is defined as a feed-forward mechanism by which activation of cardiovascular and respiratory centers is accomplished by descending signals from central nervous system [45]. TMS delivered over the primary motor cortex

	50% MI condition	10% MI condition
Relative value of LF/HF ratio	2.64 ± 3.35	1.75 ± 1.14

Table 11. Comparison of ANS activity between 10% MI and 50% MI condition.

	Rest	50% MI	post
LF/HF ratio (%)	2.04 ± 1.44	3.40 ± 2.55*	2.33 ± 1.58

*$p < 0.05$; significant difference between rest and 50% MI trial.

Table 12. Changes in LF/HF ratio under 50% MI condition.

	rest	100% MI	post
LF/HF ratio (%)	1.86 ± 1.21	4.60 ± 5.48*	2.29 ± 1.12

*$p < 0.05$; significant difference between rest and 50% MI trial.

Table 13. Changes in LF/HF ratio under 100% MI condition.

	50% MI condition	100% MI condition
Relative value of LF/HF ratio	2.69 ± 3.32	2.14 ± 1.15

Table 14. Comparison of ANS activity between 50% MI and 100% MI condition.

increased the skin sympathetic nerve activity [46]. Furthermore, transcranial direct current stimulation (tDCS) delivered over the primary motor cortex increased the LF/HF ratio [47]. Thus, the corticospinal pathway including the primary motor cortex may affect the sympathetic nerve activity. The rostral ventromedial medulla is also part of the reticulospinal tract [48]. The activation of central nervous system during MI may increase the sympathetic nerve activity via the corticospinal and reticulospinal tracts.

The imagined muscle contraction did not affect the change of the sympathetic nerve activity. This is very similar with the result of the spinal motor neuron excitability during MI at various imagined muscle contraction strengths [24–26, 28]. If central command during MI affects the sympathetic nerve activity via the corticospinal pathway, the imagined muscle contraction strength may affect the sympathetic nerve activity. Park and Li [35] reported that the imagined muscle contraction strength did not affect the corticospinal excitability. Thus, it considered that the imagined muscle contraction strength might not be involved in change of the sympathetic nerve activity.

3.4. Conclusion

Our previous woks showed significant increase of the sympathetic nerve activity during MI of isometric thenar muscle activity. However, the imagined muscle contraction strength was not involved in change of the sympathetic nerve activity.

4. The application of MI to neurorehabilitation

30–60% of patients have difficulty in using their affected upper limb after stroke [49]. Nakayama et al. [50] reported that recovery of upper limb function related activity of daily living mainly took place within the first 2 months after stroke. Further they reported that 79% of patients with mild upper limb paresis could achieve full upper limb function, whereas, in case with severe upper limb paresis, only 18% of patients who could achieve full upper limb function.

Depending on alteration of peripheral and central inputs, cortical connections and responses are continuously reorganized [51]. Motor cortex excitability will be decreased in post-stroke due to the damage of neural substrates, loss of sensory inputs, and disuse of the affected limb [52]. Described in introduction of this chapter, various brain areas including primary motor cortex corresponding to motor planning, preparation and execution were activated during MI [9–13]. Pascual-Leon et al. [53] employed TMS in the healthy subjects to map the primary motor cortex targeting the contralateral hand muscles pre- and post-MI training. Cortical representation of hand muscles in contralateral the primary motor cortex increased after MI training. Similarly, MI induced an enhancement of hand muscle cortical representation in post-stroke [54]. Thus, MI can induce the cortical plasticity after neural damage. Additionally, Wrigley et al. [55] reported that the corticospinal excitability was decreased following the significant decline of both size and number of the corticospinal neurons. Also, the spinal motor neuron excitability was significantly reduced in the post-stroke acute phase [8]. Ruffino et al. [56] indicated that neural adaptation following MI training, such as cortical reorganization, the reinforcement of synapse conductivity, and the decline of pre-synaptic inhibition, would be occurred at cortical and spinal level. Thus, in post-stroke patients, facilitating the corticospinal excitability, including the spinal motor neuron excitability should be important for improvement motor function. MI can increase the corticospinal excitability [14–16]. Further, Grosprêtre et al. [57] reported that during MI, the amplitude of cervico-medullar-evoked potentials (CMEPs) can measure directly pyramido-motoneuronal junction was significantly increased. The H-reflex amplitude, however, was unchanged. Conversely, the H-reflex amplitude was increased during MI [29]. Further, we showed significant increase the F-wave during MI [24–26, 28]. In regard to difference between two techniques, the H-reflex size can be influenced by pre-synaptic interneuron, whereas the F-wave is solely dependent on the spinal motor neuron excitability [58]. Although effect of MI on the spinal motor neuron excitability is still under debate, MI can be considered to be an effective method for improvement upper limb function in post-stroke.

Brain-machine interface (BMI) is thought to be a potentially useful technology in neurorehabilitation. BMI can supplement for the lost motor function by bypassing disabled neuromuscular system, and improve brain plasticity and restoration of motor function by using external feedback [59, 60]. Various neurophysiological technologies, such as electroencephalography (EEG), magnetencephalography (MEG), and NIRS, have been used to measure and analyze brain activities. Among, the mu (μ) rhythm (ranged from 10-12 Hz) has been commonly used to monitor brain activities [61]. The event-related desynchronization (ERD) of the μ-rhythm was observed during MI. MI plays an important role in neurorehabilitation using EEG triggered-BMI. However, many people have difficulty in performing MI. Especially MI ability was significantly decreased in post-stroke patients [62]. They have no feedback about whether MI did perform correctly, because MI is a mental rehearsal of movement without any overt

motor outputs [1]. Thus, MI training should be needed with providing appropriate feedback. Actually, kinesthetic feedback provided better hand motor recovery in MI-based BCI combined with exoskeleton [63].

From the result of our previous works [24–26, 28], we propose the spinal motor neuron excitability may be one of useful index of MI training effect, because Takemi et al. [64] suggested that the degree of ERD was significantly correlated with the spinal motor neuron excitability. Actually, Hale et al. [33] reported that the spinal motor neuron excitability was more facilitated with each MI practice. Thus, the spinal motor neuron excitability during MI may be altered depending on MI learning status. However, Oishi et al. [19] also reported that the spinal motor neuron excitability was decreased during MI in athlete of speed skating. About alteration of the spinal motor neuron excitability during MI in various learning status, further research will be required.

Conflict of interest

None declared.

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