Chapter 3

The Effect of Motor Imagery on Spinal Motor Neuron Excitability and Its Clinical Use in Physical Therapy

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Additional information is available at the end of the chapter

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Abstract

We investigated the influence of the imagined muscle contraction strengths on spinal motor neuron excitability in healthy volunteers. F-wave was used for assessing spinal motor excitability. The F-waves during motor imagery (MI) under 10, 30, 50, 70, and 100% maximal voluntary contractions (MVCs) were compared. Furthermore, we investigated changes of the F-waves during motor imagery for 5 min. Motor imagery under 10, 30, 50, 70, and 100% maximal voluntary contractions can increase spinal motor neuron excitability. However, the imagined muscle contraction strengths were not involved in changes of spinal motor neuron excitability. Additionally, spinal motor neuron excitability after 5 min from onset of motor imagery returned to the rest level. Thus, in clinical use of motor imagery, slightly imagined muscle contraction strength is enough for facilitating spinal motor neuron excitability. Also, duration of motor imagery needs to be considered.

Keywords: motor imagery, F-wave, imagined muscle contraction strength, duration, physical therapy

1. Introduction

Motor imagery (MI) is defined as a cognitive process in which the subjects imagine that they perform movements without actually performing movements and muscle contractions [1].

MI has been shown to improve various motor functions in healthy subjects. Specifically, Yue and Cole [2] suggested that MI of little finger abduction under maximal voluntary contraction (MVC) for 4 weeks could increase muscle strength. Additionally, MI of ankle dorsiflexion under MVC for 4 weeks could increase muscle strength [3]. Also, Guillot et al. [4] suggested that muscle flexibility was improved after MI of stretching for 5 weeks. Furthermore, in clinical settings, MI can be applied in physical therapy for patients with damage to the central nervous system, such as stroke, Parkinson's disease, and spinal cord injury.

The effects of MI have been discussed in numerous neurophysiological studies. Various brain activities, including primary motor area, supplementary motor area, premotor area, somatosensory area, prefrontal cortex, parietal lobule, cingulate area, cerebellum, and basal ganglia, were activated during MI by using positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and near infrared spectroscopy (NIRS) [5–8]. These regions were also activated in motor execution. Thus, MI and motor execution are considered to share common neural networks. Furthermore, enhanced corticospinal excitability may explain the increase in motor evoked potentials (MEPs) amplitude by applying transcranial magnetic stimulation (TMS) over the primary motor area during MI [9]. These previous studies suggested that MI can facilitate the central nervous system.

However, other studies could not show the certain results in spinal motor neuron excitability during MI by using the F-wave, H-reflex, and T-reflex. The F-wave, H-reflex, and T-reflex are considered as indices of spinal motor neuron excitability. We previously studied spinal motor neuron excitability during MI of isometric thenar muscle activity. The persistence and F/M amplitude ratio during MI of thenar muscle activity under 50% MVC were significantly increased compared to that at rest [10]. Taniguchi et al. [11] reported that the F/M amplitude ratio after volitional relaxation for 3 h was significantly decreased. When subjects did volitional relaxation and MI of thumb abduction simultaneously, the F/M amplitude ratio was maintained at that before volitional relaxation level. This indicated that MI can increase spinal motor neuron excitability. Whereas Kasai et al. [9] reported that the H-reflex amplitude was not changed during MI of wrist flexion movement, Oishi et al. [12] reported that there are various results in the H-reflex amplitude during MI in speed skaters. Thus, it might be suggested that spinal motor neuron excitability was not always increased during MI, although MI can increase the central nervous system.

Our final goal is to find the way that MI obtained the most beneficial effect. To assess spinal motor neuron excitability is as important as the central nervous system, because we think that facilitation of spinal motor neuron excitability is required for improvement of motor function. Thus, in this chapter, we would like to introduce our previous work about spinal motor neuron excitability during MI under various MI conditions. First, we described spinal motor neuron excitability during MI under various imagined muscle contraction strengths. Next, we described the influence of duration of MI on spinal motor neuron excitability. Additionally, at the end of the chapter, we discuss how to apply MI to physical therapy.

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2. Spinal motor neuron excitability of MI under various imagined muscle contractions

2.1. Spinal motor neuron excitability of MI under 10, 30, 50, and 70% MVC

2.1.1. Purpose

We previously reported that spinal motor neuron excitability during MI of isometric thenar muscle activity under 50% MVC was significantly increased in comparison with that at rest [10]. In actual motion, Suzuki et al. [15] compared spinal motor neuron excitability during actual isometric thenar muscle activity under 25, 50, 75, and 100% MVC. The persistence and F/M amplitude ratio increased linearly with the muscle contraction strength. Spinal motor neuron excitability during MI increases linearly with the imagined muscle contraction strength if MI and motor execution share common neural networks. However, it was unclear whether the imagined muscle contraction strength affects the changes of spinal motor neuron excitability. Then, we investigated changes of spinal motor neuron excitability during MI of isometric thenar muscle activity under various imagined muscle contraction strengths. Specifically, we used 10, 30, 50, and 70% MVC for the imagined muscle contraction strength. In addition, we assessed spinal motor neuron excitability by using F-wave.

2.1.2. Materials

We included 10 healthy volunteers (5 males and 5 females; mean age, 28.7±4.5years. All subjects provided informed consent prior to the study's commencement. This study was approved by the Research Ethics Committee at Kansai University of Health Sciences. The experiments were conducted in accordance with the Declaration of Helsinki.

2.1.3. Methods

Subjects were in a supine position with muscles relaxed and instructed to fix one eye on a pinch meter monitor [digital indicator F304A (unipulse)] throughout the test (**Figure 1**). Abrasive gel was applied to keep the skin impedance below 5kΩ. The temperature was maintained at 25°C. A Viking Quest electromyography (EMG) machine (Natus Medical Inc., Pleasanton, USA) was used for F-wave recording (**Figure 1**). We recorded F-waves from the left thenar muscles after stimulating the left median nerve. A pair of disks was attached with collodion to the skin over the belly and the bones of the metacarpophalangeal joint of the thumb. The stimulating electrodes comprised the cathode placed over the left median nerve 3cm proximal to the palmar crease, and the anode was placed 2cm more proximally (**Figure 2**). The maximal stimulus was determined by delivering 0.2-ms square-wave pulses of increasing intensity to elicit the largest compound muscle action potential (M-wave). The supramaximal stimuli (adjusted up to 20% higher than the maximum stimulus intensity) were delivered at 0.5Hz. The bandwidth filter ranged from 2Hz to 3kHz.

We showed the typical F-wave forms from thenar muscle after applying 30 electrical stimuli on the median nerve (**Figure 3**).

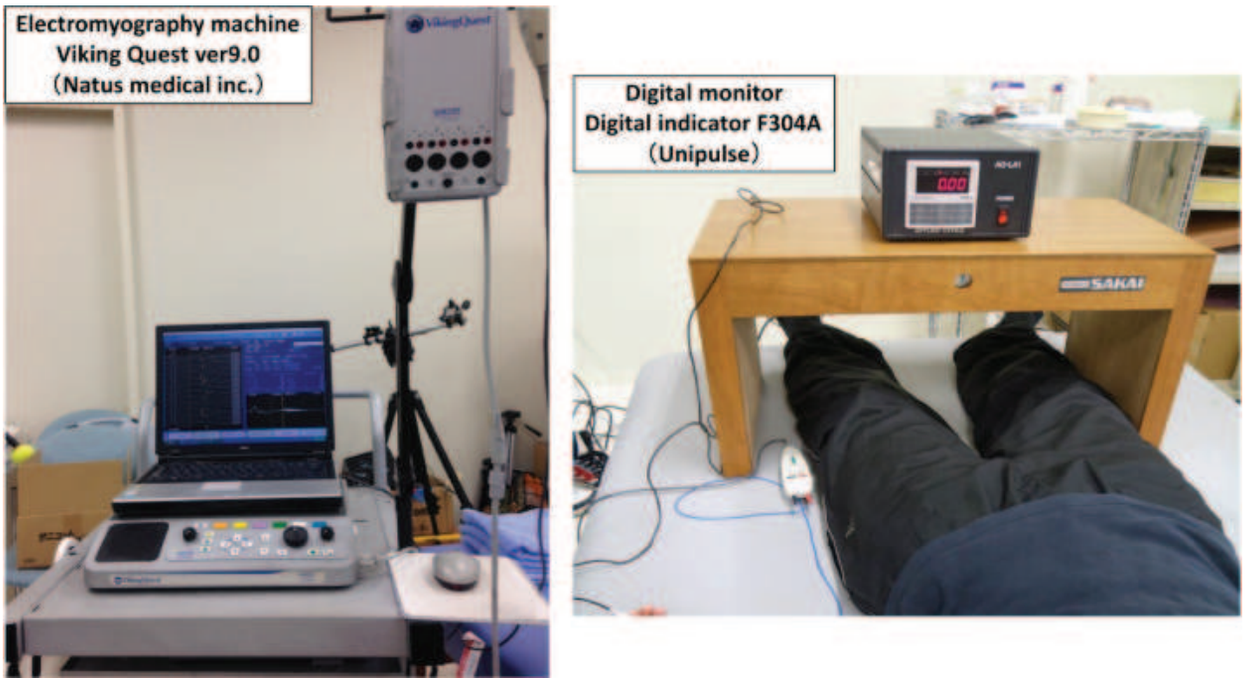

Figure 1. The F-wave recording instruments.

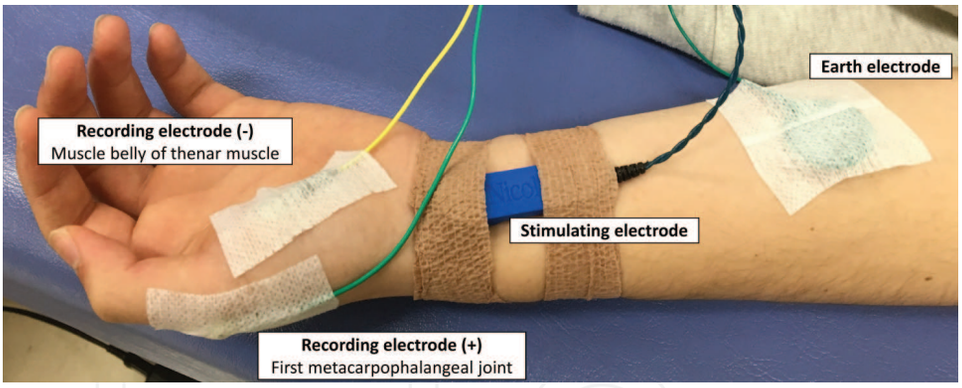

Figure 2. The F-wave recording condition.

In the resting trial (rest), the F-waves were recorded during relaxation. Next, we measured MVC by asking the subjects to apply maximum pressure to the pinch meter sensor between left thumb and index finger for 10 s. Subsequently, the subjects were required to learn isometric thenar muscle activity under 10% MVC for 1 min. The subjects were instructed to keep the 10% MVC value, which was displayed on the digital pinch meter monitor. For MI trial, the subjects were instructed to imagine 10% MVC thenar muscle activity while holding the sensor between their thumb and index finger without exerting any muscle contractions. F-waves were measured both during (10% MI) and immediately after 10% MI (post). The above process was defined as the MI using a 10% MVC condition (10% MI condition). This training process was repeated for MI of 30, 50, and 70% of MVC, and F-waves were recorded as described. Trials under these conditions were performed randomly on different days.

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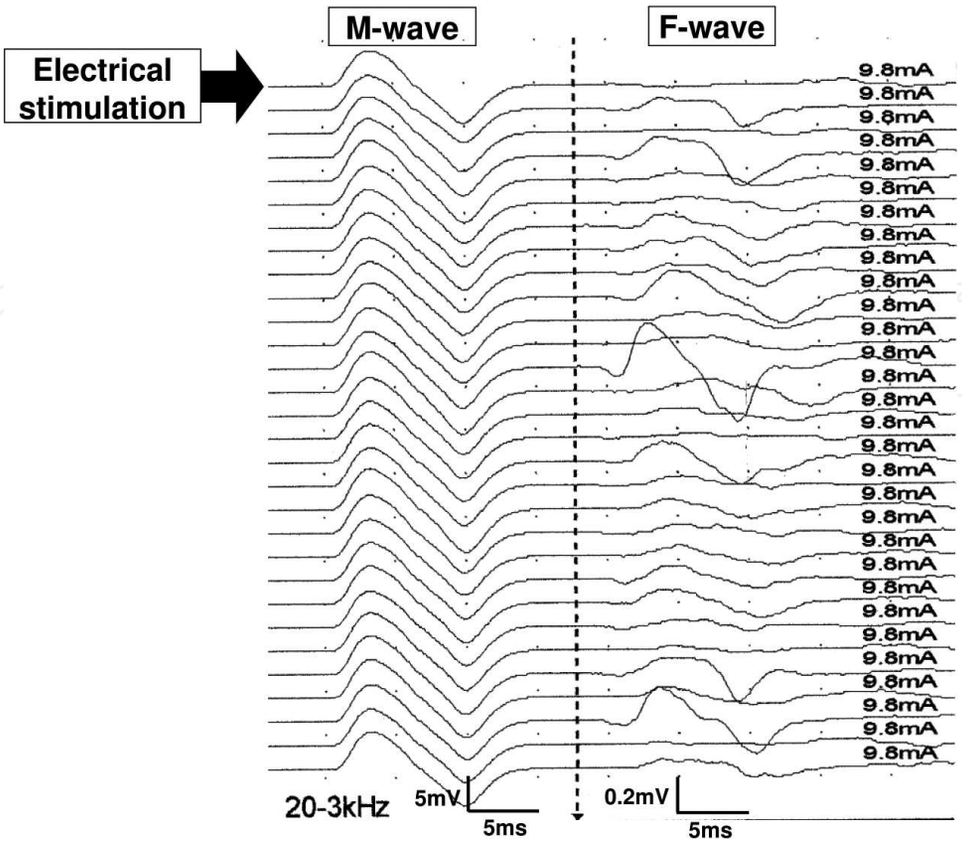

Figure 3. The typical F-wave forms.

2.1.4. Date analysis

The F-waves result from backfiring of spinal anterior horn neurons following distal antidromic electrical stimulation of α-motor neurons [16–18], in this case the median nerve. The F-waves from 30 stimuli were analyzed with respect to persistence, F/M amplitude ratio, and latency. Persistence was defined as the number of measurable F-wave responses divided by 30 supramaximal stimuli. The F/M amplitude ratio was defined as the mean amplitude of all responses divided by M-wave amplitude. Latency was defined as the mean latency from the time of stimulation to onset of measurable F-waves. Persistence reflects the number of backfiring anterior horn cells [17, 18]. The F/M amplitude ratio reflects the number of backfiring anterior horn cells and the excitability of individual cells [17, 18]. Therefore, these parameters are considered to be the indexes of spinal motor neuron excitability.

2.1.5. Statistical analysis

The normality of F-wave data was confirmed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. The persistence, F/M amplitude ratio, and latency among three trials (rest, MI, post) under each MI condition (10% MI, 30% MI, 50% MI, and 70% MI conditions) were compared using the Friedman test and Scheffe's post hoc test. The relative values among the four MI conditions were compared using the Friedman test. We used IBM SPSS statistics ver.19 for all statistical analysis.

2.1.6. Results

Persistence during MI under the four MI conditions was significantly increased compared to that at rest (Scheffe's test; 10% MI vs rest, 70% MI vs rest, $^{**}p<0.01$; 30% MI vs rest, 50% MI vs rest, $^{*}p<0.05$; **Figures 4**–**7**). Persistence immediately after MI was significantly decreased compared with that at MI (Scheffe's test; 10% MI vs post, 30% MI vs post, 70% MI vs post, $^{*}p<0.05$; **Figures 4**, **5**, and **7**). Persistence at post tended to be decreased compared with that at 50% MI (Scheffe's test; $p=0.067$; **Figure 6**).

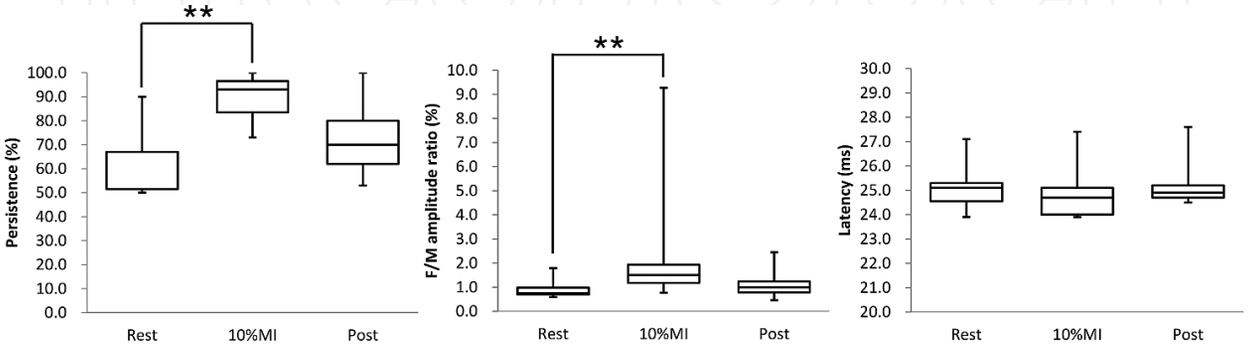

Figure 4. The F-waves at rest, MI, and post trials under the 10% MI condition.

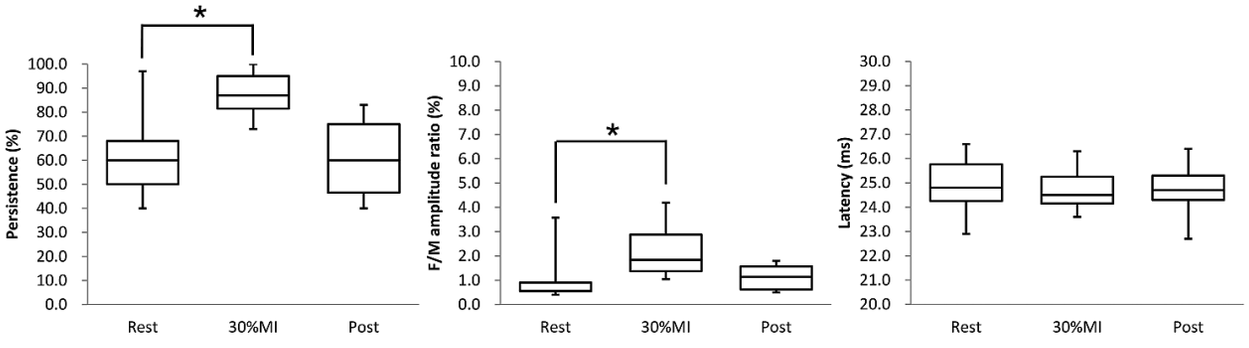

Figure 5. The F-waves at rest, MI, and post trials under the 30% MI condition.

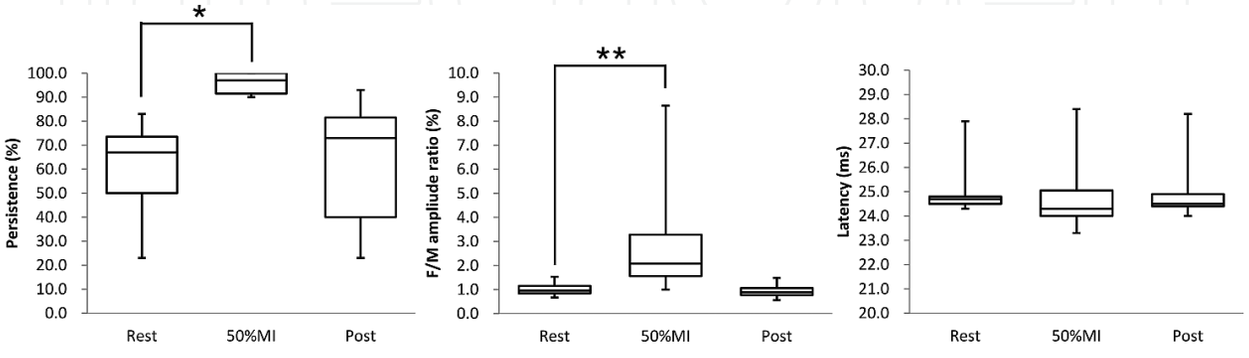

Figure 6. The F-waves at rest, MI, and post trials under 50% MI condition.

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The F/M amplitude ratio during MI under the three MI conditions was significantly increased compared to that at rest (Scheffe's test; 10% MI vs rest, 50% MI vs rest, $^{**}p<0.01$; 30% MI vs rest, $^{*}p<0.05$; **Figures 4–6**). The F/M amplitude ratio during 70% MI tended to be increased compared to that at rest (Scheffe's test; $p=0.082$; **Figure 7**). The F/M amplitude ratio immediately after 50% MI was significantly decreased compared to that at 50% MI (Scheffe's test; $^{*}p<0.05$; **Figure 6**).

Alternatively, no significant differences in latency were observed among three trials (rest, MI, and post) under the four MI conditions (**Figures 4–7**).

The relative values of persistence, F/M amplitude ratio, and latency did not exhibit significant differences among the four MI conditions (**Figures 8–10**).

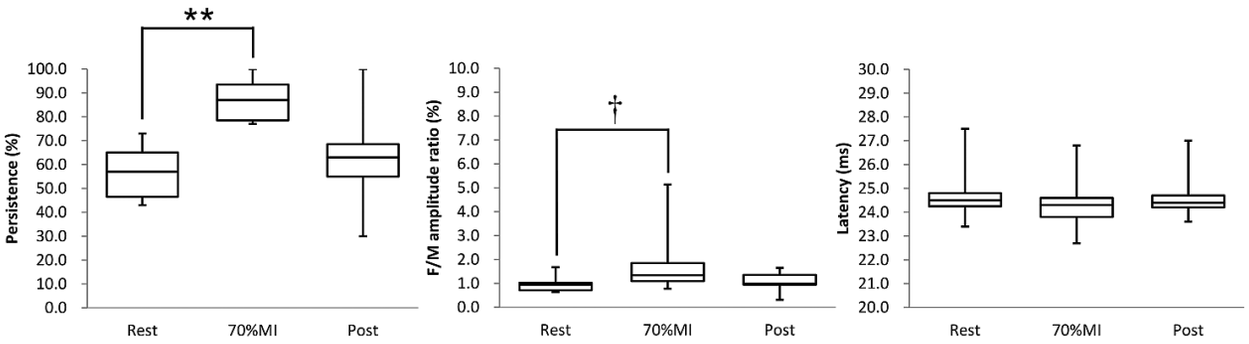

Figure 7. The F-waves at rest, MI, and post trials under 70% MI condition.

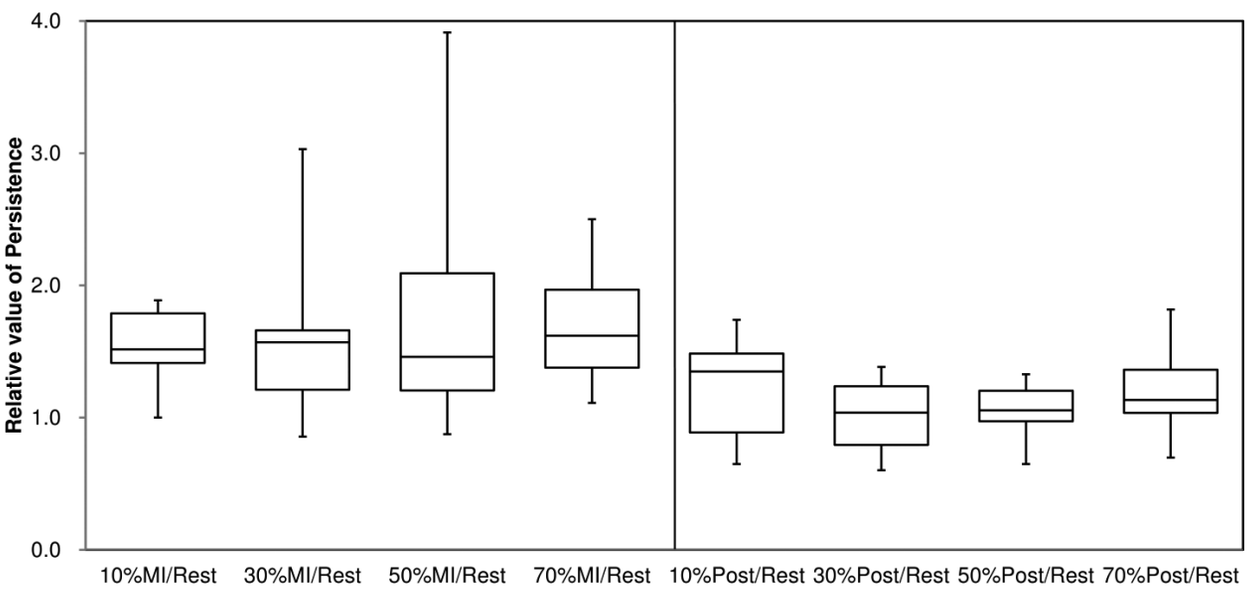

Figure 8. Comparison of relative values of persistence among the four MI conditions.

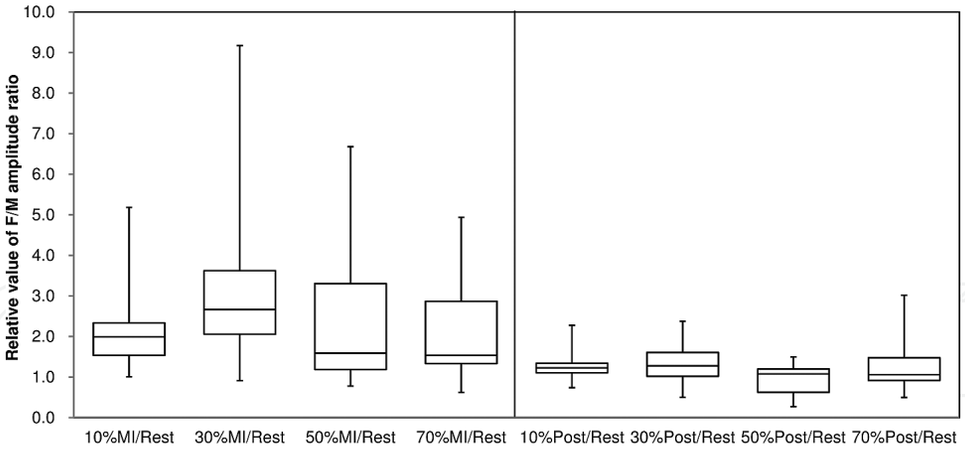

Figure 9. Comparison of relative values of F/M amplitude ratio among the four MI conditions.

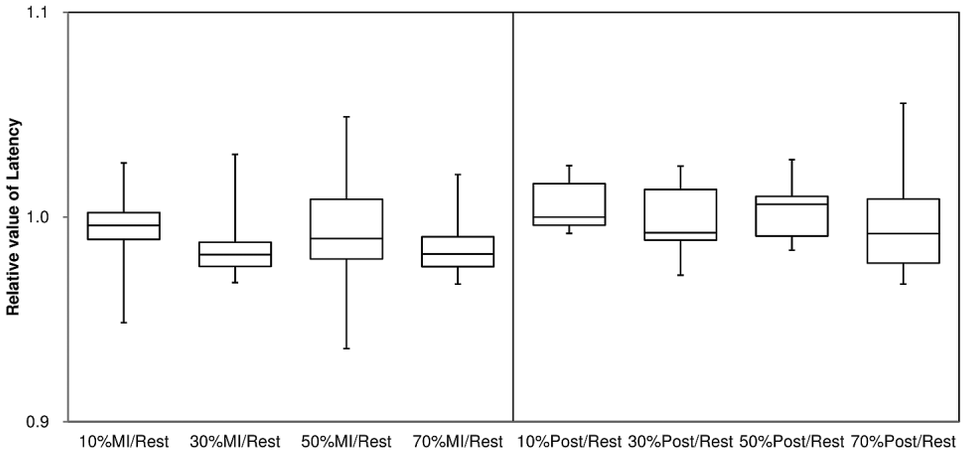

Figure 10. Comparison of relative values of latency among the four MI conditions.

2.2. Spinal motor neuron excitability during MI under 50 and 100% MVC

2.2.1. Purpose

In previous work, MI under 10, 30, 50, and 70% MVC was shown to increase spinal motor neuron excitability [13, 14]. The imagined muscle contraction strengths did not influence the facilitation amount of spinal motor neuron excitability [13, 14]. However, Cowley et al. [20] suggested that the H-reflex amplitude during MI of plantar flexion under 100% MVC was significantly higher than that under 50% MVC. Therefore, we hypothesized that the MI of thenar muscle activity under 100% MVC will be higher than that under 50% MVC. In this study, we investigated spinal motor neuron excitability during MI under 50 and 100% MVC.

2.2.2. Materials

We included 15 healthy subjects (13 males; 2 females; mean age, 25.3±5.04years). All subjects provided informed consent prior to the study's commencement. This study was approved by the Research Ethics Committee at Graduate School of Kansai University of Health Sciences. The experiments were conducted in accordance with the Declaration of Helsinki.

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2.2.3. Methods

The environment and conditions of the F-wave recording are the same as in previous work. The protocol of this study is as follows. In the resting trial (rest), the F-waves were recorded during relaxation. Next, we measured 100% MVC; that is, the subjects held the sensor of the pinch meter while exerting their maximum effort for 10 s. Subsequently, the subjects were instructed to learn the isometric thenar muscle activity under 100% MVC for 1 min as a motor task. They performed the activity using visual feedback while watching the digital monitor of the pinch meter. They were then instructed to perform MI of learned thenar muscle activity under 100% MVC by holding the sensor between the thumb and index finger. F-waves were recorded during the MI (100% MI). F-waves were recorded immediately after 100% MI trial (post). We defined the above process as the MI using the 100% MVC condition (100% MI condition). With regard to the MI using the 50% MVC condition (50% MI condition), F-waves were recorded using the same process. These conditions were randomly performed on different days.

2.2.4. Statistical analysis

For statistical analysis, the normality of F-wave data was confirmed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Persistence, F/M amplitude ratio, and latency among three trials (rest, MI, and post) under each MVC MI condition were compared using the Friedman test and Scheffe's post hoc test. We also evaluated the relative values obtained under the two MI conditions by dividing the values of persistence, F/M amplitude ratio, and latency at rest with those obtained during MI at post. The relative values between the two MI conditions were compared using the Wilcoxon signed rank test. The significance level was set at $p<0.05$. We used IBM SPSS statistics ver.19 for statistical analysis.

2.2.5. Results

Persistence during MI under the two MI conditions was significantly increased compared with that at rest (Scheffe's test; $^{**}p<0.01$; **Figures 11** and **12**). Persistence immediately after MI (at post) under the two MI conditions did not show significant differences compared with that at rest (**Figures 11** and **12**). No significant differences were observed between the relative values of persistence obtained under the two MI conditions (**Figure 13**).

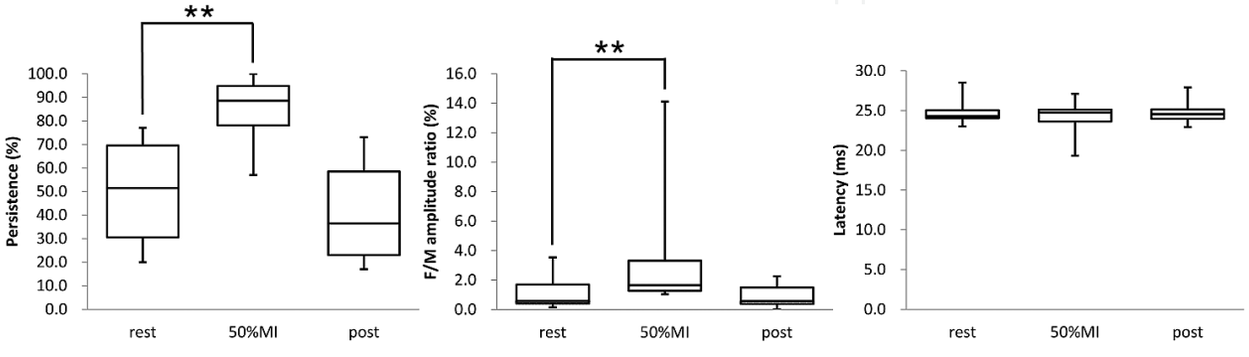

Figure 11. Changes in the F-wave under 50% MI condition.

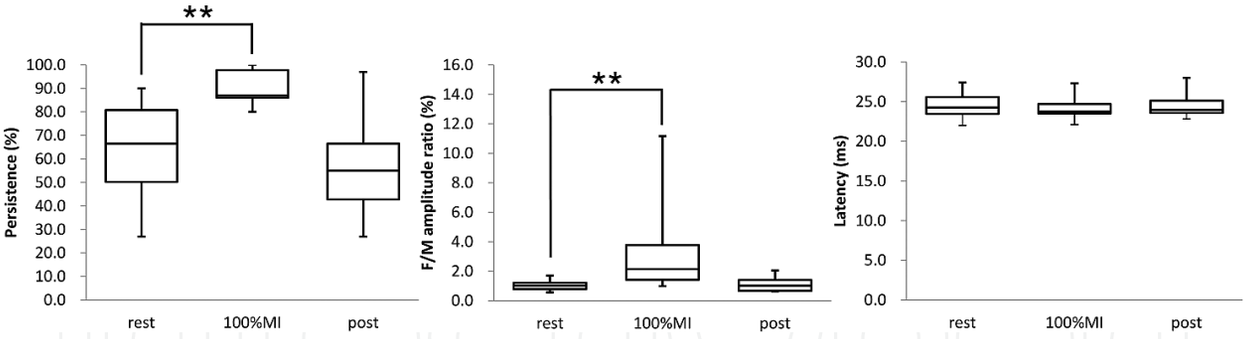

Figure 12. Changes in the F-wave under 100% MI condition.

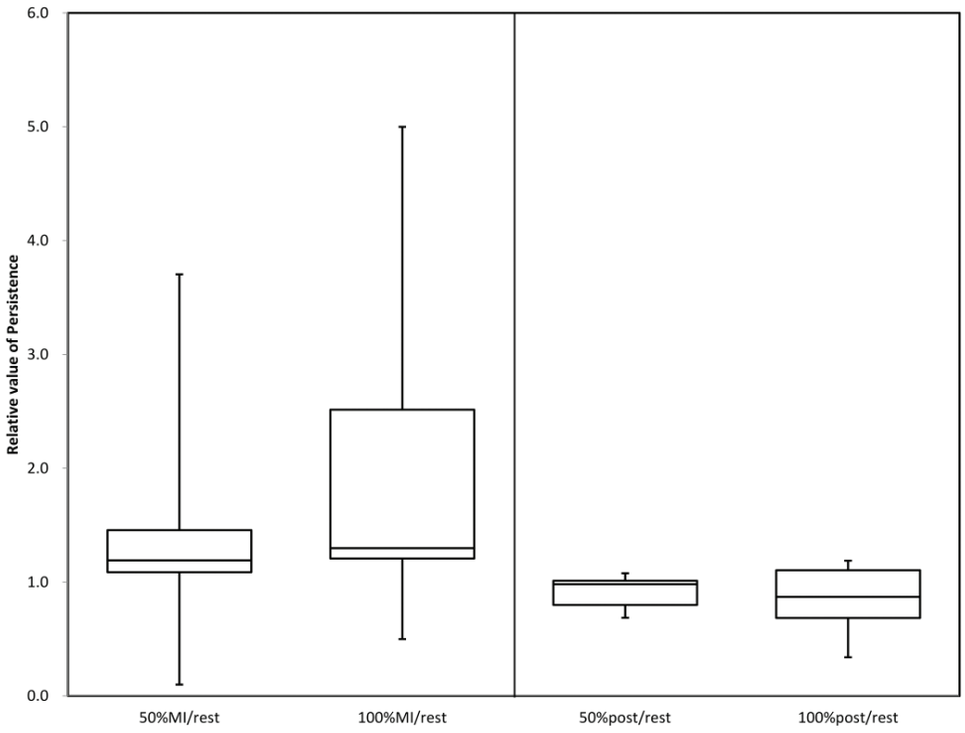

Figure 13. Comparison of relative values of persistence between 50 and 100% MI condition.

The F/M amplitude ratio during MI under the two MI conditions was significantly increased compared with that at rest (Scheffe's test; $^{**}p<0.01$; **Figures 11** and **12**). The F/M amplitude ratio immediately after MI (at post) under the two MI conditions did not show a significant difference compared with that at rest (**Figures 11** and **12**). No significant differences were observed between the relative values of F/M amplitude ratio obtained under the two MI conditions (**Figure 14**).

There were no significant differences in latency among three trials (rest, MI, post) under the two conditions (**Figures 11** and **12**). No significant differences were observed between the relative values of latency obtained under the two MI conditions (**Figure 15**).

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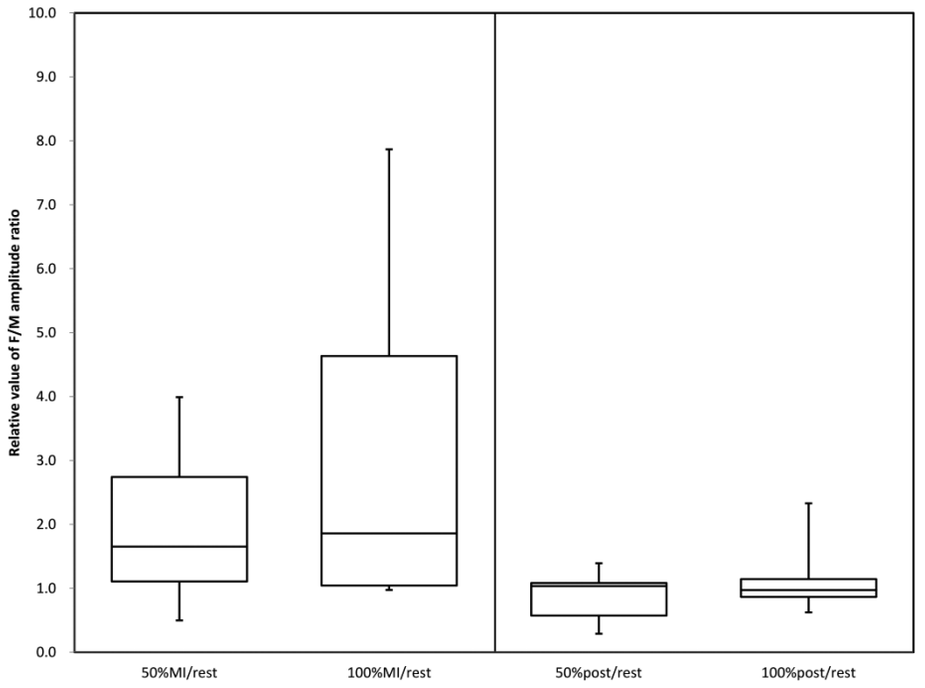

Figure 14. Comparison of relative values of F/M amplitude ratio between 50 and 100% MI condition.

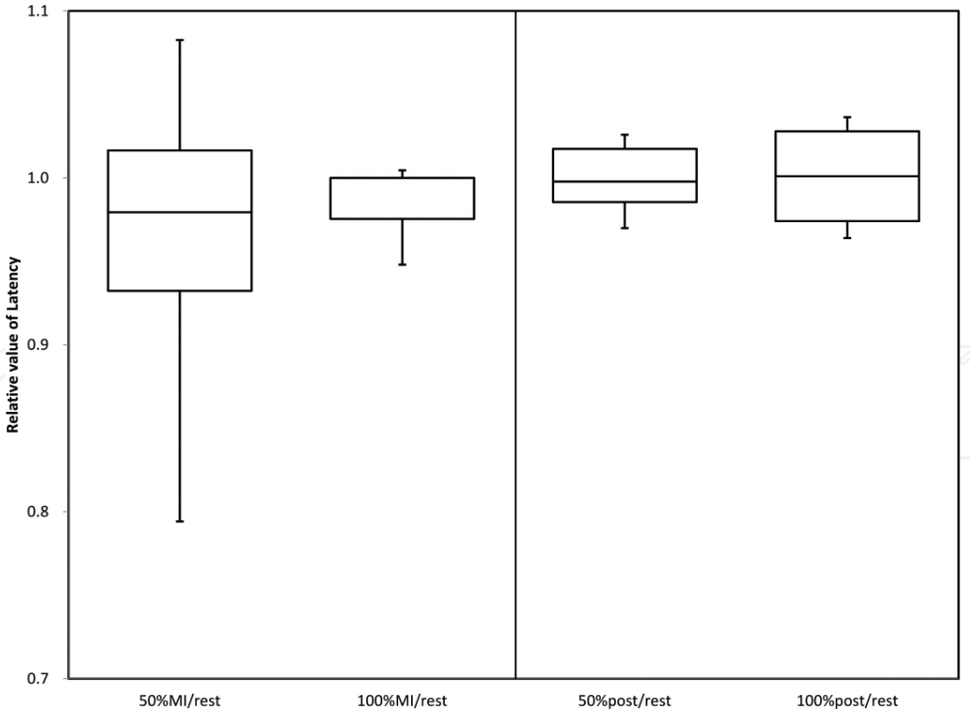

Figure 15. Comparison of relative values of latency between 50 and 100% MI condition.

2.3. Discussion

2.3.1. Spinal motor neuron excitability during MI of thenar muscle activity

Summarizing the previous work, MI of isometric thenar muscle activity under 10, 30, 50, 70, and 100% MVC can increase spinal motor neuron excitability. However, excitability does not vary with the imagined muscle contraction strengths.

Concerning the increase of spinal motor neuron excitability during MI, it was considered to influence the descending pathways corresponding to the thenar muscle. The previous studies have demonstrated that the activation of multiple cortical and subcortical regions contributes to motor preparation and planning during MI [5–8]. The activities of multiple brain regions as motor preparation and planning plausibly increased spinal motor neuron excitability via the corticospinal and/or extrapyramidal tract. Furthermore, MI is the mental rehearsal of a movement without any overt movement and muscle contraction [1]. Therefore, it is considered that motor inhibiting function was participated in simultaneously with motor preparation and planning. The supplementary motor area and premotor area are known to have functions of motor planning and inhibition in the GO/NO-GO task [21, 22]. Thus, spinal motor neuron excitability during MI may be generated by various functions (i.e., motor planning, preparation, and inhibition). In summary, it is plausible that the activation of multiple brain regions contributes to motor planning, preparation, and inhibition during MI increased spinal motor neuron excitability via the corticospinal and/or extrapyramidal tract.

Additionally, participants in all previous studies were instructed to perform MI while holding the sensor of a pinch meter. Therefore, the influence of haptic and proprioceptive perceptions during MI while holding the sensor on spinal motor neuron excitability should be considered. Mizuguchi et al. [23] reported that the MEP amplitude during MI was larger when a ball was squeezed than when no ball was held. Suzuki et al. [10] analyzed the changes in spinal motor neuron excitability between with and without holding the sensor MI tasks. The F-waves during MI while holding the sensor were greatly facilitated than without holding the sensor. The haptic and proprioceptive perceptions also contribute to the increase in spinal motor neuron excitability together with MI-activated pathways.

2.3.2. The changes of spinal motor neuron excitability during MI under different imagined muscle contraction strengths

Our previous results suggested that the facilitation amount of spinal motor neuron excitability during MI under various imagined muscle contraction strengths (i.e., 10, 30, 50, 70, and 100% MVC) was similar. There are several previous studies investigating the changes of spinal motor neuron excitability of MI under different imagined muscle contraction strengths. Hale et al. [24] reported that the soleus H-reflex amplitude was significantly increased during MI of ankle plantar flexion under 20, 40, 60, 80, and 100% MVC than that at rest. However, no significant differences were observed in changes of the soleus H-reflex amplitude among five MI conditions. Bonnet et al. [25] reported that the soleus H-reflex amplitude was significantly increased during MI of ankle plantar flexion under 2 and 10% than that at rest. Additionally, there were no significant differences in changes of the soleus H-reflex amplitude between 2

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and 10% MI condition. Similarly, Aoyama and Kaneko [26] reported that there were no differences in changes of the soleus H-reflex amplitude ratio between 50 and 100% MVC MI condition, although the H-reflex amplitude was increased during MI under two imagined muscle contraction strengths. In actual movement, spinal motor neuron excitability was increased linearly with muscle contraction strengths [15]. However, higher imagined muscle contraction strengths did not progressively enhance spinal motor neuron excitability. Concerning these results, also, one possibility is the contribution of a neural mechanism that inhibits actual movement and muscle contraction during MI. Park and Li [27] reported that the MEPs amplitude during MI of finger flexion or extension under 10, 20, 30, 40, 50, and 60% MVC was significantly higher than that at rest. However, there were no significant differences in changes of the MEPs amplitude among all MI conditions. Similarly, an event-related potential study found that the magnitude of primary motor cortex activity during MI did not correlate with the imagined contraction strengths but supplementary motor area and premotor area activities during MI did [28]. As mentioned above, supplementary motor area and premotor area have crucial roles in larger force generation [29], motor planning, preparation, and motor inhibition [21, 22]. Therefore, the supplementary motor area and premotor area may inhibit the actual muscle activity depending on the muscle contraction strength. These inputs from the supplementary motor area and premotor area may suppress any additional excitability conferred by MI with high imagined contraction strength. Furthermore, spinal motor neuron excitability during MI is thought to be affected by the central nervous system via the corticospinal and extrapyramidal tract. Thus, the degree of the changes of spinal motor neuron excitability during MI under different imagined muscle contraction strengths may be modulated by both excitatory and inhibitory inputs from the central nervous system.

MI ability is a factor that affects spinal motor neuron excitability. Lorey et al. [30] studied the relationship between activation of the cerebral cortex during MI and the vividness of MI by fMRI. The primary motor cortex, premotor area, primary somatosensory area, inferior parietal lobe and superior parietal lobe, putamen, and cerebellum showed activation during MI. In particular, activation of the premotor area, parietal lobule, and cerebellum was associated with increased vividness of MI, suggesting a correlation between the activation of the cerebral cortex and vividness of the MI. Therefore, MI ability may be a possible factor that affects spinal motor neuron excitability.

However, Bonnet et al. [25] reported that the T-reflex amplitude during MI under 10% MVC was significantly higher than that under 2% MVC. Additionally, Cowley et al. [20] reported that the soleus H-reflex amplitude ratio during MI under 100% MVC was significantly higher than that under 50% MVC. To clarify the reason why these results differed from our previous results, further research will be required.

2.4. Conclusion

We investigated spinal motor neuron excitability during MI of isometric thenar muscle activity under 10, 30, 50, 70, and 100% MVC [13, 14, 19]. As a result, MI of isometric thenar muscle activity can facilitate spinal motor neuron excitability. However, the imagined muscle contraction strengths were not involved in the changes of spinal motor neuron excitability.

3. Whether duration of MI affects spinal motor neuron excitability?

3.1. Purpose

Our previous work suggested that MI can increase spinal motor neuron excitability, and differences in the imagined muscle contraction strengths are not involved in changes of spinal motor neuron excitability. Therefore, the previous results implied that MI of isometric thenar muscle activity under slight MVC (i.e., 10% MVC) can substantially facilitate spinal motor neuron excitability. Described in the introduction, one of our final goals is to find the way that MI obtained the most beneficial effect. Hale et al. [24] suggested that spinal motor neuron excitability was gradually increased with the number of MI trials. Gentili et al. [31] proposed that a number of MI trials are necessary to improve motor performance. To obtain a more beneficial effect of MI, the number of MI practices is considered to be important. On the other hand, in the optimal duration of MI that can facilitate motor performance, the most is unclear. Previous research used various durations of MI session, which ranged from a few seconds to approximately 200 min (for review, see Driskell et al. [32]). A meta-analysis by Driskell et al. [32] suggested that a longer MI session does not always provide a beneficial effect on sports performance. Furthermore, they recommended approximately 20 min to achieve a more beneficial effect. Hinshaw [33] also suggested that MI for 10–15 min was considered to elicit the largest effect on performance, and Twining [34] indicated that 5 min is the temporal limitation when we can concentrate and perform MI. Alternatively, the influence of duration of MI on the changes of spinal motor neuron excitability is not apparent. In our previous work [10, 13, 14, 19], participants were asked to perform MI for 1 min. Thus, this research aimed to investigate the influence of MI for 5 min on spinal motor neuron excitability by analyzing F-waves.

3.2. Materials

We included 10 healthy volunteers (8 males; 2 females; mean age, 25.3 ± 5.0 years). All participants gave their written informed consent prior to the study's commencement. This study was approved by the Research Ethics Committee at Graduate School of Kansai University of Health Sciences. The experiment was conducted in accordance with the Declaration of Helsinki.

3.3. Methods

The environment and conditions of the F-wave recording are the same as those for previous work. The protocol of this study is as follows. For the resting trial (rest), the F-waves were recorded while the muscle was relaxed. For the MI trial, participants first learned how to perform isometric thenar muscle activity under 50% MVC as a motor task for 1 min. They were then instructed to imagine the isometric thenar muscle activity under 50% MVC by holding the sensor between the thumb and index finger for 5 min. The F-waves were recorded at 1, 3, and 5 min after the onset of motor imagery (1 min MI, 3 min MI, and 5 min MI, respectively). Immediately after MI, the F-waves were recorded (post).

3.4. Statistical analysis

For statistical analysis, first, the normality of F-wave data was confirmed using the Shapiro-Wilk tests. Persistence, F/M amplitude ratio, and latency among five trials (rest, 1 min MI, 3 min

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MI, 5min MI, and post, respectively) were compared using the Friedman test and Scheffe's post hoc test. The significance level was set at $p<0.05$. We used IBM SPSS statistics ver.19 for statistical analysis.

3.5. Results

Persistence at 1 and 5min MI was significantly greater than that at rest (Scheffe's test, $^{**}p<0.01$; **Figure 16**). Also, persistence at 3min MI was significantly greater than that at rest (Scheffe's test, $^{*}p<0.05$; **Figure 16**). Additionally, persistence at 1, 3, and 5min MI had similar results (**Figure 16**).

The F/M amplitude ratios at 1 and 3min MI were significantly greater than those at rest, at 1 min MI (Scheffe's test, $^{**}p<0.01$), and at 3min MI (Scheffe's test, $^{*}p<0.05$; **Figure 16**). However, the F/M amplitude ratio at 5min MI was similar compared with that at rest (**Figure 16**). Additionally, the F/M amplitude ratio at 5min MI was significantly smaller than that at 1 and 3min MI (Scheffe's test, $^{*}p<0.05$; **Figure 16**).

Immediately after MI, persistence and the F/M amplitude ratio recovered to the rest level (**Figure 16**).

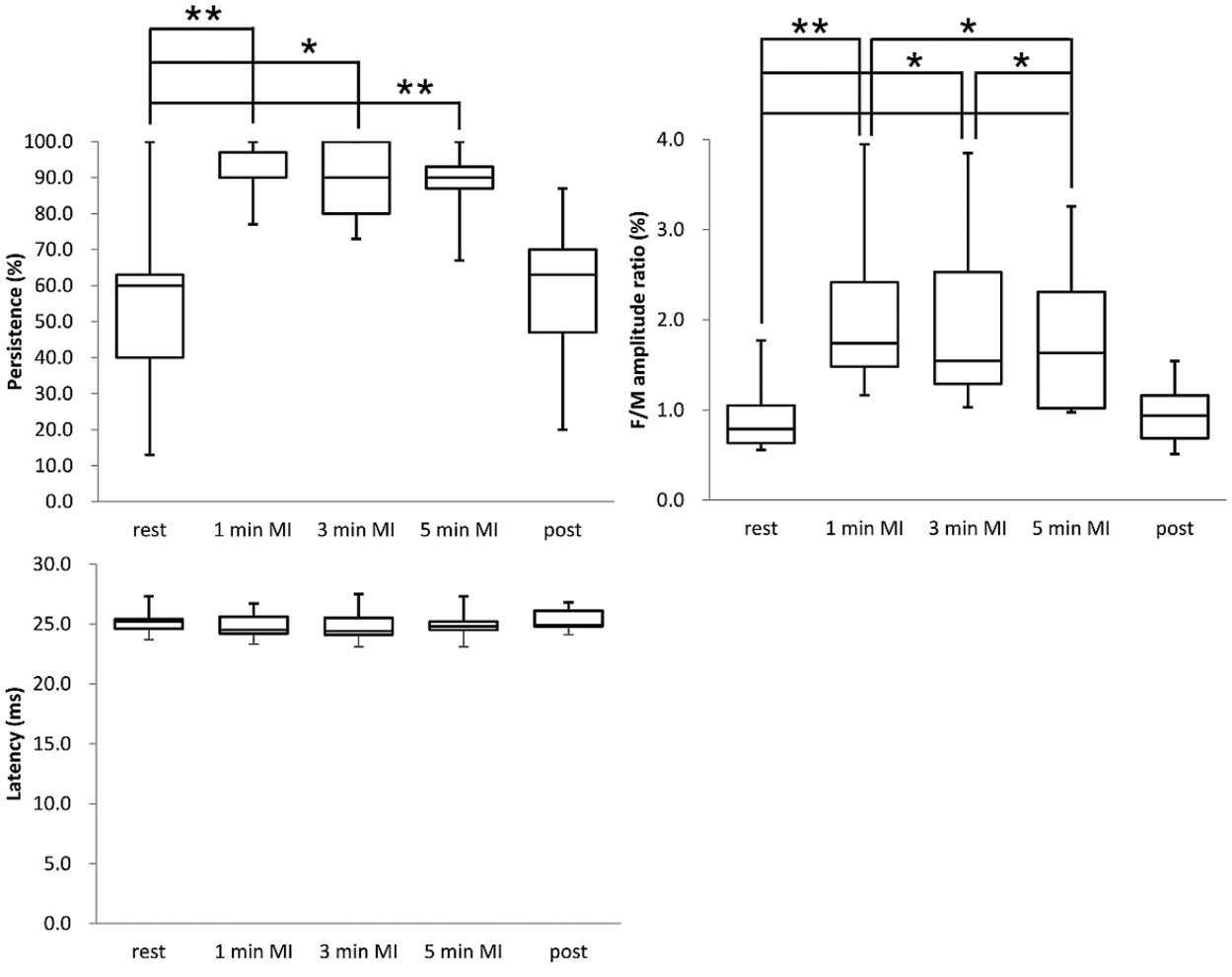

Figure 16. Changes of the F-waves during MI for 5min.

There were no significant differences in latency among all five trials (**Figure 16**).

3.6. Discussion

In our previous study, it is plausibly possible that participants did MI for 5min because the persistence and F/M amplitude ratio were increased compared with those at rest. Specifically, persistence during MI for 5min was kept significantly higher compared with that at rest. The F/M amplitude ratios at 1 and 3min MI were significantly higher compared with those at rest. However, the F/M amplitude ratio at 5min MI was significantly smaller compared with that at 1 and 3min MI. Therefore, the facilitation effect of spinal motor neuron excitability by MI may be decreased between 3 and 5min after the initial MI.

In regard to the F/M amplitude ratio at 5min MI being significantly decreased compared to that at 1 and 3min MI, there are several considerable factors. The first possible factor is the habituation of MI. MI is closely related to attentional processing [35]. Brain activation was decreased by habituation after the cognitive motor task required sustained attention (e.g., continuous performance test: CPT) for 10min. Furthermore, corticospinal excitability was diminished by habituation [36]. Also, at the spinal level, T-reflex amplitude was significantly decreased by habituation after sustained mental work load (e.g., a paced two-choice serial reaction task) for 20min [37]. Hence, it is considered that the further activation of the central nervous system and spinal level during MI might not be required by habituation.

The second possible factor is mental fatigue. Mental fatigue alters motor performance. Specifically, high-load mental cognitive tasks (e.g., incongruent Stroop task) for about 20min altered maximal force production of elbow flexor [38], and task-induced mental fatigue altered the speed accuracy of actual performance and MI [39]. Furthermore, repetitive MI led to participants having difficulties in maintaining focused attention on imagined movement. Repetitive MI of pointing tasks did significantly extend the duration of actual performance [40]. Also, in regard to influence of repetitive MI on the central nervous system excitability, repetitive MI of handgrip movements significantly decreased the MEPs amplitude compared with that at rest [41]. Considering the previous results, it is possible that mental fatigue evoked by sustained mental exertion induced significant reduction in the F/M amplitude ratio to the rest level.

In our previous study, despite reduction of the facilitation effect of the F/M amplitude ratio 5 min after MI, persistence during MI for 5min was kept at a higher level compared with that at rest. In previous research using electromyography (EMG), muscle fatigue reduced the maximal force production and mean power frequency, and it conversely increased the EMG amplitude [42]. Previous researchers interpreted these phenomena to additional recruitment of motor units, an increased firing rate, and synchronization of motor units' recruitment [43]. Furthermore, Levenez et al. [44] demonstrated that sustained dorsiflexion under 50% MVC induced decline of soleus H-reflex amplitude. Rossi et al. [45] demonstrated that sustained MVC of abductor digiti minimi induced decline of the F-wave amplitude, although the F-wave persistence was unchanged. Therefore, depression of the facilitation effect of the F/M amplitude after 5min from the onset of MI implicated decline of the individual anterior cell excitability. Further, regarding the result that persistence was kept at a higher level during MI for 5 min compared with that at rest, it is considered that there was additional recruitment and/or

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increasing firing rate of the anterior horn cells to compensate for the decrease of individual anterior horn cell excitability evoked by mental fatigue.

Finally, we considered the practice time and vividness of MI as a possible factor. Using MI in physical practice for learning motor skills, Twining [34] indicated that 5 min is the temporal limitation when we can concentrate and perform MI. In mental chronometry, the time required for actual performance and executing it mentally was similar [46]. In other words, it was difficult for participants to perform MI accurately for more than 1 min. In the present research, participants practiced isometric thenar muscle activity under 50% MVC as a motor task for only 1 min. Hence, practice time for 1 min might be insufficient to learn entirely the thenar muscle activity under 50% MVC. Indeed, introspective comments recorded from subjects after MI for 5 min indicated that they felt difficulty in performing MI vividly with time. From the viewpoint that the time required to execute and imagine the movement is similar [46], it may be necessary to match the time of task practice and MI. However, we did not study the time-dependent change of the vividness of MI precisely in the present research, and further research will be required.

3.7. Conclusion

We investigated the change of spinal motor neuron excitability during MI for 5 min. Persistence was significantly increased during MI for 5 min. However, the F/M amplitude ratio at 5 min returned to the rest level. As a result, MI for 5 min may affect spinal motor neuron excitability. Thus, the duration of MI needs to be considered.

4. The use of MI in clinical settings

From the results of our previous work [13, 14, 19], MI of isometric thenar muscle activity under 10, 30, 50, 70, and 100% MVC can facilitate spinal motor neuron excitability. Furthermore, the imagined muscle contraction strength is not involved in changes of spinal motor neuron excitability. In other words, MI under slight MVC (10% MVC) can sufficiently increase spinal motor neuron excitability. In the study about duration of MI, the F/M amplitude ratio returned to rest level between 3 and 5 min after initial MI. It is considered that the adequate duration of MI might be 1 or 3 min.

Finally, we discuss the application of MI to patients in clinical settings. Functional reorganization of the central nervous system may be elicited after brain and spinal cord injury. After brain and spinal cord injury, motor cortex excitability decreased due to various factors, including the damage of neural substrates, loss of sensory inputs, and disuse of the affected limb [47]. The corticospinal excitability would be decreased following the significant decrease of both size and number of the corticospinal neurons [48]. Therefore, we considered that facilitating the excitability of the central and spinal neural level could be necessary for improvement of motor function. MI can increase the MEPs amplitude in patients with post-stroke [49] and spinal cord injury [50], and the F-waves post-stroke [51]. From these previous results, we believe that MI is the effective method for improvement of motor function after damage to the central nervous system.

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