Chapter 5

Effectiveness of Motor Imagery on Physical Therapy: Neurophysiological Aspects of Motor Imagery

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Additional information is available at the end of the chapter

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Abstract

Immediate enrollment in physical therapy and facilitation of the spinal motor neuron excitability are very important. We previously suggested that the F-wave parameters were significantly increased during motor imagery. Thus, motor imagery is a beneficial method to facilitate the spinal motor neuron excitability for patients with various motor dysfunctions. We also indicated that the imagined muscle contraction strength may not affect the spinal motor neuron excitability. Additionally, kinesthetic imagery can more facilitate the spinal motor neuron excitability; however, longer duration of motor imagery may decrease the spinal motor neuron excitability. Thus, when applying motor imagery to physical therapy, slight imagined muscle contraction strength may be sufficient to facilitate the spinal motor neuron excitability, and the duration and strategy of imagery should be considered.

Keywords: motor imagery, F-wave, muscle contraction strength, duration, strategy

1. Introduction

Motor imagery (MI) is the mental representation of a movement in the absence of any actual overt movement. It is a cognitive process creating specific motor actions within the working memory [1]. MI may be a beneficial tool to improve various motor functions for patients with stroke-induced motor deficits [2–5]. Decline of motor evoked potential (MEP) amplitude, an index of corticospinal excitability obtained when transcranial magnetic stimulation is applied to the primary motor cortex, can be observed post-stroke [6]. Additionally, a significant reduction of spinal motor neuron excitability has been shown in the post-stroke acute phase [7]. Thus, corticospinal excitability, including that of spinal motor neurons, would be reduced

post-stroke. Corticospinal excitability is considered to be an index of functional motor recovery [8], and immediate enrollment in rehabilitation for stimulation of corticospinal and spinal motor neuron excitability may be important to achieve better outcomes.

Neuroimaging studies show that MI activates motor-related brain regions, including the primary motor cortex, supplementary motor area, premotor area, prefrontal cortex, somatosensory area, parietal lobe, cingulate gyrus, cerebellum, and basal ganglia [9, 10]. Similarly, these regions have been shown as activated during motor execution [9, 10]. Furthermore, the MEP amplitude was shown as significantly increased during MI [11–13]. Thus, MI may stimulate the central nervous system. Various patterns of spinal motor neuron excitability have been observed during MI [14–16]. The F-wave is one of the indices of spinal motor neuron excitability. It is a compound action potential resulting from re-excitation (backfiring) at spinal anterior horn cells by an antidromic impulse following the distal electrical stimulation of motor nerve fibers [17–19]. The F-wave amplitude increases when the corticospinal descending volley collides with the antidromic peripheral volley [20]. Additionally, the F-wave is a reliable index of spinal motor neuron excitability, even when motor output is extremely low, as is the case during MI [21].

As described previously in this chapter, stimulating spinal motor neuron excitability would improve motor function. Our final goal is to find the most beneficial approach by which MI can increase the spinal motor neuron excitability. In the following sections, we introduce our research on spinal motor neuron excitability under various MI conditions. At the end of the chapter, we discuss the application of MI to physical therapy from a neurophysiological perspective.

2. The spinal motor neuron excitability during MI under different imagined muscle contraction strengths

2.1. Purpose

We previously reported that the spinal motor neuron excitability increased significantly when participants performed MI of isometric thenar muscle activity under 50% maximal voluntary contraction (MVC) [22]. However, it was unclear whether the magnitude of the imagined muscle contraction strength affects the spinal motor neuron excitability. Therefore, we used F-wave measurements to investigate the spinal motor neuron excitability during MI of isometric thenar muscle activity under various imagined muscle contraction strengths. Specifically, we adopted the 10, 30, 50, 70, and 100% MVC for imagined muscle contraction strength [23–25].

2.2. Materials

We conducted two experiments to assess the spinal motor neuron excitability during MI under different imagined muscle contraction strengths. Firstly, we measured the F-wave during MI under 10, 30, 50, and 70% MVC for 10 healthy volunteers (5 males, 5 females; mean age = 28.7 ± 4.5 years). Secondly, we measured the F-wave during MI under 50 and 100% MVC for 15 healthy volunteers (13 males, 2 females; mean age = 25.3 ± 5.0 years). All participants provided informed consent before study commencement. 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.

2.3. Methods

A Viking Quest electromyography (EMG) machine ver. 9.0 (Natus Medical Inc., USA) was used for the F-wave recording. A pair of silver disc electrodes (10 mm diameter, Natus Medical Inc., USA) were placed over left thenar eminence and base of the first dorsal metacarpal bone. The skin was cleaned with an abrasive gel, and then impedance was maintained below 5 kΩ. The F-wave was evoked from the left thenar muscles by delivering supramaximal electrical stimuli, 0.2 ms in duration and 0.5 Hz in frequency, to the median nerve at the left wrist. Supramaximal stimuli were determined 20% higher than the maximal stimulus intensity required to elicit the largest compound muscle action potential (M-wave). The sensitivity for the F-wave was set at 200 μV/division and a sweep of 5 ms/division. The bandwidth filter range was 20 Hz–3 kHz.

Participants were placed in the supine posture on a bed and instructed to fix their eyes on the display of a pinch meter (Digital Indicator F304A, Unipulse Corp., Japan) throughout the F-wave recording. To determine the baseline of spinal motor neuron excitability, the F-wave was measured during relaxation for 1 min (rest). Thereafter, participants exerted isometric left thenar muscle contraction at 50% MVC (i.e., participants pressed the sensor of the pinch meter using their thumb and index finger at 50% MVC) for 1 min with visual feedback. For the MI trial, participants performed MI of isometric thenar muscle activity under 50% MVC for 1 min (50% MI). Immediately after the 50% MI trial, the F-wave was recorded during relaxation for 1 min (post). There were 30 supramaximal electrical stimuli delivered during each trial for the F-wave recording. The above process was defined as the MI at 50% MVC condition (50% MI condition). This protocol was repeated for conditions of 10, 30, 70, and 100% MI. Each condition was performed randomly on different days.

2.4. F-wave data analysis

All measured F-wave data were analyzed with respect to two parameters: persistence and the F/M amplitude ratio. The minimum F-wave peak-to-peak amplitude was 20 μV [26]. The persistence was represented as the percentage of detected F-wave responses out of 30 supramaximal electrical stimuli. It reflects the number of backfiring spinal anterior horn cells [17, 19]. The F/M amplitude ratio was obtained as the mean of the ratios of each detected F-wave response amplitude divided by the corresponding M-wave amplitude; it reflects the number of backfiring spinal anterior horn cells and individual spinal anterior horn cell excitability [19]. Therefore, the persistence and F/M amplitude ratio are considered indices of spinal motor neuron excitability.

2.5. Statistical analysis

2.5.1. The F-wave during MI under 10, 30, 50, and 70% MVC

Because the Shapiro-Wilk test did not confirm the normality of the F-wave data, a nonparametric method was used for statistical analysis. The persistence and F/M amplitude ratio among the three trials (rest, MI, and post) under each MI condition (10, 30, 50, and 70% MI) were compared using the Friedman test and Scheffe's post hoc test.

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

2.5.2. The F-wave during MI under 50 and 100% MVC

The persistence and F/M amplitude ratio among three trials (rest, MI, and post) under each MVC MI conditions were compared using the Friedman test and Scheffe's post hoc test. The relative values between the two MI conditions were compared using the Wilcoxon signed rank test.

2.6. Results

2.6.1. The F-wave during MI under 10, 30, 50, and 70% MVC

The persistence during MI under all MI conditions was significantly higher than that at rest (10% MI vs. rest and 70% MI vs. rest, $p < 0.01$; 30% MI vs. rest and 50% MI vs. rest, $p < 0.05$) (**Tables 1–4**). The F/M amplitude ratio during MI under 10, 30, and 50% MI conditions was significantly higher than that at rest (10% MI vs. rest and 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 the 70% MI condition tended to be more increased than that at rest ($p = 0.082$) (**Table 4**). The F/M amplitude ratio immediately after MI under all MI conditions was reduced to the rest level (**Tables 1–4**).

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

	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

Mean ± SD.

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

10% MI: Motor imagery of isometric opponens pollicis activity at 10% MVC

Table 1. The 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

Mean ± SD.

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

30% MI: Motor imagery of isometric opponens pollicis activity at 30% MVC

Table 2. The 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

Mean ± SD.
*p < 0.05; significant difference between rest and 50% MI trial.
**p < 0.01; significant difference between rest and 50% MI trial.
50% MI: Motor imagery of isometric opponens pollicis activity at 50% MVC

Table 3. The 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

Mean ± SD.
**p < 0.01; significant difference between rest and 70% MI trial.
70% MI: Motor imagery of isometric opponens pollicis activity at 70% MVC

Table 4. The F-wave under 70% MI condition.

	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 rati	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

Mean ± SD.
MI: Motor imagery

Table 5. Relative values of the F-wave under 10% MI, 30% MI, 50% MI, and 70% MI condition.

	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

Mean ± SD.
**p < 0.01; significant difference between rest and 50%MI trial.

Table 6. The F-wave under 50% MI condition.

2.6.2. The F-wave during MI under 50 and 100% MVC

The persistence during MI under the 50% MI and 100% MI conditions was significantly higher than that at rest (50% MI vs. rest and 100% MI vs. rest, $p < 0.01$; **Tables 6** and **7**), and the F/M amplitude ratio during MI under 50% and 100% MI conditions was significantly higher than

	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

Mean ± SD.

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

Table 7. The F-wave 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

Mean ± SD.

MI: Motor imagery

Table 8. Relative values of the F-wave under 50% MI and 100% MI condition.

that at rest (50% MI vs. rest and 100% MI vs. rest, $p < 0.01$; **Tables 6** and **7**). The F/M amplitude ratio immediately after MI (at post) under the 50% and 100% MI conditions did not show any significant differences compared with that at rest (**Tables 6** and **7**).

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

2.7. Discussion

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

Both the persistence and the F/M amplitude ratio were significantly increased during MI under 10, 30, 50, 70, and 100% MVC. Previous research has demonstrated that the activation of various brain regions contributes to motor preparation and planning during MI [9, 10]. Thus, it is considered that the activation of the central nervous system that contributes to motor preparation and planning during MI is responsible for the observed increase in spinal motor neuron excitability via the descending pathways, such as the corticospinal and extrapyramidal tracts.

Furthermore, all participants in our previous studies performed MI while holding the sensor of the pinch meter. Mizuguchi et al. [27] reported that while holding an object, the corticospinal excitability during MI was modulated by a combination of tactile and proprioceptive inputs. Thus, it is plausible that holding the pinch meter sensor during MI caused tactile and proprioceptive perceptions to cooperatively increase the spinal motor neuron excitability along with the MI-activated pathways.

2.7.2. The spinal motor neuron excitability during MI under different imagined muscle contraction strengths

Relative values of the persistence and F/M amplitude were similar among all MI conditions. This result indicated that the magnitude of imagined muscle contraction strength may not affect spinal motor neuron excitability. Bonnet et al. [28] reported that the H-reflex amplitude during MI was similar between 2 and 10% MI conditions. Hale et al. [29] also reported that the H-reflex amplitude 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 [30] reported that the H-reflex amplitude during MI was similar between 50 and 100% MI conditions. MI is the mental representation of a movement in the absence of any overt movement [1]. The neural mechanism that inhibits actual movement and muscle contraction during MI may be involved in this result. Park et al. [31] reported that the MEP amplitude during MI was similar among all six (i.e., 10, 20, 30, 40, 50, and 60% MVC) MI conditions. Furthermore, the magnitude of primary motor cortex activity during MI did not correlate with that of the imagined muscle contraction strength, although the activities of the supplementary motor and premotor area during MI were strongly correlated with it [32]. The supplementary motor and premotor areas play crucial roles in larger force generation [33], motor planning, preparation, and inhibition [34, 35]. Thus, these areas may inhibit the actual muscle contraction depending on the magnitude of the muscle contraction strength. These areas are also directly connected to the primary motor cortex, and inhibitory inputs from them may suppress additional primary motor cortex excitation conferred by MI with high imagined contraction strengths. Therefore, the degree of 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.

2.8. Conclusion

Our previous research has shown significant facilitation of the spinal motor neuron excitability during MI of isometric thenar muscle activity. The imagined muscle contraction strength may not be affected by the spinal motor neuron excitability. Thus, MI of isometric thenar muscle activity under slight MVC (i.e., 10% MVC) could substantially facilitate the spinal motor neuron excitability.

3. Does the duration of motor imagery affect the spinal motor neuron excitability?

3.1. Purpose

We previously reported that MI can increase the spinal motor neuron excitability and that the magnitude of imagined muscle contraction strength may not affect spinal motor neuron excitability [23–25]. In these studies, the duration of each MI session was 1 min. Driskell et al. [36] suggested that longer MI sessions do not always prove beneficial; they recommended a

duration of approximately 20 min for an MI training session. Another study suggested that MI for 10–15 min elicited the most significant effect on performance [37]. Moreover, Twinning et al. [38] suggested that 5 min is the temporal limit beyond which it is difficult to concentrate and perform MI. As described previously, stimulation of spinal motor neuron excitability may be important for post-stroke rehabilitation; however, time-dependent changes in spinal motor neuron excitability during MI have not yet been investigated. Additionally, MI ability has a significant effect on brain activation [39] and corticospinal excitability [40]. In this study, we used F-waves to investigate whether the duration of MI and MI ability affects the spinal motor neuron excitability [41].

3.2. Materials

Eleven healthy volunteers participated in this research (8 males, 3 females, mean age = 26.4 ± 6.0 years). All participants gave written informed consent before study commencement. The study was approved by the Research Ethics Committee at the Graduate School of Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

3.3. Methods

The environment and F-wave recording conditions were set as previously described [23–25]. For the rest trial (rest), the F-wave was measured during relaxation for 1 min. Subsequently, participants learned the isometric thenar muscle activity at 50% MVC for 1 min with visual feedback. For the MI trial, participants performed the MI of isometric thenar muscle activity under 50% MVC for 5 min. F-waves were measured at 1, 3, and 5 min after the beginning of MI (1-, 3-, and 5-min MI, respectively). Immediately after MI, the F-wave was measured again during relaxation (post). After F-wave recordings, participants were asked to evaluate their vividness of MI, how vividly they could imagine isometric thenar muscle activity at 50% MVC, at 1, 3, and 5-min using a seven-point Likert scale ranging from 1 (very difficult to perform MI vividly) to 7 (very easy to perform MI vividly).

Background electromyography (EMG) was recorded using telemetry EMG (MQ-8, Kissei Comtec Co., Ltd., Japan) and EMG recording software (Vital Recorder 2, Kissei Comtec Co., Ltd.). Surface EMG signals were recorded for 5 min from the left thenar muscles to confirm no muscle contractions during MI. A pair of disposable Ag/AgCl electrodes (Blue Sensor N-00-S, Ambu A/S, Denmark) were placed over the muscle surface with an inter-electrode distance of 20 mm. EMG signals were recorded at rest; at 1, 3, and 5 min of MI; and post-trial. The recorded EMG data were analyzed using a multi-purpose biological information analysis system (BIMUTAS-Video, Kissei Comtec Co., Ltd.) after analog to digital conversion at a sampling frequency of 1 kHz. The root mean square values of the EMG data in each trial were then calculated.

3.4. Statistical analysis

We used a nonparametric method because the normality of F-wave data was not confirmed using the Shapiro-Wilk test. The persistence and F/M amplitude ratio among five trials (rest, 1, 3, 5-min MI, and post, respectively) were compared using the Friedman test and Scheffe's post hoc test. The rating scores of MI vividness at 1, 3, and 5-min MI were compared using

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the Friedman test and Scheffe's post hoc test. The SPSS statistics ver. 19 (IBM Corp., USA) was used for statistical analysis. The threshold for statistical significance was set at $p = 0.05$.

3.5. Results

In **Figure 1** it is possible to verify that persistence and F/M amplitude ratio were significantly facilitated until 3 min from the beginning of MI task.

The score of MI vividness at 5-min MI was significantly decreased compared to 1-min MI (*$p < 0.05$; **Table 9**).

There were no significant differences in the RMS data among five trials, and thus there was no measurable muscle activity during MI for 5 min.

3.6. Discussion

Both persistence and F/M amplitude ratio were significantly higher until 3 min from the beginning of MI. This result may suggest that participants could perform MI for at least 3 min without much difficulty. However, there were no significant differences in persistence and F/M amplitude ratio between the at rest and 5-min MI conditions. Additionally, the F/M amplitude ratio for the 5-min MI conditions was significantly lower than that for 1- and 3-min conditions. These findings may be due to mental fatigue; in one study, mental fatigue was found to have altered the maximal force production of the elbow flexor [42]. It also made it difficult for participants to maintain their focus on imagined movement [43]. Furthermore, repetitive MI of a handgrip movement decreased the MEP amplitude more than that at rest [44]. Thus, mental fatigue caused by sustained mental activity may have induced a decline of the spinal motor neuron excitability.

Furthermore, a decline of spinal motor neuron excitability can be also explained by MI habituation. MI is closely related to attentional processing [45]. Brain activation decreases by habituation after performing a cognitive motor task for 10 min. Furthermore, the corticospinal excitability was also decreased by habituation [46]. Specifically, brain activity showed

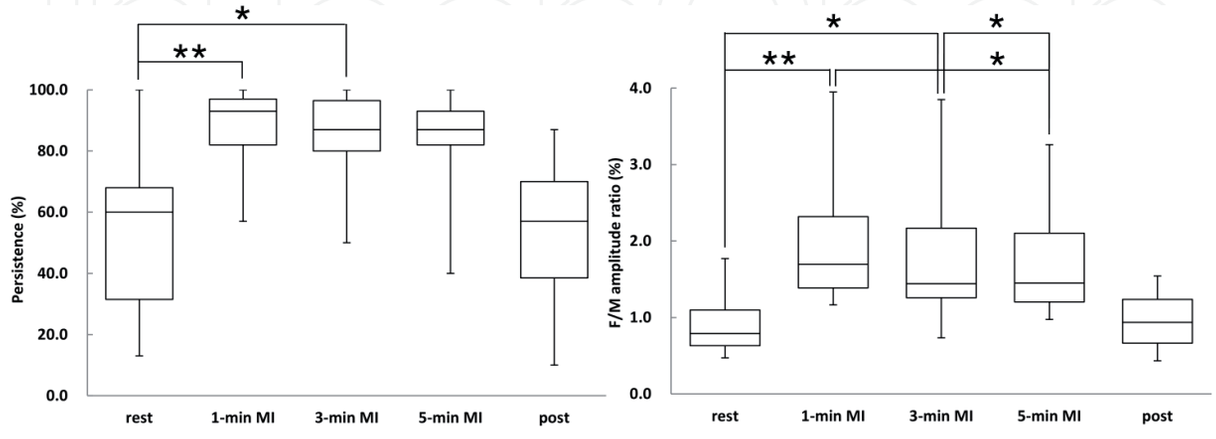

Figure 1. Changes in persistence and F/M amplitude ratio during MI for 5 min (*$p < 0.05$, **$p < 0.01$). The persistence at 1 and 3 min MI was significantly higher than that at rest. The F/M amplitude ratio at 1 and 3 min MI was significantly higher than that at rest. Additionally, the F/M amplitude ratio at 5 min MI was significantly smaller than that at 1 and 3 min MI.

	1-min MI	3-min MI	5-min MI
Rating score of MI vividness	5.71 ± 0.76	3.57 ± 0.53	2.29 ± 0.76*

Mean ± SD.
*$p < 0.05$; significant difference between 1-min and 5-min MI

Table 9. Rating scores of MI vividness at 1-min MI, 3-min MI, and 5-min MI.

an increase at 2 min before the onset of the task; however, after 4–6 min, activity decreased. Additionally, at the spinal level, the T-reflex amplitude, another index of the spinal motor neuron excitability, was significantly decreased due to habituation following sustained mental work for 20 min [47]. Our results also seemed to indicate that habituation to MI might occur approximately 4 min after its initiation and suggested that longer excitation times during MI might not be required for habituation of the central nervous system and spinal motor neurons.

Finally, practice time and MI ability were considered as possible factors affecting spinal motor neuron excitability. Regarding clinical use of MI for motor skill learning, Twining et al. [38] indicated that participants found it difficult to concentrate and perform MI for more than 5 min. Mental chronometry measured similar times for actual performance and MI [48]. Specifically, participants experienced difficulties in performing MI accurately beyond the practice time. In our study, the practice time for the motor task was only 1 min; thus, 1 min of practice time may be insufficient to continue performing MI for 5 min. Indeed, the vividness of MI tended to decrease with MI time. Furthermore, the vividness of MI at 5 min post MI initiation was significantly decreased relative to that at 1 min post MI initiation.

3.7. Conclusion

The persistence and F/M amplitudes at 1- and 3-min MI were significantly increased; however, the persistence and the F/M amplitude ratio at 5-min MI were reduced to rest levels. Thus, MI for 1–3 min may positively affect the spinal motor neuron excitability. In physical therapy, the duration of MI should be considered. As described in the Discussion section, matching the time of task practice to that of MI might be important. However, in this study, we did not investigate time-dependent changes of the spinal motor neuron excitability after motor learning for 5 min. Therefore, further research is required to resolve this issue. A limitation of this research is that differences in the brain activity during MI under 10, 30, 50, 70, and 100% MVC were not evaluated. Further study would be required to resolve this issue.

4. Imagery strategy affects the spinal motor neuron excitability: using kinesthetic and somatosensory imagery

4.1. Purpose

Previous research has demonstrated that MI increases the spinal motor neuron excitability and that the magnitude of imagined contraction strength may not affect it [23–25]. Additionally, the duration of MI should be considered in physical therapy [41].

MI includes various components of perception that can be associated with actual movement [49], which is why the effects of MI may differ depending on the choice of sensory modality. Here, we used F-wave and MI ability to investigate whether the choice of imagery strategy affects the spinal motor neuron excitability [50].

4.2. Materials

Fourteen healthy volunteers participated in this research (10 males, 4 females, mean age = 23.4 ± 4.8 years). All participants gave written informed consent before study commencement. The study was approved by the Research Ethics Committee at the Graduate School of Kansai University of Health Sciences. All recordings were conducted in accordance with the Declaration of Helsinki.

4.3. Methods

The environment and F-wave recording conditions were set as previously described [23–25, 41]. To determine the baseline of the spinal motor neuron excitability, the F-wave was measured during relaxation for 1 min (rest). Subsequently, participants exerted isometric left thenar muscle contraction at 50% MVC for 1 min with visual feedback. Simultaneously, participants were instructed to learn the two imagery strategies: somatosensory (tactile and pressure perception of thumb finger pulp during pressing of the sensor of the pinch meter) and kinesthetic (thenar muscle contraction during pressing of the sensor of the pinch meter at 50% MVC). After learning each imagery strategy, participants performed somatosensory imagery (SI), kinesthetic imagery (KI), and combined somatosensory and kinesthetic imagery (SKI) randomly for 1 min. In SKI trial, participants performed kinesthetic and somatosensory imagery simultaneously. After all the F-wave recording, participants were asked to evaluate difficulty of each imagery strategies by using a 5-point Likert scale, ranging from 1 (very hard to image vividly) to 5 (very easy to image vividly).

Background electromyography (EMG) was recorded during rest and three imagery trials.

4.4. Statistical analysis

We used a nonparametric method because the normality of F-wave data was not confirmed using the Shapiro-Wilk test. The persistence and F/M amplitude ratio among four trials (rest, SI, KI, and SKI, respectively) were compared using the Friedman test and Scheffe's post hoc test. The rating scores of each imagery strategies (SI, KI, and SKI, respectively) were compared using the Friedman test and Scheffe's post hoc test. The background EMG data were compared using the Friedman test. The SPSS statistics ver. 19 (IBM Corp., USA) was used for statistical analysis. The threshold for statistical significance was set at $p = 0.05$.

4.5. Results

The persistence during SI and KI were significantly higher than that at rest (**$p < 0.01$; **Figure 2**). The persistence during SKI was tended to be increased than that at rest ($p = 0.097$; **Figure 2**). The F/M amplitude ratio during KI was significantly higher than that at rest (*$p < 0.05$; **Figure 2**).

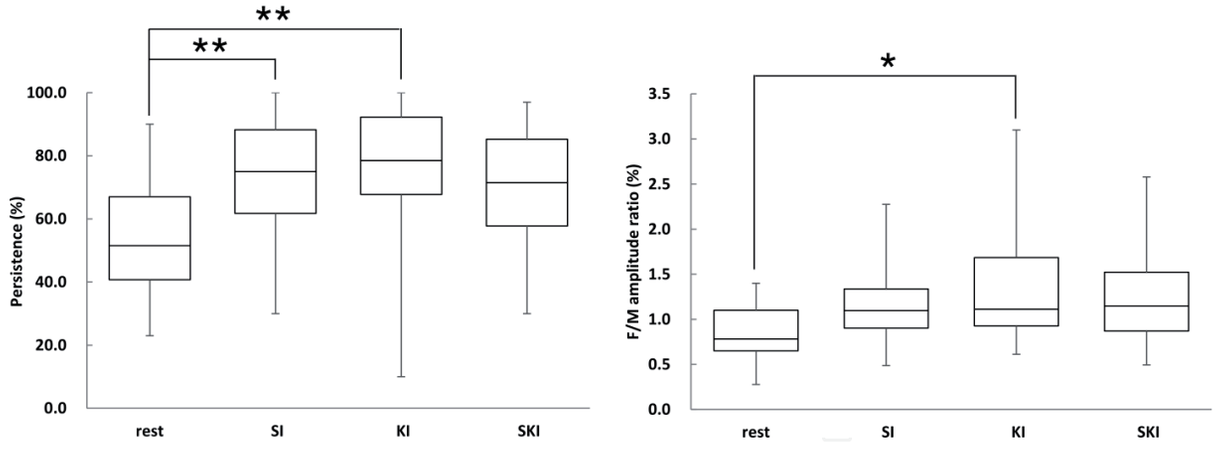

Figure 2. Changes in persistence and F/M amplitude ratio during SI, KI, and SKI (*p < 0.05, **p < 0.01). The persistence during SI and KI was significantly higher than that at rest. The persistence during SKI was tended to be increased than that at rest. The F/M amplitude ratio during KI was significantly higher than that at rest.

	SI	KI	SKI
Rating score of MI vividness	3.64 ± 0.63	3.86 ± 0.95	3.21 ± 0.89*
Mean ± SD.			
*p < 0.05; significant difference between KI and SKI trial			
SI, somatosensory imagery; KI, kinesthetic imagery; SKI, combined somatosensory and kinesthetic imagery			

Table 10. Rating scores of MI vividness during SI, KI, and SKI.

The rating score of SKI vividness was significantly lower than that at rest (*p < 0.05; **Table 10**).

There were no significant differences in the background EMG data among four trials (rest, SI, KI and SKI, respectively), and thus there was no measurable muscle contraction during three imagery trials.

4.6. Discussion

Both persistence and F/M amplitude ratio were significantly higher than the corresponding at-rest values. Previous neurophysiological studies reported that various regions of the brain related to motor functions were activated [9, 10] and that the MEP amplitude was significantly increased during KI [11, 13]. Thus, it seems that the central nervous system can better stimulate spinal motor neuron excitability via the descending pathways.

The persistence during SI was significantly higher than that at rest. This result was unexpected. We previously hypothesized that the spinal motor neuron excitability would remain unchanged because there are no motor-related factors in SI. Furthermore, there are no previous reports of tactile and proprioceptive perception SI increasing the corticospinal excitability including that of the primary motor cortex. Thus, it may be difficult to increase the spinal motor neuron excitability by SI. However, it is possible for SI to include kinesthetic

components. Participants in this research were asked to imagine tactile and pressure perception while holding the pinch meter sensor between their thumb and index finger. Thus, they might have unintentionally imagined tactile and pressure perception along with thenar muscle activity.

The persistence during SKI tended to be increased as compared to that at rest. The rating score of SKI vividness was the lowest among the three imagery strategies. These results indicate that participants may not be able to perform SKI as vividly as the other two strategies. In this study, participants were required to pay attention to kinesthetic and somatosensory perceptions simultaneously. The decline in the amount of attention that can be allocated to each imagery strategy may have made it difficult for the participants to perform SKI vividly. Indeed, there was a positive correlation between the corticospinal excitability and MI vividness [40].

4.7. Conclusion

From the result of this research, KI may be a more effective imagery strategy, which can increase the spinal motor neuron excitability. Thus, the imagery strategy should be considered in physical therapy. Also, the spinal motor neuron excitability during SI was significantly increased. However, the mechanism that SI increases spinal motor neuron excitability is unclear. As a limitation of this research, we did not investigate brain activity during SI. Further research will be required to resolve this limitation.

5. How to use MI in physical therapy?

Our research indicates that MI of the isometric thenar muscle activity can increase spinal motor neuron excitability [22–25, 41, 50]. After a stroke or a spinal cord injury, the excitability of the central nervous system decreases due to various factors, including the damage of neural substrates, loss of sensory inputs, and disuse of affected limbs [51]. Additionally, corticospinal excitability decreases following a decline in the size and number of corticospinal neurons [52]. Furthermore, decline of spinal motor neuron excitability was shown in the post-stroke acute phase [7, 53]. Thus, it may be important to stimulate corticospinal excitability, including that of the spinal motor neurons, as soon as possible. Patients in an early postoperative and post-stroke stage have difficulties in performing physical activities. However, considering the characteristics of MI, it can be a beneficial method to stimulate spinal motor neuron excitability without any overt movement and muscle contraction.

Furthermore, MI can improve not only the spinal motor neuron excitability but also various motor functions. Yue et al. [54] indicated that MI under 100% MVC for 4 weeks can increase the muscle strength of little finger abduction. Additionally, Sidaway et al. [55] indicated that MI under 100% MVC for 4 weeks can increase muscle strength of ankle dorsiflexion. About these results, Grosprêtre et al. [56] considered that MI may strengthen brain-to-muscle communication, including the enhanced recruitment of spinal motor neurons and involvement of the descending command. Although other groups [54, 55] adopted maximal imagined muscle contraction strengths for MI training, our results [23–25] revealed that the magnitude

of imagined muscle contraction strength did not affect spinal motor neuron excitability. Thus, low (i.e., 10% MVC) imagined muscle contraction strengths might be sufficient for stimulation of spinal motor neuron excitability and muscle strength. Our research [25, 41, 50] also revealed that kinesthetic imagery can better stimulate spinal motor neuron excitability and that spinal motor neuron excitability remained higher than the at-rest value until 3 min after MI initiation. Therefore, to increase the effects of MI, kinesthetic perception should be chosen as the imagery strategy. Additionally, the duration of each MI session should be less than 3 min.

In conclusion, MI can increase the spinal motor neuron excitability, and its effect would be changed depending on the duration and strategy of imagery. Thus, the duration and strategy of imagery should be considered in clinical settings.

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Conflict of interest

There is no conflict of interest.

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