We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK CITATION INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Motor Imagery for Neurorehabilitation: The F-Wave Study

Yoshibumi Bunno

Abstract

The immediate enrollment in rehabilitation program and facilitation of the excitability of spinal motor neurons are very important for post-stroke patients. We previously suggested that persistence and the F/M amplitude ratio, indicator of the excitability of spinal motor neurons, were significantly increased during MI. Thus, MI has a greater effect on the excitability of spinal motor neurons. We also indicated that the imagined muscle contraction strength may not affect the excitability of spinal motor neurons. Further, kinesthetic imagery can more facilitate the excitability of spinal motor neurons. However, longer duration of MI may not affect the excitability of spinal motor neurons. Therefore, slight imagined muscle contraction strength may be sufficient to facilitate the excitability of spinal motor neurons, and duration and strategy of imagery should be considered in neurorehabilitation.

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

1. Introduction

The excitability of the motor cortex is decreased after stroke along with damage to neural substrates, loss of sensory inputs, and disuse of the affected limb [1]. Further, the amplitude of motor evoked potentials (MEPs), obtained when transcranial magnetic stimulation (TMS) is applied over the primary motor cortex, is decreased [2]. At the spinal level, the excitability of spinal motor neurons is decreased in post-stroke patients during the acute phase [3, 4]. The excitability of central and spinal neural function is decreased after stroke. The highest level of functional recovery due to neuroplasticity, cortical reorganization, and regeneration occurs at about 4 weeks after stroke, and recovery reaches plateau within 3 months [5, 6]. Therefore, in post-stroke patients, the immediate enrollment in rehabilitation programs aiming to facilitate the corticospinal excitability, including the excitability of spinal motor neurons, should be important. Indeed, the early initiation of rehabilitation programs can facilitate the recovery of motor function [6–8].

Motor imagery (MI) is a cognitive process creating specific motor actions within working memory without an actual movement [9]. MI allows patients who cannot volitionally perform movements, such as stroke, to mentally practice a motor task. Numerous neurophysiological studies have discussed the effect of MI on the central nervous system by using positron emission tomography, functional magnetic resonance imaging, and near-infrared spectroscopy [10–13]. The primary motor cortex,

premotor area, supplementary motor area, prefrontal cortex, parietal lobule, cingulate area, cerebellum, and basal ganglia were activated during MI [10–13]. These brain areas were also activated during motor execution (ME), and thus the MI and ME have a common neural network. Further, the MEP amplitude was significantly increased during MI [2, 14, 15]. Therefore, MI can facilitate the excitability of the central nervous system.

However, the influence of MI on the excitability of spinal motor neurons is still unclear. A significant increase of the spinal motor neuron excitability was observed during MI [16, 17]. Our previous study also demonstrated a significant increase of the spinal motor neurons during MI of isometric thenar muscle activity at 50% maximal voluntary contraction (MVC) [18]. Conversely, previous studies demonstrated that excitability of spinal motor neurons is not changed during MI [14, 19, 20]. Additionally, Oishi et al. [21] identified three changing patterns (i.e., facilitation, suppression, and no change) in the excitability of spinal motor neurons during MI. These results of previous studies indicated that MI has various effects on the spinal motor neuron excitability. MI includes various components of perception, such as visual, auditory, kinesthetic, proprioceptive, and vestibular. Further, MI incorporates the spatial (e.g., direction and amplitude), temporal (e.g., synchronization and continuously), and dynamic (e.g., muscle tension) information relevant to the motor task. Therefore, the excitability of spinal motor neurons during MI may be different depending on what modality of MI will be chosen. Then, we investigated the excitability of spinal motor neurons during MI under various conditions, specifically imagined muscle contraction strength, duration, and sensory modality. One of the final goals of our group is to find the best conditions for MI to achieve the optimum outcome during the rehabilitation program. In the following sections, we introduce our previous researches and suggest the application of MI to rehabilitation.
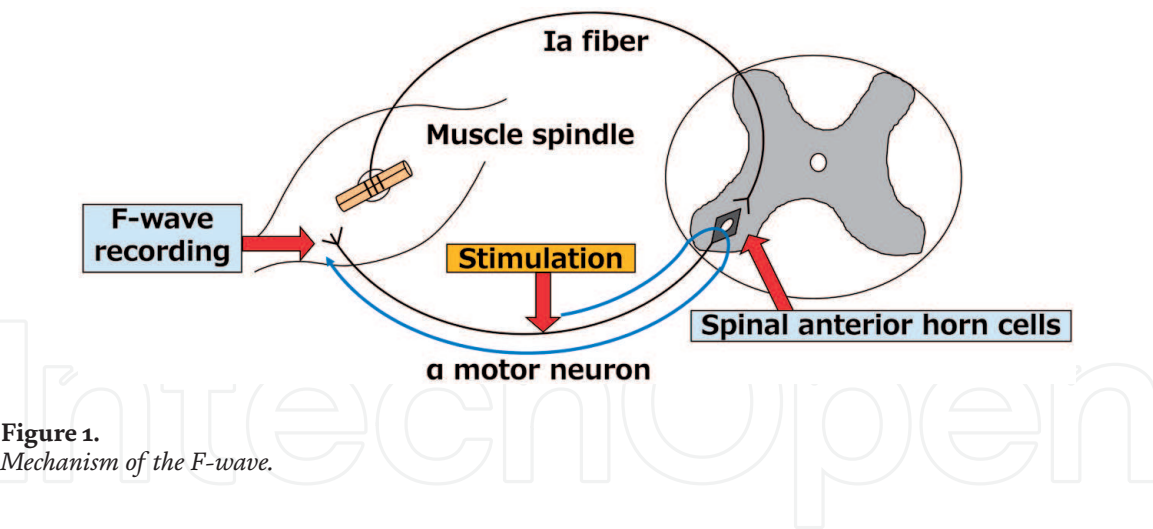
2. The excitability of spinal motor neurons during MI at different imagined muscle contractions

2.1 Background and purpose

Our research group previously reported that the excitability of spinal motor neurons was significantly increased during MI of isometric thenar muscle activity at 50% MVC [18]. In actual movement, the excitability of spinal motor neurons was increased linearly with muscle contraction strength [22]. If MI and ME share a common neural network, the excitability of spinal motor neurons increases linearly with imagined muscle contraction strength. Firstly, we aimed to investigate the excitability of spinal motor neurons during MI at different imagined muscle contraction strength. The excitability of spinal motor neurons during MI was assessed using the F-wave [23–26].

2.2 About the F-wave

The F-wave is compound action potentials resulting from the re-excitation (backfiring) of spinal anterior horn cells by an antidromic impulse following distal electrical stimulation of α motor neurons [27–29] (**Figure 1**). The F-wave amplitude was significantly increased when the corticospinal descending volley collides with the antidromic peripheral volley [30]. Therefore, the F-wave is considered to be a probe of the excitability of spinal motor neurons. Further, Rossini et al. [31] suggested that the F-wave is a reliable index of the excitability of spinal motor neurons, even when motor output is extremely minimal, as during MI.
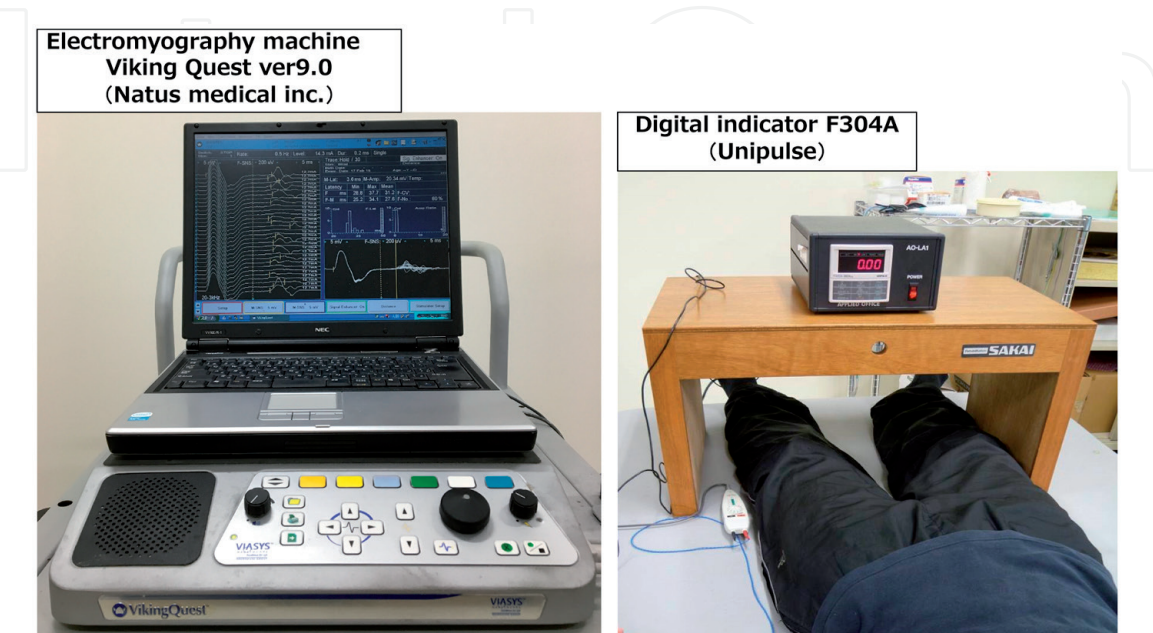
Figure 1.
Mechanism of the F-wave.

2.3 Materials and methods

2.3.1 Participants

Firstly, we assessed the excitability of spinal motor neurons during MI at 10, 30, 50, and 70% MVC for 10 healthy adults (mean age = 28.7 ± 4.5 years). Secondly, we assessed the excitability of spinal motor neurons during MI at 50 and 100% MVC for 15 healthy adults (mean age = 25.3 ± 5.0 years). Written informed consent was obtained prior to participation. The study was approved by the Research Ethics Committee at Kansai University of Health Sciences and conducted in accordance with the Declaration of Helsinki.

2.3.2 Apparatus and condition for the F-wave recording

A Viking Quest Electromyography (EMG) machine version 9.0 (Natus Medical, Inc., Pleasanton, CA, USA) was used to record the F-wave. Participants were in supine posture on a bed and instructed to fix one's eyes on the display of a pinch meter (Digital indicator F304A, Unipulse Corp., Japan) (**Figure 2**).

Figure 2.
F-wave recording status.
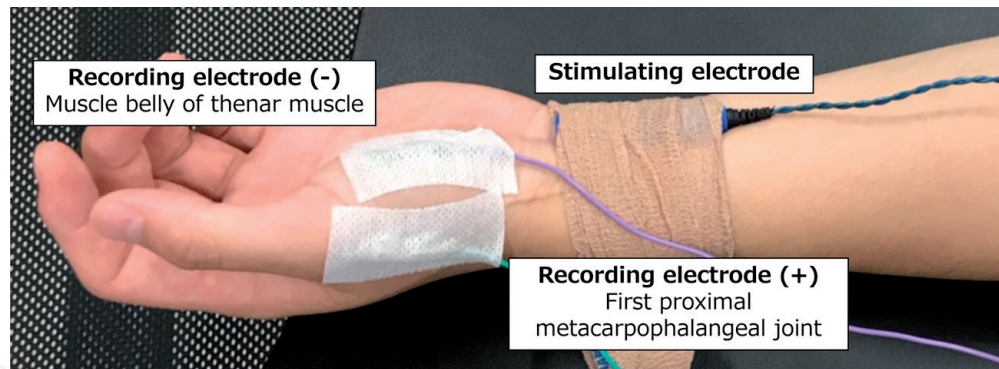
Figure 3.
F-wave recording condition.

The skin impedance was cleaned with an abrasive gel (Nuprep® Skin Prep Gel; Weaver and Company, Inc., Aurora, CO, USA) to maintain below 5 kΩ. The room temperature was maintained at 25°C. A pair of silver EEG cup electrodes (10-mm diameter; Natus Medical, Inc., Pleasanton, CA, USA) was attached over the thenar muscles and the base of the first dorsal metacarpal bone (**Figure 3**).

The F-wave was evoked from the left thenar muscles by delivering supramaximal electrical stimuli to the left median nerve at wrist. Supramaximal stimulus intensity was determined to be 20% higher than the maximal stimulus intensity that could elicit the largest M-wave amplitude. Thirty electrical stimuli in each trial were delivered at a duration of 0.2 ms and frequency of 0.5 Hz. The sensitivity for the F-wave was set at 200 μV per division and a sweep of 5 ms per division. The bandwidth filter ranged from 20 Hz to 3 kHz.

2.3.3 Experimental protocol

Firstly, to determine baseline of the excitability of spinal motor neurons, the F-wave was recorded during relaxation for 1 min (rest). After baseline of the F-wave recording, participants were instructed to learn isometric left thenar muscle activity at 50% MVC for 1 min with visual feedback. Specifically, participants press the sensor of a pinch meter by the left thumb and index finger at 50% MVC and keep the 50% MVC value numerically recorded on the display. For the MI trial, participants imagined isometric left thenar muscle activity at 50% MVC for 1 min (50% MI). After MI trial, the F-wave was recorded during relaxation for 1 min (post). This protocol was repeated for 10, 30, 70, and 100% MI conditions. Each condition was performed randomly on different days.

2.4 Data analysis for the F-wave

The F-wave data in each trial were analyzed with respect to two parameters: persistence and the F/M amplitude ratio. The minimum peak-to-peak amplitude of F-waves was 20 μV [17, 32]. Persistence was defined as the number of detected F-wave responses to 30 electrical stimuli and expressed as percentage (%). Persistence reflects the number of backfiring spinal anterior horn cells [28, 29]. The F/M amplitude ratio was defined as the mean amplitude of all detected F-wave responses divided by the M-wave amplitude and expressed as percentage (%). The F/M amplitude ratio reflects the size, number, and synchronization of backfiring spinal anterior horn cells [29, 33]. Therefore, persistence and the F/M amplitude ratio indicate the excitability of spinal motor neurons.

2.5 Statistical analysis

2.5.1 The F-wave during 10–70% MI condition

IBM SPSS statistics version 26 (IBM Corp., Armonk, NY, USA) was used for statistical analysis. A nonparametric method was used for statistical analysis because the normality of obtained data was not confirmed by the Shapiro-Wilk test.

Persistence and the F/M amplitude ratio among three trials (rest, MI, and post) under each MI condition (10, 30, 50, and 70%) 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 four MI conditions by that at rest. The relative values among four MI conditions were compared using the Friedman test. The threshold for statistical significance was set at $p = 0.05$.

2.5.2 The F-wave during 50 and 100% MI condition

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

2.6 Results

2.6.1 The F-wave during 10–70% MI condition

Persistence during MI under all MI conditions was significantly higher than the rest (**Tables 1**–**4**). The F/M amplitude ratio during MI under 10, 30, and 50% MI conditions was significantly higher than rest (**Tables 1**–**3**). The F/M amplitude ratio during MI under 70% MI condition was tended to be increased than rest (**Table 4**).

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

2.6.2 The F-wave during 50 and 100% MI condition

Persistence during MI under the two MI conditions was significantly higher than rest (**Tables 6**, **7**). The F/M amplitude ratio during MI under the two MI conditions was significantly higher than rest (**Tables 6** and **7**).

	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

Mean ± SD.

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

10% MI: Motor imagery of isometric thenar muscle 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

Mean ± SD.

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

30% MI: Motor imagery of isometric thenar muscle 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

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 thenar muscle 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

Mean ± SD.

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

70% MI: Motor imagery of isometric thenar muscle 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 ratio	2.40 ± 1.38	3.31 ± 0.56	2.52 ± 1.96	2.10 ± 1.37

Mean ± SD.

MI: Motor imagery of isometric thenar muscle activity

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

	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

Mean ± SD.

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

Table 6.
The persistence and F/M amplitude ratio 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

Mean ± SD.

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

Table 7.
The persistence and F/M amplitude ratio under 100% MI condition.

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

2.7 Discussion

Both persistence and the F/M amplitude ratio significantly increased during MI under all five MI conditions. Previous studies demonstrated that various brain regions, including the primary motor cortex, premotor area, supplementary motor area, prefrontal cortex, parietal lobule, cingulate area, cerebellum, and basal ganglia, contribute to motor preparation and planning during MI [34, 35]. Therefore, it is considered that activation of the central nervous system contributing to motor preparation and planning during MI is responsible for increased excitability of the spinal motor neurons via the descending pathways, such as the corticospinal and extrapyramidal tracts.

	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

Mean ± SD.

MI: Motor imagery of isometric thenar muscle activity

Table 8.
Comparison of relative values of the F-wave between 50% MI and 100% MI condition.

Furthermore, participants performed MI while holding the sensor of a pinch meter. Mizuguchi et al. [36] 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 excitability of the spinal motor neurons along the MI-activated pathways.

Relative values of persistence and the F/M amplitude were similar among all MI conditions. This result indicated that the magnitude of imagined muscle contraction strength may not affect the excitability of the spinal motor neurons. Bonnet et al. [37] reported that the H-reflex amplitude during MI was similar between 2 and 10% MI conditions. Hale et al. [38] 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 et al. [39] 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 [9]. The neural mechanism that inhibits actual movement and muscle contraction during MI may be involved in this outcome. Park et al. [40] reported that MEP amplitudes during MI were similar among all six (i.e., 10, 20, 30, 40, 50, and 60% MVC) MI conditions. Furthermore, magnitude of the primary motor cortex activity during MI did not correlate with the imagined muscle contraction strength, whereas activities of the supplementary motor and premotor areas during MI strongly correlated with it [41]. The supplementary motor and premotor areas have crucial roles in larger force generation [42], motor planning, preparation, and inhibition [43, 44]. Thus, these areas may inhibit actual muscle contractions depending on the magnitude of the muscle contraction strength. These areas are also connected directly to the primary motor cortex, and inhibitory inputs from them may suppress any additional primary motor cortex excitation conferred by MI with a high imagined contraction strength. Therefore, the degree of excitability of spinal motor neurons 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

The result of these previous studies demonstrated that MI can increase the excitability of spinal motor neurons. Further, MI at slight imagined muscle contraction strength (i.e., 10% MVC) can substantially facilitate the excitability of spinal motor neurons.

3. The influence of duration of MI on the excitability of spinal motor neurons

3.1 Background and purpose

In our previous studies, duration of MI was 1 min [23–26]. However, Driskell et al. [45] indicated that 10–15 min may be appropriate for duration of MI training session. Further, Twinning et al. [46] indicated that 5 min is the temporal limit to concentrate and perform MI. Therefore, we aimed to investigate the influence of duration of MI on the excitability of spinal motor neurons [25, 26, 47].

3.2 Materials and methods

3.2.1 Participants

Eleven healthy adults participated (mean age = 26.4 ± 6.0 years). Written informed consent was obtained prior to participation. The study was approved by the Research Ethics Committee at Kansai University of Health Sciences and conducted in accordance with the Declaration of Helsinki.

3.2.2 Experimental protocol

Firstly, to determine the baseline of the excitability of spinal motor neurons, the F-wave was recorded during relaxation for 1 min (rest). Subsequently, participants were instructed to learn isometric left thenar muscle activity at 50% MVC for 1 min. For MI trial, participants imagined isometric left thenar muscle activity at 50% MVC for 1 min. The F-wave was recorded at 1, 3, and 5 min after beginning of MI (1-, 3-, and 5-min MI). Immediately after MI trial for 5 min, the F-wave was recorded during relaxation for 1 min (post).

After F-wave recording, participants evaluated their vividness of MI (i.e., how vividly they could imagine isometric thenar muscle activity at 50% MVC) at 1-, 3-, and 5-min MI using a seven-point Likert scale ranging from 1 (very difficult to perform MI vividly) to 7 (very easy to perform MI vividly).

3.3 Statistical analysis

A nonparametric method was used for statistical analyses because the normality of obtained data was not confirmed with the Shapiro-Wilk test. Persistence and the F/M amplitude ratio among five trials (rest, 1-, 3-, and 5-min MI, and post) were compared using the Friedman test and Scheffe's post hoc test. Rating scores of MI vividness at 1-, 3-, and 5-min MI were compared using the Friedman test and Scheffe's post hoc test. The threshold for statistical significance was set at $p = 0.05$.

3.4 Results

Persistence at 1- and 3-min MI trial was significantly higher than rest (**Table 9**). No significant difference in persistence was observed between 5-min MI and rest trial (**Table 9**). Further, no significant differences in persistence were confirmed among 1-, 3-, and 5-min MI trial.

	rest	1-min MI	3-min MI	5-min MI	post
Persistence (%)	53.5 ± 26.8	88.4 ± 13.3	85.5 ± 14.8	83.7 ± 17.3	54.0 ± 25.5
F/M amplitude ratio (%)	0.91 ± 0.38	2.00 ± 0.86**	1.84 ± 1.00*	1.70 ± 0.71†	0.97 ± 0.39

Mean ± SD.

**$p < 0.01$; significant difference between rest and 1-min MI trial.

*$p < 0.05$; significant difference between rest and 3-min MI trial.

†$p < 0.05$; significant difference between 1-min MI and 5-min MI trial, 3-min MI and 5-min MI.

Table 9.
The F-wave during MI for 5 min.

	1-min MI	3-min MI	5-min MI
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 10.
Rating scores of MI vividness during MI for 5 min.

The F/M amplitude ratio at 1- and 3-min MI trial was significantly higher than rest (**Table 9**). The F/M amplitude ratio at 5-min MI trial was significantly smaller than 1- and 3-min MI trial (**Table 9**). Further, no significant difference in the F/M amplitude ratio was observed between 5-min MI and rest trial (**Table 9**).

The rating score of MI vividness at 5-min MI trial was significantly smaller that 1-min MI trial (**Table 10**).

3.5 Discussion

The results for the F-wave indicated that duration of MI for 1–3 min positively affects the excitability of spinal motor neurons. Further, the results of vividness of MI indicated that temporal limitation of MI, participants can perform MI vividly, may be 3 min.

It is considered that mental fatigue and/or habituation were involved in this result. Repetitive MI of a handgrip movement decreases the corticospinal excitability [48]. Rozand et al. [49] also demonstrated that participants felt difficulty to maintain their focus on imagined movement due to mental fatigue. Therefore, mental fatigue caused by sustained mental activity may affect the excitability of spinal motor neurons.

Brain activity was decreased by habituation after cognitive motor task for 10 min [50]. Further, the corticospinal excitability was also decreased by habituation [50]. At spinal level, the T-reflex amplitude was decreased after sustained mental activity for 20 min [51]. Therefore, habituation after sustained mental activity as MI can alter the corticospinal excitability, including the excitability of spinal motor neurons.

3.6 Conclusion

The result of this study demonstrated that longer duration of MI above 3 min has no facilitatory effect on the excitability of spinal motor neurons. Therefore, in physical therapy, the duration of MI should be considered.

4. The influence of imagery strategy on the excitability of spinal motor neurons

4.1 Background and purpose

Previously, we investigated the influence of MI of isometric thenar muscle activity on the excitability of spinal motor neurons [18, 23–26]. Previous results indicated that the MI of thenar muscle activity at 50% MVC can increase the excitability of spinal motor neurons. However, there were individual differences in facilitation amount of the excitability of spinal motor neurons.

MI includes various components of perception that can be associated with actual movement [52]. Therefore, the effects of MI may differ depending on the choice of sensory modality. Then, we investigated that imagery strategy on the excitability of spinal motor neurons [53].

4.2 Materials and methods

4.2.1 Participants

Fourteen healthy adults (mean age = 23.4 ± 4.8 years) participated. Written informed consent was obtained prior to participation. The study was approved by the Research Ethics Committee at Kansai University of Health Sciences and conducted in accordance with the Declaration of Helsinki.

4.2.2 Experimental protocol

For the rest trial (rest), to determine the baseline excitability of the spinal motor neurons, the F-wave was recorded during relaxation for 1 min. Subsequently, participants were instructed to exert isometric left thenar muscle contraction at 50% MVC for 1 min with visual feedback. Simultaneously, participants learned two imagery strategies: somatosensory (tactile and pressure perception of thumb finger pulp during pressing the sensor of pinch meter) and kinesthetic (thenar muscle contraction during pressing the sensor of pinch meter at 50% MVC). Subsequently, participants performed the somatosensory imagery (SI), kinesthetic imagery (KI), and combined somatosensory and kinesthetic imagery (SKI). In SKI trial, participants imagined somatosensory and kinesthetic sensation simultaneously. The duration of each MI session was 1 min.

After the F-wave recording, participants evaluated difficulty of each imagery strategy by using a five-point Likert scale, ranging from 1 (very hard to image vividly) to 5 (very easy to image vividly).

4.3 Statistical analysis

A nonparametric method was used for statistical analyses because the normality of obtained data was not confirmed with the Shapiro-Wilk test. Persistence and the F/M amplitude ratio among four trials (rest, SI, KI, and SKI) were compared using the Friedman test and Scheffe's post hoc test. Rating scores of each imagery strategy (SI, KI, and SKI) were compared using the Friedman test and Scheffe's post hoc test. The threshold for statistical significance was set at p = 0.05.

4.4 Results

Persistence was significantly higher during SI and KI trials than at rest (**Table 11**). Persistence tended to be higher during SKI than at rest (**Table 11**).

The F/M amplitude ratio was significantly higher during KI than at rest (**Table 11**).

The rating score of SKI vividness was significantly smaller than rest (**Table 12**).

4.5 Discussion

Persistence and the F/M amplitude ratio were significantly increased during KI. Described in Introduction section, numerous studies demonstrated that various brain areas, including the primary motor cortex, were activated during KI [34, 35].

	rest	SI	KI	SKI
Persistence (%)	53.7 ± 21.9	73.4 ± 19.6**	74.3 ± 23.7††	68.4 ± 21.8
F/M amplitude ratio (%)	0.83 ± 0.32	1.20 ± 0.50	1.33 ± 0.70*	1.28 ± 0.65

Mean ± SD.

††*p* < 0.01; significant difference between rest and KI trial.

**p* < 0.01; significant difference between rest and SI trial.

p < 0.05; significant difference between rest and KI trial.

Table 11.
The F-wave during SI, KI, and SKI, trail.

	SI	KI	SKI
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 12.
Rating scores of MI vividness during SI, KI, and SKI, trail.

The corticospinal excitability was significantly increased during KI [2, 15]. Therefore, the excitability of spinal motor neurons during KI may be increased via the descending pathways, such as the corticospinal and extrapyramidal tracts.

Although there was no significant difference in the F/M amplitude ratio between SI and rest trial, persistence was significantly increased during SI than rest. We did not expect this result previously, because there are no previous studies reported that SI increases the corticospinal excitability including that of the primary motor cortex. One possible is that SI adopted in this study included kinesthetic components. Participants in this study imagined tactile and pressure perception accompanied with holding the sensor of a pinch meter. Therefore, it is plausible that participants imagined tactile and perception along with thenar muscle activity.

Persistence during SKI was tended to be higher than rest, and the rating score of SKI vividness was the lowest among all imagery strategies (SI, KI, and SKI). Participants in this study were instructed to pay attention to kinesthetic and somatosensory perception simultaneously. The decline in the amount of attention that can be allocated to each imagery strategy may have increased difficulty for participants to perform SKI vividly. Indeed, Williams et al. [54] indicated that there are positive correlation between the corticospinal excitability and MI vividness.

4.6 Conclusion

The result of this study indicated that KI may have a greater effect on the excitability of spinal motor neurons.

5. How to use MI in neurorehabilitation

In post-stroke and spinal cord injury, motor cortex excitability was decreased due to damage of neural substrates, loss of sensory inputs, and disuse of affected

limb [1]. Further, the MEP amplitude was decreased after stroke [55] and spinal cord injury [56]. Additionally, a significant reduction of spinal motor neuron excitability has been shown in the post-stroke acute phase [4] and spinal cord injury [57]. Facilitating the corticospinal excitability is closely related to functional motor recovery [58]. Therefore, the immediate enrollment in rehabilitation programs aiming to facilitate the corticospinal excitability, including the excitability of spinal motor neurons, should be important. Our previous researches investigated the excitability of spinal motor neurons during MI in only healthy volunteers. However, Cicinelli et al. [59] reported that the MEP amplitude was significantly facilitated during MI in post-stroke. Naseri et al. [60] reported that the amplitude and persistence of the F-wave were significantly increased during MI in post-stroke. Further, similar effect was observed in spinal cord injury [61]. Also, in Parkinson's disease, the amplitude and persistence of the F-wave were significantly increased during MI [62]. Therefore, MI has a facilitating effect on the corticospinal excitability, including the excitability of spinal motor neurons, for central nervous system disorder.

Next, about definite method of MI, our research group revealed that MI of isometric thenar muscle activity at 50% MVC can increase the excitability of spinal motor neurons. Additionally, imagined muscle contraction strength did not affect facilitation amount of the excitability of spinal motor neurons. In physical therapy for facilitating the excitability of spinal motor neurons, slight (i.e., 10% MVC) imagined muscle contraction strength may be sufficient. Then, kinesthetic imagery could more facilitate the excitability of spinal motor neurons than somatosensory imagery. Stinear et al. [63] reported that kinesthetic imagery can significantly increase the corticospinal excitability. Therefore, to facilitate the excitability of spinal motor neurons, kinesthetic perception may be used for imagery strategy. Also considering mental fatigue and habituation, duration of MI may be less than 3 min.

Conflict of interest

The authors declare no conflict of interest.

Author details

Yoshibumi Bunno
Graduate School of Health Sciences, Graduate School of Kansai University of Health Sciences, Osaka, Japan

*Address all correspondence to: bunno@kansai.ac.jp

IntechOpen

References

[1] Liepert J, Bauder H, Wolfgang HR, Miltner WH, Taub E, Weiller C. Treatment-induced cortical reorganization after stroke in humans. Stroke. 2000;**31**:1210-1216. DOI: 10.1161/01.str.31.6.1210

[2] Foltys H, Krings T, Meister IG, Sparing R, Boroojerdi B, Thron A, et al. Motor representation in patients rapidly recovering after stroke: A functional magnetic resonance imaging and transcranial magnetic stimulation study. Clinical Neurophysiology. 2003;**114**:2404-2415. DOI: 10.1016/S1388-2457(03)00263-3

[3] Fierro B, Raimondo D, Modica A. Analysis of F response in upper motoneurone lesions. Acta Neurologica Scandinavica. 1990;**82**:329-334. DOI: 10.1111/j.1600-0404.1990.tb03311.x

[4] Drory VE, Neufeld MY, Korczyn AD. F-wave characteristics following acute and chronic upper motor neuron lesions. Electromyography and Clinical Neurophysiology. 1993;**33**:441-446

[5] Nakayama H, Jørgensen HS, Raaschou HO, Olsen TS. Recovery of upper extremity function in stroke patients: The Copenhagen stroke study. Archives of Physical Medicine and Rehabilitation. 1994;**75**:394-398. DOI: 10.1016/0003-9993(94)90108-2

[6] Kreisei SH, Hennerici MG, Bäzner H. Pathophysiology of stroke rehabilitation: The natural course of clinical recovery, use-dependent plasticity and rehabilitative outcome. Cerebrovascular Diseases. 2007;**23**:243-255. DOI: 10.1159/000098323

[7] Horn SD, DeJong G, Smout RJ, Gassaway J, James R, Conroy B. Stroke rehabilitation patients, practice, and outcomes: Is earlier and more aggressive therapy better? Archives of Physical Medicine and Rehabilitation. 2005;**86**:S101-S114. DOI: 10.1016/j.apmr.2005.09.016

[8] Coleman ER, Moudgal R, Lang K, Hyacinth HI, Awosika OO, Kissela BM, et al. Early rehabilitation after stroke: A narrative review. Current Atherosclerosis Reports. 2017;**19**:59. DOI: 10.1007/s11883-017-0686-6

[9] Guillot A, Di Rienzo F, Maclntyre T, Moran A, Collet C. Imagining is not doing but involves specific motor commands: A review of experimental data related to motor inhibition. Frontiers in Human Neuroscience. 2012;**6**:247. DOI: 10.3389/fnhum.2012.00247

[10] Lotze M, Montoya P, Erb M, Hülsmann E, Flor H, Klose U, et al. Activation of cortical and cerebellar motor areas during executed and imagined hand movements: An fMRI study. Journal of Cognitive Neuroscience. 1999;**11**:491-501. DOI: 10.1162/089892999563553

[11] Luft AR, Skalej M, Stefanou A, Klose U, Voigt K. Comparing motion- and imagery-related activation in the human cerebellum: A functional MRI study. Human Brain Mapping. 1998;**6**:105-113. DOI: 10.1002/(sici)1097-0193(1998)6:2<105::aid-hbm3>3.0.co;2-7

[12] Stephan KM, Fink GR, Passingham RE, Silbersweig D, Ceballos-Baumann AO, Frith CD, et al. Functional anatomy of the mental representation of upper extremity movements in healthy subjects. Journal of Neurophysiology. 1995;**73**:373-386. DOI: 10.1152/jn.1995.73.1.373

[13] Nakano H, Ueta K, Osumi M, Morioka S. Brain activity during the observation, imagery, and execution of tool use: An fNIRS/EEG study. Journal of Novel Physiotherapies. 2012;**S1**:009. DOI: 10.4172/2165-7025.S1-009

[14] Kasai T, Kawai S, Kawanishi M, Yahagi S. Evidence for facilitation of motor evoked potentials (MEPs) induced by motor imagery. Brain Research. 1997;**744**:147-150. DOI: 10.1016/S0006-8993(96)01101-8

[15] Stinear CM, Byblow WD. Modulation of corticospinal excitability and intracortical inhibition during motor imagery is task-dependent. Experimental Brain Research. 2004;**157**:351-358. DOI: 10.1007/s00221-004-1851-z

[16] Taniguchi S, Kimura J, Yamada T, Ichikawa H, Hara M, Fujisawa R, et al. Effect of motion imagery to counter rest-induced suppression of F-wave as a measure of anterior horn cell excitability. Clinical Neurophysiology. 2008;**119**:1346-1352. DOI: 10.1016/j.clinph.2007.11.179

[17] Hara M, Kimura J, Walker DD, Taniguchi S, Ichikawa H, Fujisawa R, et al. Effect of motor imagery and voluntary muscle contraction of the F-wave. Muscle & Nerve. 2010;**42**:208-212. DOI: 10.1002/mus.21667

[18] Suzuki T, Bunno Y, Onigata C, Tani M, Uragami S. Excitability of spinal neural function during several motor imagery tasks involving isometric opponens pollicis activity. NeuroRehabilitation. 2013;**33**:171-176. DOI: 10.3233/NRE-130942

[19] Hashimoto R, Rothwell JC. Dynamic changes in corticospinal excitability during motor imagery. Experimental Brain Research. 1999;**125**:75-81. DOI: 10.1007/s002210050660

[20] Stinear CM, Fleming MK, Byblow WD. Lateralization of unimanual and bimanual motor imagery. Brain Research. 2006;**1095**:139-147. DOI: 10.1016/j.brainres.2006.04.008

[21] Oishi K, Kimura M, Yasukawa M, Yoneda T, Maeshima T. Amplitude reduction of H-reflex during mental movement simulation in elite athletes. Behavioural Brain Research. 1994;**62**:55-61. DOI: 10.1016/0166-4328(94)90037-X

[22] Suzuki T, Fujiwara T, Takeda I. Excitability of the spinal motor neuron pool and F-waves during isometric ipsilateral and contralateral contraction. Physiotherapy Theory and Practice. 1993;**9**:19-24. DOI: 10.3109/09593989309036482

[23] Bunno Y, Onigata C, Suzuki T. The imagined muscle contraction strengths did not affect the changes of spinal motor neurons excitability. Journal of Novel Physiotherapies. 2016;**S3**:008. DOI: 10.4172/2165-7025.S3-008

[24] Bunno Y, Fukumoto Y, Todo M, Onigata C. The effect of motor imagery on spinal motor neuron excitability and its clinical use in physical therapy. In: Suzuki T, editor. Neurological Physical Therapy. United Kingdom: IntechOpen; 2017. pp. 29-50. DOI: 10.5772/67471

[25] Bunno Y. The application of motor imagery to neurorehabilitation. In: Larrivee D, editor. Evolving BCI Therapy-Engaging Brain State Dynamics. United Kingdom: Intech; 2018. pp. 53-71. DOI: 10.5772/intechopen.75411

[26] Bunno Y. Effectiveness of motor imagery on physical therapy: Neurophysiological aspects of motor imagery. In: Bernardo-Filho M, Sá-Caputo D, Taiar R, editors. Physical Therapy Effectiveness. United Kingdom: Intech; 2019. pp. 1-19. DOI: 10.5772/intechopen.90277

[27] Kimura J. F-wave velocity in the central segment of the median and ulnar nerves. A study in normal subjects and in patients with Charcot-Marie-tooth disease. Neurology. 1974;**24**:539-546. DOI: 10.1212/WNL.24.6.539

[28] Mesrati F, Vecchierini MF. F-waves neurophysiology and clinical

value. Neurophysiologie Clinique. 2004;**34**:217-243. DOI: 10.1016/j. neucli.2004.09.005

[29] Fisher MA. F-waves-physiology and clinical uses. The Scientific World Journal. 2007;**7**:144-160. DOI: 10.1100/tsw.2007.49

[30] Mercuri B, Wassemann EM, Manqanotti P, Ikoma K, Samii A, Hallett M. Cortical modulation of spinal excitability: An F-wave study. Electroencephalography and Clinical Neurophysiology. 1996;**101**:16-24. DOI: 10.1016/0013-4694(95)00164-6

[31] Rossini PM, Rossi S, Pasqualetti P, Tacchio F. Cortical excitability modulation to hand muscles during movement imagery. Cerebral Cortex. 1999;**9**:161-167. DOI: 10.1093/cercor/9.2.161

[32] Fisher MA. H reflexes and F waves fundamentals, normal and abnormal patters. Neuroimaging Clinics of North America. 2002;**20**:339-360. DOI: 10.1016/s0733-8619(01)00004-4

[33] Peioglou-Harmoussi S, Fawcett PR, Howel D, Barwick DD. F-responses: A study of frequency, shape and amplitude characteristics in healthy control subjects. Journal of Neurology, Neurosurgery, and Psychiatry. 1985;**48**:1159-1164. DOI: 10.1136/jnnp.48.11.1159

[34] Hanakawa T, Dimyan MA, Hallett M. Motor planning, imagery, and execution in the distributed motor network: A time-course study with functional MRI. Cerebral Cortex. 2008;**18**:2775-2788. DOI: 10.1093/cercor/bhn036

[35] Hanakawa T. Organizing motor imageries. Neuroscience Research. 2016;**104**:56-63. DOI: 10.1016/j. neures.2015.11.003

[36] Mizuguchi N, Sakamoto M, Muraoka T, Nakagawa K, Kanazawa S, Nakata H, et al. The modulation of corticospinal excitability during motor imagery of action with objects. PLoS One. 2011;**6**:e26006. DOI: 10.1371/journal.pone.0026006

[37] Bonnet M, Decety J, Jeannerod M, Requina J. Mental simulation of an action modulates the excitability of spinal reflex pathways in man. Cognitive Brain Research. 1997;**5**:221-228. DOI: 10.1016/S0926-6410(96)00072-9

[38] Hale BS, Raglin JS, Koceja DM. Effect of mental imagery of a motor task on the Hoffmann reflex. Behavioural Brain Research. 2003;**142**:81-87. DOI: 10.1016/S0166-4328(02)00397-2

[39] Aoyama T, Kaneko F. The effect of motor imagery on gain modulation of the spinal reflex. Brain Research. 2011;**1372**:41-48. DOI: 10.1016/j. brainres.2010.11.023

[40] Park WH, Li S. No graded responses of finger muscles to TMS during motor imagery of isometric finger forces. Neuroscience Letters. 2011;**494**:255-259. DOI: 10.1016/j.neulet.2011.03.027

[41] Romero DH, Lacourse MG, Lawrence KE, Schandler S, Cohen MJ. Event-related potentials as a function of movement parameter variations during motor imagery and isometric action. Behavioural Brain Research. 2000;**117**:83-96. DOI: 10.1016/S0166-4328(00)00297-7

[42] Oda S, Shibata M, Moritani T. Force-dependent changes in movement-related cortical potentials. Journal of Electromyography and Kinesiology. 1996;**6**:247-252. DOI: 10.1016/S1050-6411(96)00010-7

[43] Nakata H, Sakamoto K, Ferretti A, Perrucci MG, Gratta CD, Kakigi R, et al. Somato-motor inhibitory processing in humans: An event-related functional MRI study. NeuroImage. 2008;**39**:1858-1866. DOI: 10.1016/j. neuroimage.2007.10.041

[44] Watanabe J, Sugiura M, Sato K, Sato Y, Maeda Y, Matsue Y, et al. The human prefrontal and parietal association cortices are involved in NO-GO performances: An event-related fMRI study. NeuroImage. 2002;**17**:1207-1216. DOI: 10.1006/nimg.2002.1198

[45] Driskell J, Copper C, Moran A. Does mental practice enhance performance? Journal of Applied Phychology. 1994;**79**:481-492. DOI: 10.1037/0021-9010.79.4.481

[46] Twining WE. Mental practice and physical practice in learning a motor skill. Research Quarterly. 1949;**20**:432-435

[47] Bunno Y. Does the duration of motor imagery affect the excitability of spinal anterior horn cells? Somatosensory & Motor Research. 2018;**35**:223-228. DOI: 10.1080/08990220.2018.1538963

[48] Kluger BM, Palmer C, Shattuck JT, Triggs WJ. Motor evoked potential depression following repetitive central motor initiation. Experimental Brain Research. 2012;**216**:585-590. DOI: 10.1007/s00221-011-2962-y

[49] Rozand V, Lebon F, Stapley PJ, Papaxanthis C, Lepers R. A prolonged motor imagery session alter imagined and actual movement durations: Potential implications for neurorehabilitation. Behavioural Brain Research. 2016;**297**:67-75. DOI: 10.1016/j.bbr.2015.09.036

[50] Tana MG, Montin E, Cerutti S, Bianchi AM. Exploring cortical attentional system by using fMRI during a continuous performance test. Computational Intelligence and Neuroscience. 2010;**2010**:329213. DOI: 10.1155/2010/329213

[51] Brunia CH, Zwaga HJ, van Boxtel A. Tendon reflex amplitude with increasing task difficulty. Ergonomics. 1973;**16**:495-499. DOI: 10.1080/00140137308924538

[52] McNorgan C. A meta-analytic review of multisensory imagery identifies the neural correlates of modality-specific and modality-general imagery. Frontiers in Human Neuroscience. 2012;**6**:285. DOI: 10.3389/fnhum.2012.00285

[53] Bunno Y. Imagery strategy affects spinal motor neuron excitability -using kinesthetic and somatosensory imagery. Neuroreport. 2019;**30**:463-467. DOI: 10.1097/WNR.0000000000001218

[54] Williams J, Pearce AJ, Loporto M, Morris T, Holmes PS. The relationship between corticospinal excitability during motor imagery and motor imagery ability. Behavioural Brain Research. 2012;**226**:369-375. DOI: 10.1016/j.bbr.2011.09.014

[55] Wrigley PJ, Gustin SM, Macey PM, Nash PG, Gandevia SC, Macefield VG, et al. Anatomical changes in human motor cortex and motor pathways following complete thoracic spinal cord injury. Cerebral Cortex. 2009;**19**: 224-232. DOI: 10.1093/cercor/bhn072

[56] Diehl P, Kliesch U, Dietz V, Curt A. Impaired facilitation of motor evoked potentials in incomplete spinal cord injury. Journal of Neurology. 2006;**253**:51-57. DOI: 10.1007/s00415-005-0921-x

[57] Curt A, Keck ME, Dietz V. Clinical value of F-wave recordings in traumatic cervical spinal cord injury. Electroencephalography and Clinical Neurophysiology. 1997;**105**:189-193. DOI: 10.1016/s0924-980x(97)96626-1

[58] Triggs WJ, Calvanio R, Levine M. Transcranial magnetic stimulation reveals a hemispheric asymmetry correlate of intermanual differences in motor performance. Neurophychologia. 1997;**35**:1355-1363. DOI: 10.1016/s0028-3932(97)00077-8

[59] Cicinelli P, Marconi B, Zaccagnini M, Pasqualetti P, Filippi MM, Rossini PM.

Imagery-induced cortical excitability changes in stroke: A transcranial magnetic stimulation study. Cerebral Cortex. 2006;**16**:247-253. DOI: 10.1093/cercor/bhi103

[60] Naseri M, Petramfar P, Ashraf A. Effect of motor imagery on the F-wave parameters in hemiparetic stroke survivors. Annals of Rehabilitation Medicine. 2015;**39**:401-408. DOI: 10.5535/arm.2015.39.3.401

[61] Cramer SC, Orr EL, Cohen MJ, Lacourse MG. Effects of motor imagery training after chronic, complete spinal cord injury. Experimental Brain Research. 2007;**177**:33-242. DOI: 10.1007/s00221-006-0662-9

[62] Suzuki T, Bunno Y, Onigata C, Tani M, Uragami S, Yoshida S. Excitability of spinal neural function during motor imagery in Parkinson's disease. Functional Neurology. 2014;**29**: 263-267

[63] Stinear CM, Byblow WD, Steyvers M, Levin O, Swinnen SP. Kinesthetic, but not visual, motor imagery modulates corticomotor excitability. Experimental Brain Research. 2006;**168**:157-164. DOI: 10.1007/s00221-005-0078-y