Chapter

Excitability of Spinal Motor Neurons in the Upper Extremity during Voluntary Movement with Different Difficult Tasks in the Lower Extremity

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Abstract

The purpose of this study was to examine the relationship between excitability of the spinal motor neurons in the upper extremity and difficulty of tasks applied to the lower extremities. Twenty healthy volunteers agreed to participate. Our findings suggest that the excitability of spinal motor neurons in the right arm was increased during voluntary movement of the lower extremities. Excitability of the spinal motor neurons might be increased by the facilitatory effect at the spinal and cortical levels. Regarding the facilitatory effects at the cortical level, the effects of difficult tasks might be larger than those of simple tasks, but the most difficult task might be affected by the facilitatory and inhibitory effects of the central nervous system.

Keywords: F-wave, spinal motor neuron, remote muscle, leg movement, task difficulty

1. Introduction

It is important to understand the effects of remote muscle contractions on other muscles during physical therapy. For example, associative reactions observed in hemiplegic patients with cerebrovascular disorders include tonic reflexes from the muscle groups of one limb to those of the other limb. Associative reactions often occur during or before the start of exercise and worsen abnormal synergic movements, making selective exercises difficult in the upper extremities of the paralyzed side. In physical therapy, it is necessary to reduce associative reactions, perform selective exercises, and evaluate the exercise types that trigger such associative reactions. Furthermore, the facilitatory and inhibitory effects of muscle contractions in remote regions can be used to manipulate central nervous system input and output during physical therapy. As such, to enable the efficacy of physical therapy, the neurophysiological effects of muscle contractions of remote regions on other muscles must be examined.

The mechanism of the facilitatory effect of muscle contractions of remote regions has been analyzed using H-waves, F-waves, and motor-evoked potentials induced by transcranial magnetic stimulation [1–6]. The Jendrassik maneuver, a method for enhancing the reflexes, is widely known in clinical practice. The facilitatory effects of this maneuver on the cerebral cortex and spinal motor neurons differ between the upper and lower extremities [3] and are affected by the timing from the start of exercise [2]. Furthermore, studies have shown that the facilitatory effects of the contraction of muscles in remote regions, such as the upper and lower extremities, on other regions are affected by contraction intensity [4, 5] and the number of muscle spindles [5, 6].

Some reported cases of hemiplegic patients with cerebrovascular disorders undergoing physical therapy did not differ significantly in terms of contraction strength of the muscles involved in the movements or limb position. However, the appearance of associative reactions in the upper extremities of the paralyzed side seems to depend on exercise task difficulty. In our previous study, we reported that more difficult voluntary movements of the upper extremities increased the excitability of spinal motor neurons in the contralateral upper extremities [7]. However, because there are cases in which associative reactions appear when voluntary movements of the lower extremities such as stepping are induced, the excitability of spinal motor neurons in the upper extremity during movement of the lower extremities requires examination. In this study, we investigated the effect of differences in the difficulty of lower extremity movement tasks on the excitability of upper extremity spinal motor neurons using F-waves evoked by electromyography (EMG).

2. Subjects and methods

2.1 Participants

Twenty healthy right-footed adults (17 men, 3 women; mean age, 25.7 ± 6.2 years) with no orthopedic or neurological abnormalities participated in this study. To determine each participant's dominant foot, we used the dominant foot test described by Chapman et al. [8]. From the test results, those with a total score ≥ 28 on the 11 items were identified as left-footed and excluded from the study.

In addition to receiving explanations of the study objectives, the subjects were informed that their test data would be strictly confidential and that they could withdraw from the study at any time. Subjects' signatures on the study consent forms were obtained once they had agreed to participate. This study received approval from the ethics committee of Kobe College of Rehabilitation.

2.2 Conditions for recording the F-wave

F-waves were derived from the right abductor pollicis brevis (APB) muscle during the rest and motor tasks of the bilateral lower limbs using the Viking Quest EMG system (Nicolet Biomedical, Madison, WI, USA; **Figure 1**). Each subject was seated on a chair during the test with the neck flexed at 30°; hip flexed at 80°; knee joints flexed at 90°; and the ankle, shoulder, elbow, and hand joints at 0°.

Stimulation conditions for F-wave elicitation were 30 consecutive stimulations of the median nerve at the right wrist with an intensity of 120% of the stimulation intensity required to evoke the maximum M-wave, a duration of 0.2 ms, and a frequency of 0.5 Hz. Bipolar surface-stimulating electrodes used in general motor nerve conduction velocity tests were used as the stimulating electrodes with the cathode at the center and the anode at the periphery. For the recording conditions, the exploring electrode was placed over the belly of the right APB muscle, the reference electrode on the proximal phalanx of the thumb, and the ground electrode on the forearm (**Figure 2**).

The electrode sites were rubbed with a cotton pad that was moistened with alcohol to remove any oil and the horny layer of the skin was removed using a skin preparation gel. Ten-millimeter-diameter silver-silver chloride disk electrodes were affixed to the skin surfaces using a conductive paste. Bioelectrical signals obtained at the electrodes were conducted to the input via lead wires, amplified with a bioamplifier, converted from analog to digital signals with an AD converter, and displayed on a personal computer as waveforms. All signals were digitized at a sampling frequency of 24 kHz and recorded on the hard disk. The data were band-pass filtered between 20 and 3 kHz with a sweep speed of 5 ms/div and amplitude sensitivity of 200 μV/div.

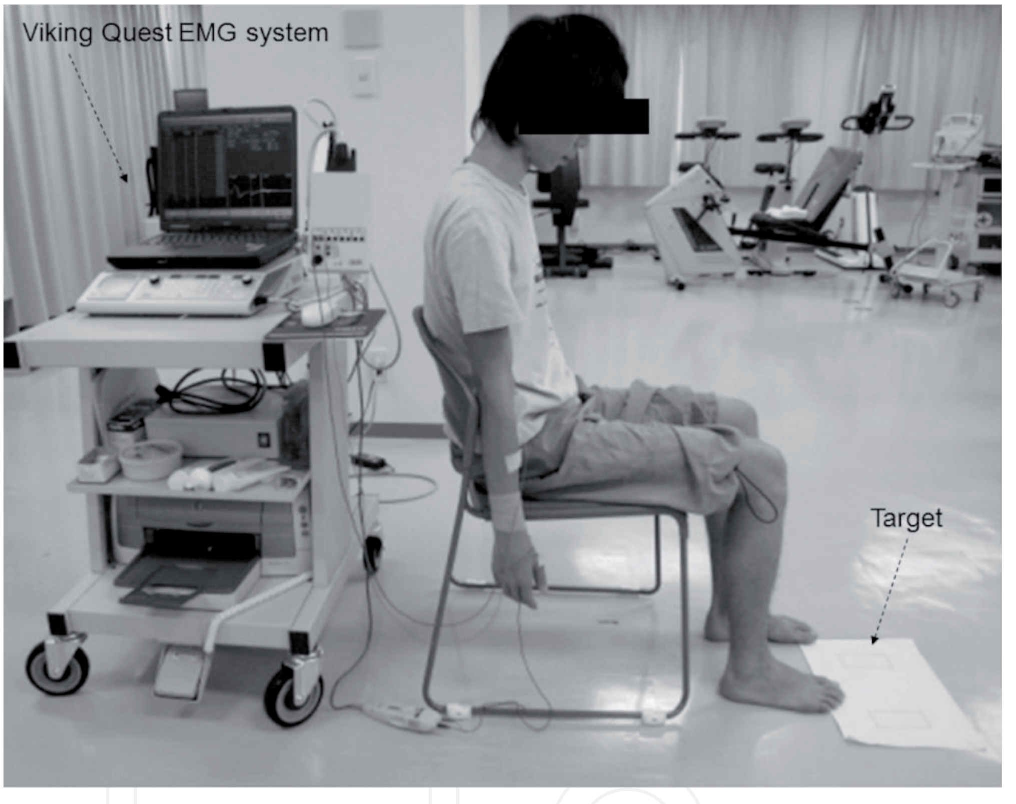

Figure 1.
Measurement of the F-wave.

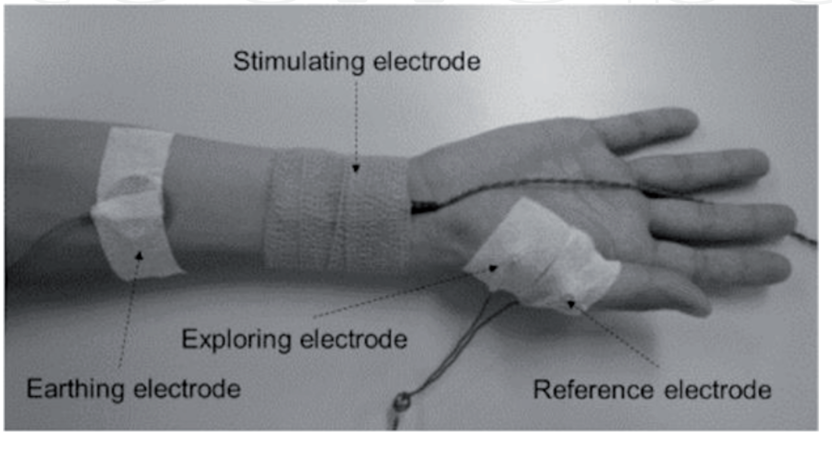

Figure 2.
Placement of the electrode.

The F-waves were analyzed for the amplitude ratio of the F/M. The amplitude ratio of the F/M was calculated as the ratio of the average peak-to-peak F-wave amplitude and the maximum M-wave amplitude.

2.3 Motor tasks

There are cases of stepping exercise to a specified space in physical therapy. This ability is necessary when avoiding obstacles or walking in defined places. In this study, the following different difficult tasks were performed.

In the lower extremity movement task, the participants stepped alternately to the left and right under four different difficulty levels. The difficulty index was defined by the exercise distance and target width, and the exercise duration was proportional to it [9]. Because exercise speed and distance can affect the excitability of the spinal motor neurons in the upper extremity, we manipulated the degrees of task difficulty by changing the target width (**Figure 3**). In Task 1, the participants' feet landed randomly. In Task 2, two 7.5 cm × 10.0 cm (width × length) targets were set and the participants were asked to land on the targets with the thumb of the foot. In Task 3, two 5.0 cm × 10.0 cm targets were set and the participants were asked to land on the targets with their big toe. In Task 4, two 2.5 cm × 10.0 cm targets were set and the participants were asked to land on the targets with their big toe. These target widths were set two and three times based on the width of big toe, respectively (i.e., 2.5, 5.0, and 7.5 cm). There were 20.0-cm intervals between targets. The exercise frequency was 1 Hz. Each task was performed on the right and left lower extremities. The order of the tasks was randomized with a 1-minute rest between tasks. During the lower extremity movement task, electrical stimulation for F-wave derivation was given when the hip joint was adducted.

The success rate of each task and motor activity of the lower extremities were investigated using surface EMG in five adult men (mean age, 24.6 ± 3.5 years) before the exercise tasks. Surface EMG was performed using the MQ8 telemetry

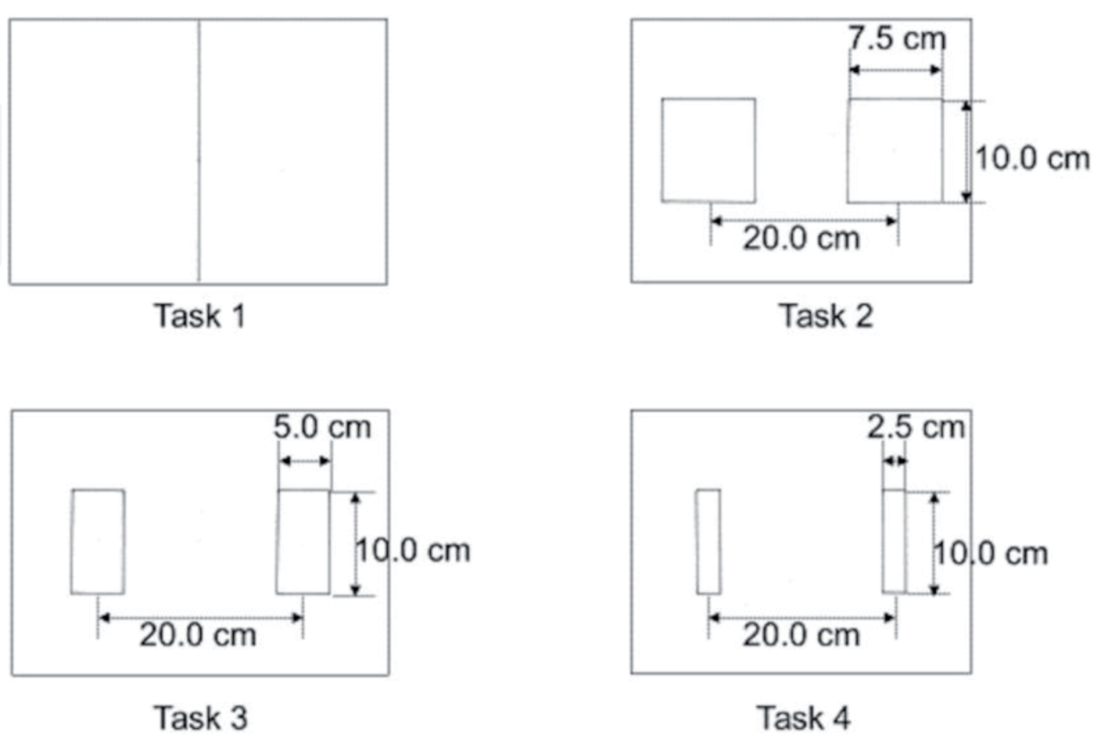

Figure 3.
Task targets.

Motor task	Relative value of iEMG		Success rate (%)
	Rectus femoris	Adductor of hip joint	
Right leg			
Task 1	1.16 (1.06–1.46)	1.02 (1.01–1.02)	
Task 2	1.35 (1.11–1.46)	1.02 (1.01–1.03)	100.0
Task 3	1.45 (1.11–2.54)	1.09 (1.02–1.12)	86.4
Task 4	1.44 (1.15–2.57)	1.03 (1.01–1.04)	40.2
Left leg			
Task 1	1.24 (1.01–2.35)	0.98 (0.97–1.06)	
Task 2	1.32 (0.92–2.58)	1.01 (0.98–1.45)	99.2
Task 3	1.39 (1.23–3.12)	1.04 (0.98–1.46)	81.0
Task 4	1.50 (0.81–3.00)	1.04 (0.96–1.49)	30.2

Relative integrated electromyography (iEMG) values are shown as median (interquartile range).

Table 1.
Relative value of iEMG and success rates.

EMG measuring system (KISSEICOMTEC; Matsumoto, Nagano, Japan). The recording muscles were the rectus femoris and adductor muscles of the hip joint. The derivation method was bipolar, and the electrodes were positioned 2 cm apart. The electrode on the adductor of the hip joint was placed at the midpoint of the line that connected the pubic symphysis and the medial epicondyle of the femur, while the electrode on the rectus femoris was placed 15 cm above the patella. The earthing electrode was placed on the patella. The skin where the electrodes were placed was cleaned with alcohol. The electrodes were disposable. The EMG signal analysis program BIMUTAS-Video (KISSEICOMTEC) was used to analyze the derived signal. The analysis item of the surface EMG was the relative value of the integrated EMG (iEMG). The relative value of iEMG was calculated from each task based on the iEMG of the sitting position. The success rate was determined from images taken using an IXY digital camera (Canon; Ota, Tokyo, Japan) that were synchronized with surface EMG. The relative values of iEMG were compared using Friedman's test. Statistical significance was accepted for values of $p < 0.05$.

Table 1 shows the success rate of each task and relative value of iEMG of the muscle groups of the lower extremities. The relative value of iEMG of the rectus femoris and adductor of hip joint did not differ significantly among the tasks for either lower extremity. These results show that the tasks used in this study differed in the degree of difficulty but not in the activities of the muscle groups that were involved in the exercises. In this way, there was no difference in muscle activities because exercise speed and distance were similar for all tasks.

2.4 Statistical analysis

The amplitude ratios of the F/M during the rest and movement tasks were compared using Dunnett's test. Statistical significance was accepted for values of $p < 0.05$.

3. Results

Figure 4 shows a typical waveform of the F-wave, while **Table 2** shows changes in the amplitude ratio of the F/M for each task.

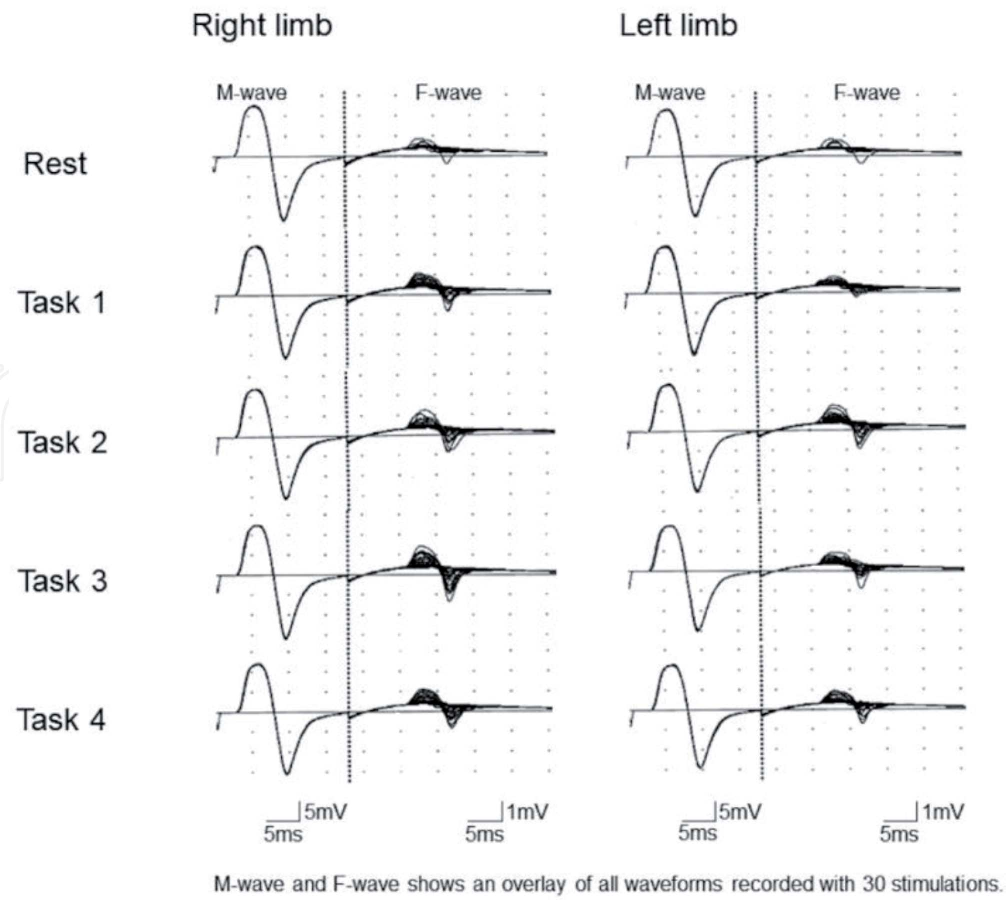

Figure 4.
The typical F-wave.

	Rest	Task 1	Task 2	Task 3	Task 4
Right leg (%)	0.70 ± 0.29	1.17 ± 0.54*	1.18 ± o.53**	1.32 ± 0.69**	1.07 ± 0.53
Left leg (%)	0.65 ± 0.32	0.98 ± 0.44	1.23 ± 0.74**	1.33 ± 0.57**	1.04 ± 0.49
Values are shown as mean ± SD. *p < 0.05 vs. rest; **p < 0.01 vs. rest					

Table 2.
Change in the amplitude ratio of the F/M during lower extremity movement by task.

During the right lower extremity tasks, the amplitude ratio of the F/M increased significantly in Task 1, 2, and 3 compared to that at rest. During the left lower extremity tasks, the amplitude ratio of the F/M increased significantly in Task 2 and 3 compared to that at rest.

4. Discussion

F-waves originate from retrograde excitations of the α motor neurons through the stimulation of peripheral motor nerve axons [10]. The amplitude ratio of the F/M represents the percentage of motoneurons activated by antidromic stimulation [11]. Therefore, they were applied as a test for the excitability of spinal motor neuron pools and upper nerve systems. In this study, the amplitude ratio of the F/M of APB muscle increased in Task 1, 2, and 3 for the right lower extremities and in Task 2 and 3 for the left lower extremities. This finding suggests that the voluntary movement of the lower extremities increases the excitability of the spinal motor neurons in the upper extremity.

Sensory input from the muscles is suggested to be involved in the facilitatory effects from the lower to upper extremities [12, 13]. However, the excitability of the cerebral cortex and spinal motor neurons reportedly varies even in motor imagery without muscle contraction [14–16]. Hess et al. [17] studied amputees with phantom limb syndrome and reported increased contralateral motor-evoked potentials through transcranial magnetic stimulation from images of the muscle contractions of the amputated limb. This revealed the involvement of facilitatory effects by intracortical mechanisms. Furthermore, Baldissera et al. [18] reported that the excitability of the forearm region fluctuated with ankle movement by discovering that suppressing the area of the motor cortex controlling the forearm by magnetic stimulation eliminated fluctuations in the H-waves of the radial carpal flexors accompanying the plantar/dorsiflexion motion of the ankle. Studies using functional magnetic resonance imaging and positron tomography also reported that the cerebral cortex has common activated sites during hand and foot movements [19, 20]. Similarly, in this study, the excitability of the spinal motor neurons in the upper extremity may have increased due to proprioceptive input from voluntary movements of the lower extremities and facilitation effects from the upper central nervous system from movement recall. The effects of the proprioceptive input include excitatory effects from an increase in efferent impulses through the brainstem and cortex as well as those via the propriospinal tract. In terms of the influence of the upper central nervous system, the motor regions activated during lower extremity movement are most likely also affected during upper extremity movement via the association fibers. Because the amplitude ratio of the F/M of the right APB muscle also increased during exercises involving the left lower extremities on the contralateral side, the facilitatory effect described above affected the contralateral upper extremity spinal motor neurons via the commissural fibers and non-crossed projection fibers.

Activities of the lower extremities tended to increase the spinal motor neuron excitability during the motor task. On the other hand, the results differed between the tasks. There was no significant difference in the amplitude ratio of the F/M during Task 4 for the right lower extremities or during Task 1 or 4 for the left lower extremities compared with that during rest. Because all tasks had the same exercise speed, range, and activity of the involved muscle groups, differences in exercise style corresponding to task difficulty were considered related. Voluntary movements can be simple or complex and are performed consciously or unconsciously. Kitamura et al. [21] compared simple and complex movements using movement-related potentials and reported that supplemental and sensory-motor areas were more active in complex than in simple movements. Winstein et al. [22] reported that the activities in areas related to the planning of complex movements requiring visuomotor processing increased as the task difficulty increased using positron emission tomography. In this way, motor-related areas are more activated by difficult exercises. The cerebellum plays an important role in regulating movement. Ugawa et al. [23] reported that applying magnetic stimulation to the cerebral cortex after applying electrical stimulation to the cerebellum reduced motor-evoked potentials for a few seconds. This inhibitory effect is thought to affect the cerebral motor area via the cerebello-thalamo-cortical pathway. Furthermore, neuronal activities at other sites may be reduced because more attention is needed to improve movement accuracy [24]. This study demonstrated that it is difficult to clearly explain the excitatory and inhibitory effects on the spinal motor neurons in the upper extremity, but the following points were considered possible factors affected by differences in exercise style. The participants were able to exercise more autonomously in Task 1 than in the other tasks, which suggests involvement of the excitatory effect of proprioceptive input in the spinal cord. Task 2 and 3 required more difficult movements than Task 1, which suggests that the upper central nervous system was involved in addition to proprioceptive input. Task 4 of the most difficult task required greater accuracy than the other tasks, which suggests involvement of the cerebellum and cerebral cortex in addition to the abovementioned excitatory effect.

There was a difference in the results of Task 1 between the motor tasks of the right and left lower extremities. In the right lower extremities, because the amplitude ratio of the F/M of the right APB muscle increased in Task 1 compared to that at rest, the excitatory effect on the spinal motor neurons in the upper extremity was considered superior to that of the contralateral lower extremities during voluntary movements of the lower leg.

5. Conclusions

In this study, we used F-waves to investigate the effect of different degrees of motor task difficulty of the lower extremities on the excitability of the spinal motor neurons in the upper extremity. We found that both lower extremities tended to increase the excitability of the spinal motor neurons in the upper extremity during motor tasks. This was due to the effect of proprioception on voluntary movements of the lower extremities and increased excitability of the spinal motor neurons in the upper extremity from the excitation of the upper central nervous system. Regarding the differences in task difficulty, the effect on the spinal motor neurons in the upper extremity was greater in tasks that required accurate voluntary movements, such as Task 2 and 3, than in those that could be performed autonomously, such as Task 1. However, for Task 4, which required the greatest degree of accuracy, both inhibitory effects related to the adjustment of movements and excitatory effects were involved.

When inducing voluntary movement of the lower extremities in physical therapy, the potential effects of differences in task difficulty on the facilitation and inhibition of the spinal motor neurons in the upper extremity must be considered. However, the excitability of the reflex arch of the spinal cord is different in hemiplegic patients with cerebrovascular disorders than in healthy individuals. Because the excitatory effects are expected to be significant, further studies are required to validate our results.

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Conflict of interest

The author declares no conflicts of interest.

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