Minireviews

Precision pinch force control via brain and spinal motor neuron excitability during motor imagery

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ABSTRACT

This study presents a novel approach for identifying neural substrates underlying the beneficial effects of motor imagery. For motor imagery, participants were instructed to imagine contraction of the left thenar muscle at 50 % maximal voluntary contraction (MVC). The participants then performed isometric contractions of the thumb and index finger at 50 % MVC as accurately as possible after motor imagery and without motor imagery. F-waves and oxygen-hemoglobin levels were examined with and without motor imagery relative to the resting condition. These data were analyzed using structural equation modeling. The degree of changes in the excitability of spinal motor neurons using F-waves during motor imagery may be modulated by inputs from the supplementary motor area. F-waves were analyzed with respect to persistence and the F-wave/maximum M-wave amplitude ratio. We found an association between precision pinch force control after motor imagery and spinal motor neuron excitability during motor imagery. The excitability of the supplementary motor area was not directly associated with precision pinch force control. However, spinal motor neuron excitability was adjusted by the supplementary motor area. Thus, the ability to perform precision pinch force control may be influenced by the supplementary motor area through the excitability of spinal motor neurons.

1. Introduction

Motor imagery is a cognitive process in which individuals internally simulate a movement or action being performed by themselves in the absence of a movement [1]. Motor imagery can be used when learning motor tasks as a complement to physical training or to improve overall motor performance [2,3]. Previously, we showed that the use of motor imagery enhances the accuracy of a pinch action through isometric contraction [4]. These studies suggest that motor imagery may be valuable in situations in which motor execution is impaired or absent owing to neurological disease; however, its effect in neurorehabilitation has yielded mixed results [5]. This inconsistency is likely due to an incomplete understanding of the neural mechanisms underlying motor imagery.

Behaviorally, motor imagery and motor execution are closely related [6] and share similar neural networks [7]. Numerous studies [8–10] have shown that the activation of central brain regions is involved in motor execution during motor imagery, including the supplementary motor area (SMA) and primary motor area (M1). According to neurological-based studies, there is strong activation of the SMA during motor imagery. Regarding M1, there are contradictory reports regarding its activation [8,11] or lack of activation [9,12]. In addition, spinal motor neuron excitability may not always increase during motor imagery. Persistence and the F-wave/M-wave (F/M) amplitude ratio during motor imagery of a pinch action at 50 % maximal voluntary contraction (MVC) were significantly increased compared to that during rest [13]. However, no significant differences were observed in the amplitude of the H-reflex between the resting condition and motor imagery involving flexion-extension movements of the wrist joint [14].

Many of these previous studies did not measure simultaneously the activity of central brain regions involved in motor execution, the excitability of spinal motor neurons, and performance, which might have led to the inconsistent results. Therefore, the neural mechanisms of motor imagery have not been elucidated fully. M1 excitability is directly related to motor execution, and motor imagery is performed without any overt movements; therefore, it can be hypothesized that M1 is not directly involved in the generation of motor imagery. Previously, motor imagery was shown to improve pinch force precision and increase spinal

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motor neuron excitability [15]. We considered that the increased excitability of spinal motor neurons might be influenced by regions other than M1 and be centered on the SMA.

The main purpose of the present study was to examine the effects of motor imagery on the precision of pinch force control based on the neural mechanisms involved in the excitability of brain and spinal motor neurons during motor imagery.

2. Materials and methods

2.1. Participants

Eighteen healthy volunteers (9 men and 9 women; mean age, 21.3 ± 0.5 years) participated in the study. Written informed consent was obtained from all participants. The experiments were conducted in accordance with the Declaration of Helsinki, and the study was approved by the Research Ethics Committee of Kansai University of Health Sciences (approval number: 19-39).

2.2. Study procedure

Participants were placed in a supine position for 30 s. They were instructed to execute the learned pinch force at 50 % MVC by isometrically contracting and holding a pinch meter sensor (F340A; Unipulse, Inc., Tokyo, Japan) between the left thumb and index finger for 30 s. Visual feedback was provided to the participants on the display of the digital pinch meter indicator during motor practice. For the pinch force matching task (Pinch Task 1), the participants were required to perform

Fig. 1. Pinch task method.
The participant performed three steps during the pinch task: 1) the participant holds a pinch sensor in preparation for a pinch action, 2) the participant performs a pinch action and tries to adjust the pinch force to 50 % MVC, and 3) the participant was instructed to press only one button the moment the 50 % MVC adjustment was completed. The button is connected to the measurement PC, and a spike appears on the PC screen when the button is pushed. The force control error between the measured pinch force and 50 % MVC was analyzed at the timing of spike appearance.
isometric contraction of the left thumb and index finger at 50% MVC as quickly and accurately as possible without visual feedback. For the motor imagery condition, the participants were instructed to imagine performing the contraction at 50% MVC for 30 s. For the without motor imagery condition, participants were instructed to relax for 30 s. Subsequently, they were instructed to repeat Pinch Task 1 with and without motor imagery (Pinch Task 2). Both pinch tasks were performed twice. There was no difference in the subjects’ ability to perform motor imagery according to their responses to the Visual Analog Scale.

2.3. Comparison between each pinch task

In each pinch task, the subject was not given visual feedback and was required to subjectively adjust to the target pinch force (50% MVC). In addition, the participants were instructed to push only one button while subjectively thinking of performing 50% MVC adjustment. The button was connected to the measurement PC, and a spike appeared on the PC screen when the button was pushed. The force control error between the measured pinch force and 50% MVC was analyzed at the timing of spike appearance. Pinch force was analyzed using recording software (Vital Recorder2; KISSEI COMTEC, Inc., Nagano, Japan) and a biological analysis system (BIMUTAS-Videoscope, KISSEI COMTEC, Inc.). The method of the pinch task is shown in Fig. 1.

2.4. Measurement of oxy-Hb and F-waves during motor imagery

NIRS (OT-R41; HITACHI, Inc., Tokyo, Japan) was used to measure cerebral blood flow oxygenation at rest, during motor imagery, and without motor imagery with a sampling rate of 10 Hz. NIRS is non-invasive, safe, places few restrictions on the participants, and has a high degree of freedom in the measurement environment. In order to unify the probe positions among the subjects, a probe-fixing 3 × 3 holder was fitted to C4 based on the International 10-20 system. The regions of interest (ROIs) were the SMA and M1 on the right side. Channel position and brain region were identified using Virtual registration [16]. Specifically, channels 8, 9, and 12 were estimated as the SMA on the right side, and channels 3 and 6 were estimated as M1 on the right side. Data analysis was performed using the system software attached to the OT-R41 spectroscope. We used oxy-Hb levels as a marker of cortical activity because oxy-Hb is the most sensitive indicator of change in regional cerebral blood flow, but t-Hb and deoxy-Hb might not change [17,18]. Moreover oxy-Hb signal has been used previously in measurements of cortical activation in motor imagery studies [9,19]. NIRS data analysis was performed with a 5-s moving average, and high-frequency components were removed. For the measurement protocol, each task was performed once, with 30 s for each task (resting condition and with and without motor imagery) with correction processing based on baseline fitting before and after performing the task.

A Viking Quest electromyograph (Natus Medical, Inc., Tokyo, Japan) was used to record F-waves at rest and with and without motor imagery. For stimulating electrodes, the cathode was placed over the left median nerve at 3 cm proximal to the palmar crease of the wrist joint, and the anode was placed at 2 cm proximally. F-waves were recorded from the left thenar muscles using a pair of disks that were attached to the skin over the belly of the thumb and the bones of the metacarpophalangeal joint of the thumb using collodion. Supramaximal shocks (adjusted to a value that was 20% higher than that of the maximal stimulus) were applied to the left median nerve at the wrist. The stimulus was delivered 30 times at 1.0 Hz for 0.2 ms. Electrical stimulation was used to induce F-waves. A previous report suggested that electrical stimulation at 1.0 Hz for 30 s would not significantly affect the measurement of cerebral blood flow [20]. Persistence was defined as the number of measurable F-wave responses from 30 stimuli. The F/M amplitude ratio was defined as the mean amplitude of all responses F-waves divided by the amplitude of the M-wave. F-waves and oxy-Hb levels during the resting condition were set as the baseline. Therefore, relative F-waves and oxy-Hb levels were used for comparisons between the with and without motor imagery conditions.

2.5. Data analysis

The Shapiro-Wilk tests found data that were not normally distributed (Force control error; p = 0.189 (motor imagery), p = 0.296 (without motor imagery), Persistence; p = 0.832 (motor imagery), p = 0.738 (without motor imagery), F/M amplitude ratio; p = 0.000 (motor imagery), p = 0.536 (without motor imagery), oxy-Hb levels at SMA; p = 0.002 (motor imagery), p = 0.237 (without motor imagery), oxy-Hb levels at M1; p = 0.000 (motor imagery), p = 0.000 (without motor imagery). The Wilcoxon signed-rank test was used to compare the force control error results for Pinch Task 2 between the with and without motor imagery conditions based on Pinch Task 1. Moreover, the Wilcoxon signed-rank test was used to compare F-waves (persistence and the F/M amplitude ratio) and oxy-Hb levels (ROI at the SMA and M1) between the with and without motor imagery conditions relative to the resting condition. The relationships between oxy-Hb levels, F/M amplitude ratio, and persistence were examined using Spearman’s correlation coefficients.

Structural equation modeling (SEM) was used to calculate the standardization coefficient for each factor. SEM is a statistical model that extends factor analysis and multiple regression analysis and can be used to understand and identify the putative causal associations between latent and observed variables. Moreover, SEM introduces latent variables that cannot be observed directly. Therefore, it is possible to analyze the association between variables without providing a control group. We assessed the data from the model for fitness with a goodness-of-fit index, comparative fit index, and root-mean-square error of approximation [21,22].

Statistical significance was set at p < 0.05. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) Statistics version 26.0 (SPSS, Inc., Chicago, IL, USA), and SEM was performed using SPSS Amos version 26.0 (SPSS, Inc.).

3. Results

3.1. Post-hoc power analysis

According to post hoc analysis using G*Power, the detection power was ≥0.9; therefore, the sample size was considered to be appropriate.

3.2. Force control error, F-waves, and oxy-Hb levels

Force control error was higher without motor imagery compared to with motor imagery (r = 0.80, p = 0.001). Persistence and the F/M amplitude ratio were higher with motor imagery compared to without motor imagery (persistence: r = 0.79, p = 0.001; F/M amplitude ratio: r = 0.88, p = 0.000). Oxy-Hb levels in the SMA were higher for motor imagery compared to without motor imagery (r = 0.85, p = 0.000). However, there was no difference in oxy-Hb levels at M1 between with and without motor imagery (r = 0.38, p = 0.107) (Fig. 2 a-d).

Fig. 3 shows typical oxy-Hb levels, F-waves, and background EMG as evidence that the F wave was not primarily affected by muscle contraction. Moreover, we examined the relationships between oxy-Hb levels, F/M amplitude ratio, and persistence using Spearman’s correlation coefficients (Fig. 3). Positive correlations were found between oxy-Hb levels at the SMA and F/M amplitude ratio (rs = 0.962, p = 0.000) and persistence (rs = 0.969, p = 0.000). No correlations were observed between oxy-Hb levels at M1 and the F/M amplitude ratio (rs = 0.096, p = 0.705) and persistence (rs = 0.100, p = 0.694).

3.3. SEM during motor imagery

Factor analysis of the four variables scored from all participants
showed a one-factor solution, which was used to construct a model in which a category affected neural output during motor imagery. We analyzed this model using SEM. The p-value for the model fitting the $\chi^2$ value (2.703) was 0.440. In addition, goodness-of-fit index, comparative fit index, and root-mean-square error of approximation were 0.920, 0.860, and 0.000, respectively. Hence, all three fitness statistics indicated a good fit with the overall model. The final estimated model with standardized path coefficients is presented in Fig. 2e. The direction of

![Force control error, oxy-Hb, persistence, and F/M amplitude ratio.](image_url)

**Fig. 2.** Force control error, oxy-Hb, persistence, and F/M amplitude ratio.

Force control error was higher without motor imagery compared to with motor imagery (a). Oxy-Hb levels at SMA (b), the F/M ratio (c), and persistence (d) were higher with motor imagery than without motor imagery. Those factors were analyzed this model (e) using SEM. All fitness statistics indicated a good fit with the overall model. The strength of the relationship between the variables is expressed by the standardization coefficient value.
Fig. 3. Typical waveform and Relationship between oxy-Hb levels, F/M amplitude ratio, and persistence.
The upper part of the figure shows a typical waveform for Oxy-Hb level at SMA, M1, and F/M amplitude ratio and persistence. Moreover, F-wave was not majorly affected by muscle contraction from background EMG activity. The lower part of the figure shows scatter plots in F-wave (F/M amplitude ratio and persistence) and Oxy-Hb (ROIs were SMA and M1). Orange line: positive correlation observed between oxy-Hb levels at the SMA and the F/M amplitude ratio and persistence. Red line: no correlations observed between oxy-Hb levels at M1 and the F/M amplitude ratio and persistence.
the relationship between the variables is represented by the direction of the arrows in the figure. The strength of the relationship between the variables is expressed by the standardization coefficient value. The standardized coefficient was $-0.15$ from “SMA” to “M1,” 1.00 from “SMA” to “excitability of spinal motor neurons,” and $-13.58$ from “M1” to “excitability of spinal motor neurons.” Conversely, the standardized coefficient was 0.47 from “excitability of spinal motor neurons” to “F/M amplitude” and 1.00 from “excitability of spinal motor neurons” to “persistence.” The standardized coefficients from “SMA” to “M1” and from “M1” to “excitability of spinal motor neurons” were both negative. Therefore, “SMA” was interpreted as having a positive effect on “excitability of spinal motor neurons.”

4. Discussion

4.1. Motor imagery prevents the loss of precision pinch force control

The purpose of this study was to measure and statistically interpret central brain regions involved in motor execution, spinal motor neuron excitability, and performance. As a result, motor imagery prevented the loss of precision pinch force control.

We found that force control error was higher without motor imagery than with motor imagery. Moreover, spinal motor neuron excitability (F/M amplitude ratio and persistence) was higher with motor imagery than without motor imagery.

Ohashi [23] reported difficulty in maintaining intensity during isometric contractions. Previously, we reported that motor imagery after 30-s motor practice improves precision pinch force control and increases spinal motor neuron excitability [4]. Regulation of the excitatory changes at the spinal cord level is important for improving precision pinch force control [24]. The effect of motor imagery is dependent on an individual’s ability [25], and motor imagery improves the ability to perform an actual motion only in people with learning corresponding to the motor imagery task [26]. In this study, the 30-s motor practice might have enabled the participants to acquire sufficient working memory to perform motor imagery. Motor imagery might adjust the gain control of spinal cord excitability in preparation for the motion, thus, increasing the excitability of spinal motor neurons in preparation to prevent the loss of information pertaining to intensity.

4.2. Spinal motor neuron excitability and oxy-Hb levels at the SMA are increased during motor imagery

Oxy-Hb levels in the SMA and the F/M amplitude ratio and persistence were increased during motor imagery. However, there was no significant difference in oxy-Hb levels at M1 between the presence and absence of motor imagery. Moreover, there was a strong relationship between oxy-Hb levels at the SMA and the F/M amplitude ratio and persistence. From SEM, SMA activity during motor imagery was found to be involved in the increased excitability of spinal motor neurons and inhibited M1 activity.

The SMA simulates movement from previous memory and predictive information [27]. During motor imagery, the SMA is activated because one of its main functions concerns the recall of motor tasks. In addition, electrical stimulation of the SMA induces motor execution because it contains an independent motion execution area [28]. Spinal motor neuron excitability is influenced by descending pathways from central brain regions during motor execution [13]. Therefore, it is possible that the increased activity in the central nervous system, including the SMA, induced by motor imagery, increased spinal motor neuron excitability via descending pathways. In contrast to the excitability of the SMA, there was no difference at M1 between the presence and absence of motor imagery. In a previous study, M1 was not excitable during motor imagery [29]. Even in a study that reported M1 activation during motor imagery, it was only at $\sim 30 \%$ of that observed during motor execution [11]. Furthermore, there is positive connectivity from the SMA to M1 during exercise execution, but motor imagery is associated with negative connectivity between these regions [30]. In this study, as revealed by SEM, SMA activity during motor imagery inhibited M1 activity. Therefore, the difference in M1 activity between the results of this and previous studies was considered to be due to the degree of inhibition from the surrounding region. In other words, previous studies regarding M1 activation during motor imagery suggest that some level of suppression is required for obvious motor avoidance, but movement cannot be suppressed completely, which may have led to the excitability of M1 detected in previous studies. However, M1 activity was recognized in motor imagery studies using fMRI [8,11] and TMS [14]. TMS is highly sensitive to detect neural activity [31], and this difference in sensitivity may explain the different results related to M1 activity between this study and the previous study.

4.3. Study limitation

This study has some limitations. Different tasks may have been added during the motor imagery task. However, even if a task does not involve motor imagery, just focusing your attention can increase SMA activity [32]. In this study, an attention task was not set, so motor imagery and other elements could not be separated clearly. In future study, it will be necessary to provide control tasks such as attention tasks, in addition to with and without motor imagery tasks, to clarify the relationship between the F-wave parameters and NIRS related parameters in SMA.

4.4. Conclusion

Motor imagery increased spinal motor neuron excitability (persistence and F/M amplitude ratio) and oxy-Hb levels at the SMA. On the basis of the neural mechanisms identified using SEM, spinal motor neuron excitability was found to be modulated by input from the SMA.

Author contributions

Study conception and design: all authors.

Material preparation and data collection and analysis: Yuki Fukumoto, Marina Todo, Hiroki Bizen, Daisuke Kimura, Toshiaki Suzuki.

Writing – original draft: Yuki Fukumoto.

Writing – review and editing: all authors.

Final approval: all authors.

Data statement

The datasets and/or analyses generated during the current study are available from the corresponding author upon reasonable request.

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Declaration of Competing Interest

The authors report no declarations of interest.

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References

[1] M. Farah, The neural basis of mental imagery, Trends Neurosci. Educ. 12 (1989) 395–399, https://doi.org/10.1016/0166-2236(89)90079-9.

[2] G. Yue, K.J. Cole, Strength increases from of motor program: comparison of training with maximal voluntary and imagined muscle contractions,
[1] T. Suzuki, Y. Bunno, C. Onigata, M. Tani, S. Uragami, Excitability of spinal neural signals: a study with a newly developed perfused rat brain model, J. Appl. Physiol. 90 (2001) 1657–1662, https://doi.org/10.1151/jappl.2001.90.5.1657.

[2] J. Neurophysiol. 67 (1992) 1114–1123, https://doi.org/10.1152/jn.1992.67.5.1114.

[3] C. Schuster, R. Hilfinger, O. Amft, A. Scheidlbauer, B. Andrews, J. Butler, U. Kischka, T. Ertl, Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines, BMC Med. 9 (2011) 75, https://doi.org/10.1186/1741-7015-9-75.

[4] Y. Fukumoto, T. Suzuki, H. Iwatsuki, The influence of motor imagery and practice time on the accuracy and excitability of spinal anterior horn cells, Jpn. J. Clin. Neurophysiol. 47 (2019) 82–92, https://doi.org/10.1142/jcn.47.82 (in Japanese).

[5] F. Malouin, C. Richards, Clinical applications of motor imagery in rehabilitation, in: S. Lacey, R. Lawson (Eds.), Multisensory Imagery, Springer, New York, 2013, pp. 397–419.

[6] J. Decety, M. Jeannerod, C. Prablanc, The timing of mentally represented actions, J. Neurophysiol. 43 (1980) 118–136, https://doi.org/10.1152/jn.1980.43.1.118.

[7] M. Jeannerod, The representing brain: neural correlates of motor intention and imagery, Behav. Brain Sci. 17 (1994) 187–201, https://doi.org/10.1017/ S0140525X00004026.

[8] M. Lotze, P. Montoya, E. Hülsmann, H. Flor, U. Klose, N. Birbaumer, W. Grodd, Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study, J. Cogn. Neurosci. 11 (1999) 491–501, https://doi.org/10.1162/0898929995635553.

[9] H. Nakano, K. Ueta, M. Osumi, S. Morioaka, Brain activity during the observation, imagery, and execution of tool use: an fNIRS/EGG study, J. Nov. Physioth. (2012) S1, https://doi.org/10.4172/2165-7025.S1-009.

[10] P.E. Roland, B. Larsen, N.A. Lassen, E. Kihlström, Subjunctive motor area and other cortical areas in organization of voluntary movements in man, J. Neurophysiol. 43 (1980) 118–136, https://doi.org/10.1152/jn.1980.43.1.118.

[11] C.A. Porro, M.P. Francescato, V. Cettolo, M.E. Diamond, P. Baraldi, C. Zuiani, M. Bazzocchi, P.E. di Prampero, Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study, J. Neurosci. 16 (1996) 7688–7698, https://doi.org/10.1523/jneurosci.16-23-07688.1996.

[12] K.M. Stephan, G.R. Fink, R.E. Passingham, D. Silbersweig, A.O. Ceballos-Baumann, C.D. Frist, R.S. Frackowiak, Functional anatomy of the mental representation of upper extremity movements in healthy subjects, J. Neurophysiol. 73 (1995) 373–386, https://doi.org/10.1152/jn.1995.73.1.373.

[13] M. Nishida, A. Katsube, K. Inomata, S. Koyama, Y. Okazawa, M. Ito, A factor analytical study on vividness of motor imagery, Jpn. Soc. Phys. Educ. 26 (1981) 189–205, https://doi.org/10.5432/jpesh.JK0003402662 (in Japanese).

[14] T. Mulder, S. Zijlstra, W. Zijlstra, J. Hochstenbach, The role of motor imagery in learning a totally novel movement, Exp. Brain Res. 154 (2004) 211–217, https://doi.org/10.1007/s00221-004-1647-6.

[15] T. Kasai, S. Kawai, M. Kawanishi, S. Yahagi, Evidence for facilitation of motor evoked potentials (MEPs) induced by motor imagery, Brain Res. 744 (1997) 147–150, https://doi.org/10.1016/S0006-8993(96)01101-6.

[16] Y. Fukumoto, The effects of motor imagery after a variety of motor learning times on excitability of spinal motor neurons and accurate motion, in: T. Suzuki (Ed.), Neurological Physical Therapy, InTech, 2017, pp. 71–94.

[17] O. Jansen, Effector-independent representations of simple and complex imagined finger movements: a combined fMRI and TMS study, Eur. J. Neurosci. 18 (2003) 3375–3387, https://doi.org/10.1046/j.1460-9568.2003.03066.x.

[18] H. Onishi, K. Sugawara, K. Yamashiro, D. Sato, M. Suzuki, H. Kurihoto, H. Tamaki, H. Murakami, S. Kaneyama, Neuromagnetic activation following active and passive finger movements, Brain Behav. 3 (2013) 178–192, https://doi.org/10.1002/brb3.126.

[19] G. Strangman, M.A. Franceschini, D.A. Boas, Factors affecting the accuracy of near-infrared spectroscopy concentration calculations for focal changes in oxygenation parameters, Neuroimage 18 (2003) 865–879, https://doi.org/10.1016/s1053-8119(03)00021-1.

[20] M. Mihara, I. Miyai, N. Hattori, M. Hatakenaka, H. Yagura, T. Kawano, M. Okihayashi, N. Danjo, A. Ishikawa, Y. Inoue, K. Kubota, Neurofeedback using real-time near-infrared spectroscopy enhances motor imagery related cortical activation, PLoS One 7 (2012), e32234, https://doi.org/10.1371/journal. pone.0032234.

[21] R. Suzuki, S. Koton, M. Nakagawa, S. Miyaguchi, S. Kojima, K. Saito, Y. Imukai, H. Onishi, Presence and absence of muscle contraction elicited by peripheral nerve electrical stimulation differentially modulate primary motor cortex excitability, Front. Hum. Neurosci. 11 (2017) 146, https://doi.org/10.3389/fnhum.2017.00146.

[22] T.A. Brown, Confirmatory Factor Analysis for Applied Research, Guilford Press, 2006.

[23] W. Penfield, K. Welch, Supplementary motor area of the cerebral cortex: a clinical and experimental study, AMA Arch. Neurol. Psychiatry 66 (1951), https://doi.org/10.1001/archneurpsyc.1951.023200900380047, 289–231.

[24] C.H. Kases, C. Windischberger, R. Cunnington, R. Lanzenberger, L. Pezawas, E. Mosera, The suppressive influence of SMA on M1 in motor imagery revealed by fMRI and dynamic causal modeling, Neuroimage 40 (2008) 828–837, https://doi.org/10.1016/j.neuroimage.2007.11.040.

[25] A. Solodkin, P. Hlustik, E.E. Chen, S.L. Small, Fine modulation in network connectivity during motor imagery, InTech, 2017, pp. 71–94.

[26] J.P. Kupsz-Buchbeck, C. Mahnkopf, C. Holzknecht, H. Siebner, S. Ulmer, O. Jansen, Effector-independent representations of simple and complex imagined finger movements: a combined fMRI and TMS study, Eur. J. Neurosci. 18 (2003) 1246–1255, https://doi.org/10.1046/j.1460-9568.2003.03066.x.