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Motor Imagery and Its Practical Application

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The physiological mechanisms underlying the process of motor imagery have significant similarities with the mechanisms of motor control, and this can be used for the rehabilitation of patients with movement disorders. In patients with severe paresis, motor imagery may be the only method producing movement recovery. Over the last decade, this has led to increasing interest in studies of the function of motor imagery. Brain–computer interface technologies can be used monitor training with imaginary movements.

Keywords: motor imagery, motor system, neurorehabilitation, brain–computer interface.

Motor imagery is a cognitive-perceptive process and is the mental performance of movements not accompanied by any kind of peripheral (muscular) activity. Visual and kinesthetic forms of motor imagery are discriminated. In the former, a person produces a visual image of their own movement, seeing it as though it was a third person's. In the latter case, subjects generate the kinesthetic sensation of movement. In recent years, studies of the function of motor imagery have involved paying special attention to a number of assumptions. Firstly, imaginary movements have been shown to be linked to conscious activation of areas of the brain which are also involved in the preparation and execution of the movement [28, 39]. This can be used in the neurorehabilitation of patients with profound post-stroke pareses, as existing methods of motor training, based on active use of the paralyzed limb, are inappropriate for this category of patients. This type of training can also be used in patients with mild motor impairments for training to better movement planning and greater accuracy of execution [57]. Secondly, kinesthetic motor imagery is the most common paradigm for the use of noninvasive brain–computer interfaces [1, 40], so studies of the physiological bases of this process may facilitate its further development. Finally, this nervous system function has as yet received little study, so fundamental neurophysiological studies using contemporary neuroimaging methods will allow deeper understanding of the physiology of the motor nervous system and the mechanisms of neuroplasticity.

This review assesses studies mainly addressing kinesthetic motor imagery and the potential for using it for motor rehabilitation.

Anatomical-Physiological Bases. Many studies of healthy subjects have shown that imaginary movements produce activation of those brain structures which are activated on performed of voluntary movements. However, the degree of CNS activation is generally weaker in imaginary movements than on movement execution, and the final afferent command is missing or suppressed. The structures involved in imaginary movements are the premotor and accessory motor zones (Brodmann field 6), the parietal cortex and cingulate gyrus, the basal ganglia, and the cerebellum [17, 38, 53]. These brain structures are known to have a role in the planning and monitoring of movement execution. These studies also demonstrated activation of the primary motor cortex (Brodmann field 4). At the same time, other analogous studies have not identified activation of this area during imaginary movements [13, 25, 44]. In this regard, many authors believe that activation of the primary

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motor zone is obligatory for imaginary movements. This cortical area is primarily involved in movement execution, which does not occur in motor imagery. The same study, reported by Sirigu et al, showed that a patient with a stroke focus in the primary motor cortex was able to imagine movements just like healthy people [56].

Furthermore, imaginary movements of different parts of the body (legs, arms, tongue) are accompanied by activation of the cerebral cortex, this being somatotopic in nature, which has been confirmed by results from studies using functional magnetic resonance tomography (fMRI) [12, 19, 60].

These data are consistent with previous studies in which transcranial magnetic stimulation (TMS) was used to study the effects of motor imagery on the excitability of the corticospinal tract. A UK group studied changes in the amplitude of motor evoked potentials induced by transcranial magnetic stimulation of the left motor cortex during imaginary movements. The amplitude of evoked electromyographic responses from the flexor muscles was greater during the period when the participant imagined flexion of the wrist than when extension was imagined, as well as in the opposite situation, when the amplitude of signals from the extensor muscles was greater during imagination of extension [26]. It was also demonstrated that during motor imagery, the excitability of the corticospinal tract was modulated by the same temporal and spatial characteristics as during the actual movements. Later studies reported by Stinear in 2006 yielded analogous results. These studies showed that kinesthetic, but not visual imagination of movement could modulate the excitability of motor structures at the supraspinal level [59].

In addition, results of TMS studies performed in Fadiga's laboratory provided grounds for suggesting lateralization of the function of motor imagery, with dominance of the left hemisphere [20]. This study involved magnetic stimulation of the right and left motor cortex with simultaneous recording of evoked potentials from the hand muscles during imagination of flexion and extension of the wrist. Magnetic stimulation of the left motor cortex increased the excitability of the corticospinal tract during imagination of both the right and left hands, while on stimulation of the right motor cortex this effect was only seen during imagination of left hand movements.

How does motor imagery modulate the excitability of the corticospinal tract? According to Abbruzzese et al., modulation occurs as a result of significant levels of suppression of inhibitory processes at the cortical level [2]. Having demonstrated experimentally that motor imagery does not affect the H reflex, Hashimoto also suggested that changes in the excitability of the motor tract have a cortical origin [26].

Although most studies in this area are oriented to imaginary movements of the hands (fingers) or tongue, it is important to note that activation of the corresponding cortical representation areas also occurs during imagination of large movements. Malouin et al. reported activation of the primary motor cortex and zones adjacent to the accessory motor cortex during the imagining of locomotor movements, as demonstrated in studies using positron emission tomography (PET) [34].

Completion of movements and imagination of movements also have common electroencephalographic signs: modulation of the sensorimotor rhythm, or mu rhythm. This rhythm, in the frequency ranges 7–13 Hz (mu-alpha) and 14–26 Hz (mu-beta), is recorded over the primary areas of the somatosensory and motor areas of the cortex at rest. During movement performance, preparation for movement, and imagination of movements, there are reductions in (desynchronization of) the sensorimotor rhythm in the cortical representation areas of the motor executive organ. Increases in the mu rhythm, i.e., event-linked synchronization, are seen after movements and during relaxation [47]. It has long been believed that the mu rhythm can only be recorded in a small proportion of the population (only 15% of cases), though studies in recent years using new EEG processing methods have shown that the mu rhythm can be recorded in virtually all humans [33]. Movement execution and movement demonstration in stroke patients has also been shown mainly to involve mu rhythm components for both the healthy hand and the paralyzed hand [37].

There are also similarities in behavior between imagining a movement and executing it. Movement imagination and execution are known to be virtually identical in duration. This phenomenon has been termed "mental isochronism." The time take for mental rotation of the hand is similar to the time taken for execution the analogous real hand movement [43]. Decety et al. followed the cardiac rhythm and respiratory frequency in subjects imagining and executing foot movements. Both real movements and imaginary movements were accompanied by increases in heart rate and respiratory rate [16].

A number of studies have compared patterns of brain activation in post-stroke patients as they executed or imagined movements. Studies using TMS have demonstrated increases in cortical representation areas in both hemispheres and in muscle response strength during motor imagery in patients with mild-moderate post-stroke hemiparesis in the subacute period (average two months after stroke). Thus, the authors concluded that motor imagery produced significant increases in cortical arousal even on the side of the hemisphere with the stroke focus [11]. Studies reported by Sharma's group [54] included 20 patients with good recovery of motor function after subcortical stroke and 17 healthy subjects as controls. During training sessions, subjects were shown or executed abduction of the thumb. fMRI was used to study activation of the primary motor cortex (Brodmann field 4), and the dorsal premotor and accessory motor cortex (Brodmann field 6). As a result, the pattern of brain activation during execution of the movement with the impaired hand was no different from that in the control group. However, during imagination of the movement, the pattern of activation of the lesioned hemisphere had a number of features: 1) in contrast to the control group and the intact hemisphere, activation of the primary motor and dorsal premotor cortex during motor imagery was no weaker than during movement execution; 2) the level of activation of the primary motor cortex on the lesioned side correlated positively with the level of movement recovery. The authors came to the conclusion that the motor system in patients with good recovery of motor function after stroke is activated on presentation of movements, despite the focal damage. However, disorganization of this activation was found to correlate with the extent of motor impairment [54].

Assessment of the Ability to Imagine Movements. However, the following questions remained open: 1) are there differences in the ability to imagine movements in healthy people? 2) To what extent is this function impaired when there is damage to the nervous system? 3) Can the ability to imagine be assessed?

Despite data supporting the view that motor imagery is preserved after stroke, the intensity of the feeling and the temporal link can be impaired – so-called chaotic motor imagery [53]. A relationship has been demonstrated between the intensity of motor imagery and the level of familiarity with the movement and the level of retention of working memory [17]. The ability to imagine movements can now be assessed using special questionnaire scales.

The Movement Imagery Questionnaire (MIQ) and Vividness of Motor Imagery Questionnaire (VMIQ) scales are based on questions addressing the ease with which particular movements of the upper and lower limbs can be imagined on 7- and 5-point scales respectively. Before assessment of each movement, subjects were asked to perform the movement. Motor imagery was assessed twice, once for visual imagination of movement execution (subjects were asked to “see” themselves performing the movement in their minds) and once for kinesthetic imagery (subjects were asked feel how their bodies executed the movement). The stability of MIQ test results from trial to trial was 87%. Data have been obtained supporting a direct relationship between points scores on the MIQ and the rate of acquisition of motor skills. The stability of VMIQ test results was 76%; correlations between the visual and kinesthetic subscales of the VMIQ and the same subscales on the MIQ were 0.65 and 0.49, respectively [4, 9, 23, 49].

While the MIQ and VMIQ were compiled for healthy subjects, the newer KVIQ (kinesthetic and visual imagery questionnaire) scale was developed to assess the ability of patients with post-stroke pareses to imagine [35], the KVIQ uses a five-point scale for assessment of the clarity of imagery (visual: the V subscale) and intensity (kinesthetic: the K subscale) of first-person sensations. The questionnaire lists simple movements such as tapping with the foot and bending the arms at the elbow, which can be executed more easily than the tasks in the MIQ and VMIQ. Stability of the results from test to test was demonstrated for healthy people (coefficient of intraclass correlation [ICC] = 0.72–0.81) and for people with post-stroke paresis (ICC = 0.81–0.90). This questionnaire confirmed the capacity for visual and kinesthetic motor imagery in stroke patients, patients with amputations or immobilization of the lower limbs, blind people, and healthy subjects of the control group.

Some authors have suggested use of the mental rotation method to assess the ability to imagine movements [14, 52]. The essence of this method is that the subject has to identify whether an image presented is of a left hand or a right hand. A sequence of images of hands in different positions is presented and the subject is asked to rotate them mentally to obtain the answer. The number of errors and the task performance time are measured.

As it is possible to learn motor imagery, at least in healthy people, resulting in increases in points scores on the VMIQ [24], the initial scores on these scales should not be used to guide inclusion of patients in rehabilitation programs based on motor imagery.

Motor Training Based on Motor Imagery. The literature contains data supporting the possibility of learning motor skills using motor imagery training in healthy people, producing not only higher-quality performance of motor tasks after training, but also neural rearrangement of cortical structures. In one of the first studies, subjects either imagined or completed a set of movements with the five fingers of one hand in a defined sequence on piano keys for two hours a day for five days [45]. The investigators used TMS to map the cerebral cortex. These studies showed that both imagination of and physical training to finger movement produced similar reorganization in the brain. Similar results have been obtained in a number of further studies [17, 27, 31, 32, 51]. Apart from plastic changes to the cerebral cortex, some studies have demonstrated reorganization in the cerebellum as a result of both physical exercise and training to imagine movements [27, 29].

Positive results have been obtained with the use of motor imagery in sportsmen, with improvements in measures of muscle strength and the speed and accuracy of task performance, as well as the level of acquisition of the new motor skill [5, 6, 62, 63].

The use of muscle training methods based on motor imagery in rehabilitation began in the late 1980s and early 1990s [15, 21, 61]. The development of neuroimaging methods such as fMRI, PET, and TMS and the use of these methods to identify the neural substrates for the motor imagery function has led in the last decade to studies of the efficacy of motor imagery methods in patients with neuromuscular diseases, especially post-stroke hemiparesis [17, 55].

Detailed descriptions of studies using motor imagery training for post-stroke rehabilitation and their results have been described in three reviews [7, 53, 64]. The data presented in these reviews indicate that most studies have used

TABLE 1. Characteristics of Studies Addressing Methods of Motor Imagery in Stroke Patients

Reference	Type of study	Details of patients	Treatment method	Results evaluation
[30]	RC	*n* = 46, primary ischemic stroke, duration of illness 14 months, FIM motor score = 42	**Study group:** 15 h of standard rehabilitation (5 times a week, 60 min) + 15 motor imagery procedures (5 times a week, 60 min). **Reference group:** 15 h of standard rehabilitation (5 times a week, 60 min) + demonstration of exercise followed by training (5 times a week, 60 min).	FMS
[18]	C	*n* = 20, duration of stroke 24 months, GS 68%, Barthel 95.5	**Study group:** daily motor imagery training at home for 4 weeks. **Reference group:** 1) visual imagination; 2) without motor imagery.	NHPT, GS
[42]	RC	*n* = 11, duration of stroke 23 months, ARAT = 33.1	**Study group:** 12 standard rehabilitation procedures (twice a week, 0.5 h) + 12 motor imagery procedures (twice a week, 0.5 h). **Reference group:** 12 standard rehabilitation procedures (twice a week, 0.5 h) followed by relaxation methods (0.5 h).	ARAT
[41]	RPC	*n* = 32, duration of stroke 43 months, moderate paresis	**Study group:** 12 standard rehabilitation procedures (twice a week, 0.5 h) + 12 motor imagery procedures (twice a week, 0.5 h). **Reference group:** 12 standard rehabilitation procedures (twice a week, 0.5 h) followed by relaxation methods (0.5 h).	ARAT, FMS
[50]	RC	*n* = 39, duration of stroke 42 months	**Study group 1:** 6 sessions (45 min each) of physiotherapy including motor imagery procedures. **Study group 2:** 6 sessions (30 min each) of physiotherapy followed by motor imagery for 15 min. **Reference group:** 6 sessions (30 min each) of physiotherapy followed by listening to a training audio for 15 min.	Movement time, FIM

Notes. C = controlled trial; RC = randomized controlled trial; RPC = randomized, placebo-controlled trial; NHPT = nine-hole peg test; GS = grip strength; Barthel = Barthel's index; ARAT = action research arm test; FMS = Fugl-Meyer scale; FIM = functional independence measure.

imagination only of one or another familiar movement. Patients were trained under the investigators' observation [30, 42] or at home [18]. Motor imagery training was often combined with traditional and/or non-traditional rehabilitative therapy or physiotherapy (PT). The frequency of training ranged from three days a week [41] to five days a week [30], sessions lasting 30–60 min, for periods of 2–6 weeks. Efficacy was generally assessed using the Fugl–Meyer or ARAT scales. The scale of these studies varied from descriptions of clinical cases [22] to a randomized, controlled trial involving 46 subjects [41]. The general characteristics of the main studies focused on methods of imagining hand movements in post-stroke rehabilitation are presented in Table 1.

It is important to note that most investigations covered in the reviews have shown that motor imagery improves rehabilitation of the upper limbs in stroke patients [7, 53]. Motor improvements are stable after a three-month observation period [58], and this is not restricted to the movements presented during the training period [30].

Although the designs of these studies were different, motor imagery training produced significantly greater rehabilitation of motor functions than obtained in controls, as evidenced by improvements in values on the Fugl–Meyer and ARAT scales, the Motricity index, and others. Nonetheless, it is difficult to produce general conclusions because of the heterogeneity of groups of patients, rehabilitation program methods, and approaches to evaluating the restoration of motor functions.

Motor Imagery and Brain–Computer Interfaces. Brain activity associated with motor imagery can be used in brain–computer interfaces (BCI). BCI are invasive or non-invasive technologies allowing various neurophysiological signals to be transformed into commands for an external apparatus or computer. This technology has been under active development in recent years for use in the rehabilitation of patients with neurological diseases [1, 55]. Interfaces of this type can provide a system for interactions with the surrounding world for patients with locked-in syndrome. Interfaces allow patients with motor disorders to control robotic prostheses, wheelchairs, and other devices (so-called assistance interfaces). By monitoring the process of motor imagery, interfaces with feedback can promote the correct reorganization of the motor cortex after lesioning ("rehabilitative interfaces").

Sensorimotor rhythms are among the best studies of EEG signals used for the non-invasive control by BCI [40]. The discovery of phenomena such as event-linked rhythm desynchronization and synchronization (motor activity, movement planning and execution), provided grounds for developing BCI controlled by sensorimotor rhythms [46]. There are several reports as to why the mu and beta rhythms have the greatest potential for use in BCI. Firstly, these rhythms are associated with brain areas with the most direct connections to the motor outputs. Secondly, desynchronization of the mu rhythm does not required real movements, but only their imaginary counterparts. Thus, the natural type of mental activity which can be recognized by BCI systems is the representation of any of the executive organs. Thirdly, presentation of movements of different organs creates different representations of activity on the cortical surface and, thus, different spatial EEG patterns, easing the task of the interface classifier [36]. Modulation of the sensorimotor rhythm can be used to control the movement of a cursor in one, two, or three directions, and to control the functional electrostimulation of the arm muscles, arm prostheses, accessory devices, and wheelchairs [55].

With the aim of verifying the potential use of rehabilitation programs including physical training and training using an rehabilitative BCI, an Irish group performed a study involving five patients with post-stroke paresis [48]. Patients underwent 12 30-min training sessions with BCI two days a week for six weeks (in combination with sessions of physical training of similar duration). The task consisted of imagining clenching the fist, with visual presentation of feedback consisting of movement of an object on a screen. The efficacy of biological feedback using BCI was assessed in terms of the accuracy of classification. Rehabilitation of upper limb function was assessed using a set of output parameters, including points scores on the ARAT scale and grip strength, with regular evaluation of tiredness and mood. All patients showed improvements in at least one of the output parameters considered. The authors concluded that the use of BCI for motor imagery provides a suitable method for use in post-stroke rehabilitation protocols combining physical exercise and training to motor imagery with BCI control.

Results from a study combining training to control BCI with targeted physiotherapy in a post-stroke patient were also reported [8]. A 67-year-old patient with hemiparesis following subcortical hemorrhage received three blocks of training using BCI combined with physical training for 12 months. Before training, the patient had no active finger movements, at home was dependent on assistance from others, and was able to travel no more than half a mile using a wheelchair. Each rehabilitation block consisted of daily training sessions for 30 days using an interface based on recording the sensorimotor rhythm (SMR). The first block used 275 megnetoencephalographic (MEG) tests and the second and third blocks recorded EEG signals. Targeted physiotherapy continued for 12 months. During the study, hand motor function and gait were tested repeatedly (using the Fugl–Mayer (FMA), Wolf Motor Function Test (WMFT), and the Ashworth scale), as was the organization of brain motor structures using neuroimaging methods. At one year, measures on the FMA, WMFT, and Ashworth scale were an average of 46.6% better. The patient could already unclench the paralyzed hand and move distances of more than half a mile independently. Analysis of the spectral amplitudes of MEG data reflecting cerebral cortex activity demonstrated significantly more marked SMR desynchronization in the lesioned hemisphere during presentation of a movement and its execution. Neuroplastic changes were evaluated clinically by multimodal neuroimaging based on fMRI and a diffusion tensor imaging method [10]. Analysis of the psychophysiological interaction showed that premotor cortex activity correlated with activity in the primary and secondary sensorimotor areas on the lesioned side. Results from studies of the spinal cord suggested that the anterior fibers of the corticospinal tract, arising in the anterior part of the primary motor cortex (M1) or the premotor cortex, may play a role in this clinical improvement. An increase in activity was seen in the dorsal premotor area and accessory motor areas on the lesioned side at the ends of sequential blocks of treatment. On the basis of these results, the authors suggested that training with BCI based on recording of the SMR combined with targeted physiotherapy could induce useful neuroplastic changes in the areas adjacent to the lesioned area, which may promote recovery of motor functions.

Another study involved patients in the subacute and chronic periods of stroke (1–35 months after stroke) with predominantly subcortical brain lesions (80%) who received rehabilitation either with a robotic apparatus (n = 10) or BCI (n = 8) as 12 sessions over four weeks [3]. The robotic apparatus was attached to the hands of patients of group 1 (MIT-Manus). Participants were encouraged to move the paretic arm to a visual target displayed on a screen in front of them. If the patient was unable to perform the movement independently, the robot provided assistance, actively guiding the patient's arm to the target. In the BCI group, movements were performed, but only if desynchronization of the sensorimotor rhythm could be seen over the lesioned hemisphere during the experiment. Both groups were evaluated clinically using the FMA scale before and after training. Before training, measures on the FMA ranged from 4 to 61 points (mean 29.7 ± 17.7). The BCI group showed more marked improvement, and results two months after treatment were better than those in the group receiving rehabilitation with the robotic apparatus.

Conclusions. Thus, there are scientific grounds for introducing motor imagery training into the rehabilitation of patients with motor disorders. Thus, numerous studies have demonstrated that the brain areas responsible for motor execution and the imagination of movements overlap. In addition, execution of movements and the imagination of movements have common electroencephalographic signs: modulation of the sensorimotor rhythm or mu rhythm. During motor imagery training, presentation of feedback plays an enormous role which can now be fulfilled using EEG-based brain–computer interface techniques. Further assessment of the potential role of BCI technologies in the rehabilitation of patients with neurological diseases requires study of the anatomical and functional bases for the successful control of BCI and the mechanisms underlying clinical improvements. Further development of BCI systems based on motor imagery should be addressed with consideration of deeper investigation of the neurophysiological properties and characteristics of the "behavior" of the corresponding zones of the brain. This will lead to significant increases in the range of control commands. New, simpler sensory EEG-recording technologies convenient for patients also need to be developed, for example using wireless electrodes.

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REFERENCES

1. O. A. Mokienko, O. A. Chernikova, and A. A. Frolov, "Brain–computer interfaces as a new rehabilitation technology," *Annals Klin. Eksperim. Nevrol.*, **5**, No. 3, 46–52 (2011).
2. G. Abbruzzese, A. Assini, A. Buccolieri, et al., "Changes of intracortical inhibition during motor imagery in human subjects," *Neurosci. Lett.*, **263**, No. 2–3, 113–116 (1999).
3. K. K. Ang, C. Guan, K. S. Chua, et al., "Clinical study of neurorehabilitation in stroke using EEG-based motor imagery brain–computer interface with robotic feedback," in: *Conf. Proc. IEEE Eng. Med. Soc. 2010, Buenos Aires* (2010), pp. 5549–5552.
4. F. Atienza, I. Balaguer, and M. L. Garcia-Merita, "Factor analysis and reliability of the movement imagery questionnaire," *Percept. Mot. Skills*, **78**, No. 3, Part 2, 1323–1328 (1994).
5. A. Blair, C. Hall, and G. Leyshon, "Imagery effects on the performance of skilled and novice soccer players," *J. Sports Sci.*, **11**, No. 2, 95–101 (1993).
6. M. S. Boschker, F. C. Bakker, and M. R. Rietberg, "Retroactive interference effects of mentally imagined movement speed," *J. Sports Sci.*, **18**, No. 8, 593–603 (2000).
7. S. M. Braun, A. J. Beurskens, P. J. Borm, et al., "The effects of mental practice in stroke rehabilitation: a systematic review," *Arch. Physiol. Med. Rehabil.*, **87**, No. 6, 842–852 (2006).
8. D. Broetz, C. Braun, C. Weber, et al., "Combination of brain–computer interface training and goal-directed physical therapy in chronic stroke: a case report," *Neurorehabil. Neural. Repair*, **24**, No. 7, 674–679 (2010).
9. A. J. Butler, J. Cazeaux, A. Fidler, et al., "The movement imagery questionnaire – revised, Second Edition (MIQ-RS) is a reliable and valid tool for evaluating motor imagery in stroke populations," *Evid. Based Complement. Alternat. Med.*, 2012:497289–497301 (2012).
10. A. Caria, C. Weber, D. Brotz, et al., "Chronic stroke recovery after combined BCI training and physiotherapy: A case report," *Psychophysiology*, **48**, No. 4, 578–582 (2011).
11. P. Cicinelli, B. Marconi, M. Zaccagnini, et al., "Imagery-induced cortical excitability changes in stroke: a transcranial magnetic stimulation study," *Cereb. Cortex*, **16**, No. 2, 247–253 (2006).
12. D. J. Crammond, "Motor imagery: never in your wildest dream," *Trends Neurosci.*, **20**, No. 12, 54–57 (1997).
13. F. P. De Lange, P. Hagoort, and I. Toni, "Neural topography and content of movement representations," *J. Cogn. Neurosci.*, **17**, No. 1, 97–112 (2005).
14. S. De Vries and T. Mulder, "Motor imagery and stroke rehabilitation: a critical discussion," *J. Rehabil. Med.*, **39**, No. 1, 5–13 (2007).
15. J. Decety and D. H. Ingvar, "Brain structures participating in mental stimulation of motor behavior: a neuropsychological interpretation," *Acta Psychol.*, **73**, No. 1, 13–34 (1990).
16. J. Decety, M. Jeannerod, D. Durozard, and G. Baverel, "Central activation of autonomic effectors during mental stimulation of motor actions in man," *J. Physiol.*, **461**, 549–563 (1993).
17. R. Dickstein and J. E. Deutsch, "Motor imagery in physical therapist practice," *Phys. Ther.*, **87**, No. 7, 942–953 (2007).
18. H. C. Dijkerman, M. Ietswaart, M. Johnston, and R. S. MacWalter, "Does motor imagery training improve hand function in chronic stroke patients? A pilot study," *Clin. Rehabil.*, **18**, No. 5, 538–549 (2004).
19. H. H. Ehrsson, S. Geyer, and E. Naito, "Imagery of voluntary movement of fingers, toes, and tongue activates corresponding body-part-specific motor representations," *J. Neurophysiol.*, **90**, No. 5, 3304–3316 (2003).
20. L. Fadiga, G. Buccino, L. Craighero, et al., "Corticospinal excitability is specifically modulated by motor imagery: a magnetic stimulation study," *Neuropsychologia*, **37**, No. 2, 147–158 (1999).
21. C. L. Fansler, C. L. Poff, and K. F. Shepard, "Effects of mental practice on balance in elderly women," *Phys. Ther.*, **65**, No. 9, 1332–1338 (1985).
22. A. Gaggioli, A. Meneghini, F. Morganti, et al., "A strategy for computer-assisted mental practice in stroke rehabilitation," *Neurorehabil. Neural Repair*, **20**, No. 4, 503–507 (2006).
23. C. R. Hall, "Individual differences in the mental practice and imagery of motor skill performance," *Can. J. Appl. Sport. Sci.*, **10**, No. 4, 17–21 (1985).
24. M. F. Hamel and Y. Lajoie, "Mental imagery. Effects on static balance and attentional demands of the elderly," *Aging. Clin. Exp. Res.*, **17**, No. 3, 223–228 (2005).
25. T. Hanakawa, I. Immisch, K. Toma, et al., "Functional properties of brain areas associated with motor execution and imagery," *J. Neurophysiol.*, **89**, No. 2, 989–1002 (2003).
26. R. Hashimoto and J. C. Rothwell, "Dynamic changes in corticospinal excitability during motor surgery," *Exp. Brain Res.*, **125**, No. 1, 75–81 (1999).
27. P. L. Jackson, M. F. Lafleur, F. Malouin, et al., "Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery," *Neuroimage*, **20**, No. 2, 1171–1180 (2003).
28. M. Jeannerod, "Neural stimulation of action: a unifying mechanism for motor cognition," *Neuroimage*, **14**, No. 1, Part 2, 103–109 (2001).
29. M. G. Lacourse, E. L. Orr, S. C. Cramer, and M. J. Cohen, "Brain activation during execution and motor imagery of novel and skilled sequential hand movements," *Neuroimage*, **27**, No. 3, 505–519 (2005).
30. K. P. Liu, C. C. Chan, T. M. Lee, and C. W. Hui-Chan, "Mental imagery for promoting relearning for people after stroke: a randomized controlled trial," *Arch. Physiol. Med. Rehabil.*, **85**, No. 9, 1403–1408 (2004).
31. M. Lotze and L. G. Cohen, "Volition and imagery in neurorehabilitation," *Cogn. Behav. Neurol.*, **19**, No. 3, 135–140 (2006).
32. M. Lotze and U. Halsband, "Motor imagery," *J. Physiol.*, **99**, No. 4–6, 386–395 (2006).
33. S. Makeig, M. Westerfield, T. P. Jung, et al., "Dynamic brain sources of visual evoked responses," *Science*, **295**, No. 5555, 690–694 (2002).
34. F. Malouin, C. L. Richards, P. L. Jackson, et al., "Brain activation during motor imagery of locomotor-related tasks: a PET study," *Hum. Brain Mapp.*, **19**, No. 1, 47–62 (2003).
35. F. Malouin, C. L. Richards, P. L. Jackson, et al., "The kinesthetic and visual imagery questionnaire (KVIQ) for assessing motor imagery in persons with physical disabilities: a reliability and construct validity study," *J. Neurol. Physiol. Ther.*, **31**, No. 1, 20–29 (2007).
36. D. J. McFarland, L. A. Miner, T. M. Vaughan, and J. R. Wolpaw, "Mu and beta rhythm, topographies during motor imagery and actual movements," *Brain Topogr.*, **12**, No. 3, 177–186 (2000).
37. A. Mohapp and R. Scherer, "Single-trial EEG classification of executed and imagined hand movements in hemiparetic stroke patients," in: *3rd Int. BCI Workshop and Training Course* Graz (2006), pp. 80–81.
38. T. Mulder, "Motor imagery and action observation: cognitive tools for rehabilitation," *J. Neural Transm.*, **114**, No. 10, 1265–1278 (2007).

39. C. Neuper, R. Scherer, M. Reinber, and G. Pfurtscheller, "Imagery of motor actions: differential effects of kinesthetic and visual-motor mode of imagery in single-trial EEG," *Brain Res. Cogn. Brain Res.*, **25**, No. 3, 668–677 (2005).
40. L. F. Nicolas-Alonso and J. Gomez-Gil, "Brain computer interfaces, a review," *Sensory (Basel)*, **12**, No. 2, 1211–1279 (2012).
41. S. J. Page, P. Levine, and A. Leonard, "Mental practice in chronic stroke: results of a randomized, placebo-controlled trial," *Stroke*, **38**, No. 4, 1293–1297 (2007).
42. S. J. Page, P. Levine, and A. C. Leonard, "Effects of mental practice on affected limb use and function in chronic stroke," *Arch. Physiol. Med. Rehabil.*, **86**, No. 3, 399–402 (2005).
43. L. M. Parsons, "Integrating cognitive psychology, neurology and neuroimaging," *Acta Psychol.*, **107**, No. 1–3, 155–181 (2001).
44. L. M. Parsons, P. T. Fox, J. H. Downs, et al., "Use of implicit motor imagery for visual shape discrimination as revealed by PET," *Nature*, **375**, No. 6526, 54–58 (1995).
45. A. Pascual-Leone, D. Nguyet, L. G. Cohen, et al., "Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills," *J. Neurophysiol.*, **74**, No. 3, 1037–1045 (1995).
46. G. Pfurtscheller and A. Aranibar, "Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement," *EEG Clin. Neurophysiol.*, **46**, No. 2, 138–146 (1979).
47. G. Pfurtscheller, C. Brunner, A. Schlogel, and F. Lopes da Silva, "Mu rhythm (de)synchronization and EEG single-trial classification of different motor imagery tasks," *Neuroimage*, **31**, 153–159 (2006).
48. G. Prasad, P. Herman, D. Coyle, et al., "Applying a brain–computer interface to support motor imagery practice in people with stroke for upper limb recovery: a feasibility study," *J. Neuroeng. Rehabil.*, **7**, No. 1, 60–78 (2010).
49. R. Roberts, N. Callow, L. Hardy, et al., "Movement imagery ability: development and assessment of a revised version of the vividness of movement imagery questionnaire," *J. Sport. Exerc. Psychol.*, **30**, No. 2, 200–221 (2008).
50. C. Schuster, J. Butler, B. Andrews, et al., "Comparison of embedded and added motor imagery training in patients after stroke: results of a randomised controlled pilot trial," *Trials*, **13**, 11–30 (2012).
51. C. Schuster, R. Hilfiker, O. Amft, et al., "Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines," *Biol. Med. Centr. Med.*, **9**, 75–110 (2011).
52. N. Sharma, P. S. Jones, T. A. Carpenter, and J. C. Baron, "Mapping the involvement of BA 4a and 4p during motor imagery," *Neuroimage*, **41**, No. 1, 92–99 (2008).
53. N. Sharma, V. M. Pomeroy, and J. C. Baron, "Motor imagery: a backdoor to the motor system after stroke?" *Stroke*, **37**, No. 7, 1941–1952 (2006).
54. N. Sharma, L. H. Simmons, P. S. Jones, et al., "Motor imagery after subcortical stroke: a functional magnetic resonance imaging study," *Stroke*, **40**, No. 4, 1315–1324 (2009).
55. J. J. Shih, D. J. Krusieski, and J. R. Wolpaw, "Brain–computer interfaces in medicine," *Mayo Clin. Proc.*, **87**, No. 3, 268–279 (2012).
56. A. Sirigu, L. Cohen, J. R. Duhamel, et al., "Congruent unilateral impairments for real and imagined hand movements," *Neuroreport*, **6**, No. 7, 997–1001 (1995).
57. B. Steenbergen, C. Craje, D. M. Nilson, and A. M. Gordon, "Motor imagery training in hemiplegic cerebral palsy: a potentially useful therapeutic tool for rehabilitation," *Dev. Med. Child. Neurol.*, **51**, No. 9, 690–696 (2009).
58. J. A. Stevens and M. E. Stoykov, "Using motor imagery in the rehabilitation of hemiparesis," *Arch. Physiol. Med. Rehabil.*, **84**, No. 7, 1090–1092 (2003).
59. C. M. Stinear, W. D. Byblow, M. Steyvers, et al., "Kinesthetic, but not visual, motor imagery modulates corticomotor excitability," *Exp. Brain Res.*, **168**, No. 1–2, 157–164 (2006).
60. C. Stippich, H. Ochmann, and K. Sartor, "Somatotopic mapping of the human primary sensorimotor cortex during motor imagery and motor execution by functional magnetic resonance imaging," *Neurosci. Lett.*, **331**, No. 1, 50–54 (2002).
61. L. Warner and M. E. McNeill, "Mental imagery and its potential for physical therapy," *Physiol. Ther.*, **68**, No. 4, 516–521 (1988).
62. L. Yaguez, D. Nagel, H. Hoffman, et al., "A mental route to motor learning: improving trajectorial kinematics through imagery training," *Behav. Brain Res.*, **90**, No. 1, 95–106 (1998).
63. G. Yue and K. J. Cole, "Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions," *J. Neurophysiol.*, **67**, No. 5, 1114–1123 (1992).
64. A. Zimmermann-Schlatter, C. Schuster, M. A. Puhan, et al., "Efficacy of moor imagery in post-stroke rehabilitation: a systematic review," *J. Neuroeng. Rehabil.*, **5**, 8–18 (2008).