

Motor imagery of foot dorsiflexion and gait: Effects on corticospinal excitability

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ARTICLE INFO

Article history:

Accepted 12 July 2008

Available online 5 October 2008

Keywords:

Gait

Transcranial magnetic stimulation

Motor imagery

Motor-evoked potentials

Foot dorsiflexion

ABSTRACT

Objective: We examined how corticospinal excitability was affected by motor imagery of foot dorsiflexion and motor imagery of gait.

Methods: Transcranial magnetic stimulation was applied over the primary motor cortex of 16 young healthy subjects while they performed imaginary foot dorsiflexions (Experiment I) and imaginary walking (Experiment II). Motor-evoked potentials (MEPs) were recorded from the tibialis anterior (TA) and first dorsal interosseus (FDI). MEPs recorded during motor imagery were compared to those recorded during a matched visual imagery task.

Results: Imagined foot dorsiflexions increased MEP areas in both TA and FDI. The increase in TA was stronger than in FDI. Overall, imagined walking did not change MEP areas. However, subjects with larger increases in TA during imagined foot dorsiflexion also showed larger increases in TA during imagined walking.

Conclusions: Imagined foot dorsiflexions increase corticospinal excitability in both a task-related muscle (TA) and a task-unrelated muscle (FDI), with larger increases in the task-related muscle. Imagined gait only increases corticospinal excitability in those subjects with the largest increments during imagined foot dorsiflexion.

Significance: Imagery of a simple lower extremity movement evokes increases in corticospinal excitability. Furthermore, corticospinal effects of a simple motor imagery task can predict corticospinal effects of a more complex motor imagery task involving the same muscle.

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1. Introduction

Studies in cats and rodents indicate that gait is an automatic motor task regulated largely at the level of the brainstem and spinal cord (Dietz, 2003). However, the fine control of stepping movements is believed to depend on higher brain centers, including the motor cortex, which are involved in adapting walking movements to environmental and motivational demands (Armstrong, 1988). In humans, little is known about the cerebral control of gait. It has been suggested that, contrary to cats, the activation of human locomotor structures within the brainstem and spinal cord is more dependent upon cortical and subcortical inputs (Calancie et al., 1994; Bussel et al., 1996). Several different approaches and techniques have been used to explore the cerebral bases of human gait (see Bakker et al., 2007b, for a review). One such approach is to record cerebral activity during motor imagery of walking. Motor

imagery involves the mental simulation of an action without its actual execution (Jeannerod, 1994, 2006). The rationale behind the approach is that motor imagery and actual movements share, at least in part, common neural substrates (Porro et al., 1996; Roth et al., 1996; Deiber et al., 1998). The majority of studies examining the cerebral structures involved in motor imagery of gait have found that motor imagery of gait increases cerebral activity in several motor cortical structures (Miyai et al., 2001; Malouin et al., 2003; Sacco et al., 2006; Bakker et al., 2008). For example, using functional magnetic resonance imaging (fMRI), we found that motor imagery of gait changes activity in the dorsal premotor cortex (Bakker et al., 2008). However, it remains unclear whether this increase in premotor cortical activity during imagined walking is accompanied by an increased corticospinal excitability.

One possibility to further explore this question is the use of transcranial magnetic stimulation (TMS) over the primary motor cortex, which is a widely accepted technique to examine changes in excitability of the corticospinal system (Petersen et al., 2003; Reis et al., 2008). Prior TMS studies on imagery have mainly

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focused on relatively simple hand movements, such as finger flexion–extension, finger opposition, or hand rotation. Motor imagery of both complex and simple hand movements induces a muscle-specific and temporally modulated increase in corticospinal excitability (Fadiga et al., 1999; Rossini et al., 1999; Kuhtz-Buschbeck et al., 2003; Stinear and Byblow, 2004; Fourkas et al., 2006a). For example, during imagined repetitive wrist flexion/extension movements, corticospinal excitability in the flexor muscle was larger during the phase of imagined flexion, whilst the opposite was true for the extensor muscle (Hashimoto and Rothwell, 1999). Furthermore, the increases in corticospinal excitability were not accompanied by concomitant changes in spinal excitability, as revealed by H-reflex testing (Abbruzzese et al., 1996; Kasai et al., 1997; Hashimoto and Rothwell, 1999). Taken together, these findings suggested that the increases in corticospinal excitability for imagined hand movements are probably mediated mainly via an increased excitability of cortical circuits.

Few studies have examined changes in corticospinal excitability during motor imagery of lower limb movements (Tremblay et al., 2001; Hiraoka, 2002). Tremblay et al. (2001) found a specific increase in corticospinal excitability of the quadriceps during motor imagery of leg extension as compared to a rest condition. Furthermore, Hiraoka (2002) found that corticospinal excitability of the soleus muscle decreased significantly during imagined stumbling, without accompanying changes in soleus H-reflex areas. To date, no study has examined changes in corticospinal excitability during a more complex lower limb task, such as motor imagery of gait.

Here, we examined whether motor imagery of a simple foot dorsiflexion (Experiment I) and motor imagery of gait (Experiment II) can modulate corticospinal excitability. We assessed the specificity of the effects by using matched visual imagery tasks. For motor imagery of foot dorsiflexion, we used a protocol that was adapted from previous TMS studies on motor imagery of hand movements (Fourkas et al., 2006a,b). For motor imagery of gait, we used a protocol that was adapted from our previous fMRI study on motor imagery of gait (Bakker et al., 2008). This allowed us to examine whether the changes in premotor activity during motor imagery of gait observed in our fMRI experiment were accompanied by an increase in corticospinal excitability. Furthermore, this protocol had the advantage that it was a validated motor imagery protocol that allowed us to quantify imagery of gait performance by recording imagery times (Bakker et al., 2007a).

2. Methods

2.1. Subjects

Eighteen healthy volunteers participated after giving written informed consent according to the institutional guidelines of the Local Ethics Committee. During the preparation phase, two subjects decided not to continue with the experiment, because they experienced the TMS pulses as being too uncomfortable. The remaining 16 subjects completed the experiment (10 women, 21.6 ± 0.4 years, mean \pm SEM). All subjects had normal or corrected-to-normal vision, and were consistent right-handers (Edinburgh Handedness Inventory (Oldfield, 1971) score $84 \pm 4\%$). They had no metal or electronic implants, and no history of neurological or orthopedic disorders. Imagery ability scores as determined by the Vividness of Motor Imagery Questionnaire (Isaac et al., 1986) ranged from 26 to 89 for first person imagery (51 ± 4), and from 27 to 80 for third person imagery (56 ± 4), which is comparable to the scores found recently in a very large group of young healthy subjects (Mulder et al., 2007). All subjects participated in two experiments, first assessing imagery of foot dorsiflexion, and next assessing imagery of gait. The study was approved by the Local Ethics Committee.

2.2. Electromyography

To record electromyography (EMG), pairs of self-adhesive 10-mm diameter silver–silver chloride electrodes (Kendall-LTP, Chichester, MA) were placed 3 cm apart along the muscle belly of right tibialis anterior (TA) and gastrocnemius (GM) muscles, and in a “belly-tendon” arrangement on the right first dorsal interosseus (FDI) muscle (FDI was taken as a reference muscle, being an intrinsic hand muscle whose corticospinal excitability does not change during gait (Schubert et al., 1997)). Therefore, it was expected that corticospinal excitability in this muscle would not be modulated during imagery.) EMG signals were amplified (gain 200) and filtered (2–1000 Hz) using an Ekida amplifier (Ekida GmbH, Helmsstadt, Germany) before being digitized ($0.76 \mu\text{V/bit}$, 5000 Hz) by a Power 1401 data acquisition system (Cambridge Electronic Design, Cambridge, United Kingdom). Recordings of EMG data commenced 1 s prior to TMS stimuli and were collected for 2 s. Data were processed offline using MATLAB (MathWorks, Natick, MA) with Field-Trip, an open source toolbox for the analysis of electrophysiological data (<http://www.ru.nl/fcdonders/fieldtrip/>). The TMS pulses induced sharp peaks in the EMG recordings. Before filtering, these artifacts were cut out and the respective samples were replaced using spline interpolation. This was done to prevent expanding of the artifacts during filtering, which would create a risk of interference with the MEP. EMG was further filtered digitally (2–400 Hz) and segmented into epochs running from 100 ms before to 400 ms after each TMS pulse. We used a high-pass filter of 2 Hz instead of the more commonly used 10 Hz high-pass filter, because the 10 Hz filter-induced MEP-related filter artefacts during the period prior to the TMS pulse. To prevent that any remaining low frequency drifts influenced the data, baseline correction was performed based on the period 100 ms prior to the TMS pulse.

2.3. Transcranial magnetic stimulation

Transcranial magnetic stimulation (TMS) was applied using a custom-made angled double cone coil (wing diameter 120 mm) connected to a Magstim BiStim² stimulator (Magstim Company, Whitland, UK). Subjects wore earplugs, and a swimming cap was fitted onto the subject's head on which the vertex was marked. The crossover of the coil was positioned one centimeter left and anterior of the vertex. Stimulus intensity was set at 35% of maximum stimulator output and was then increased with steps of 5% until a motor-evoked potential (MEP) was elicited in the TA. Then the coil was moved in small steps to determine the scalp position at which the MEPs in the TA were largest, i.e. the hotspot. Once the hotspot was found, the position of the coil was marked on the swimming cap, and stimulus intensity was set to the intensity that reproducibly elicited a MEP of around 0.5–1.0 mV peak-to-peak. On average, the stimulus intensity used was $44.6\% \pm 2.4$ (SEM) (range: 31–60%) of maximal stimulator output. In the TA, the mean peak-to-peak MEP area across all trials was 0.66 ± 0.03 mV in Experiment I, and 0.60 ± 0.02 mV in Experiment II. While stimulating at the TA hotspot, we were able to reliably record MEPs in the FDI as well; i.e. mean peak-to-peak MEP area in the FDI was 1.44 ± 0.08 mV in Experiment I, and 1.25 ± 0.05 mV in Experiment II. We were not able to record reliable MEPs in the medial gastrocnemius muscle, peak-to-peak amplitude: 0.081 ± 0.004 mV in Experiment I, and 0.097 ± 0.005 mV in Experiment II. Therefore, we only included recordings from the TA and FDI in our analyses.

2.4. Task and procedures. Experiment I: imagined foot dorsiflexion

In the first experiment, we examined the effect of imagined foot dorsiflexion on corticospinal excitability. We always performed this experiment prior to the imagined gait experiment because

imagined foot dorsiflexion is a simple motor imagery task which allowed subjects to become familiar with performing motor imagery.

2.4.1. Experimental set-up

Subjects were seated comfortably in a chair that was adjusted in height so that the subjects' feet rested comfortably on the floor. Written instructions were projected on a computer screen located in front of the subject. Subjects were sitting with their right leg extended. Their arms and hands were resting, pronated, on a pillow on their lap. Auditory and visual stimuli presentation was controlled through a PC running Presentation software (Neurobehavioral systems, Albany, USA). The experimenter was standing behind the subject and held the TMS coil above the TA hotspot while gently fixating the head.

2.4.2. Tasks

Subjects performed two tasks: motor imagery of foot dorsiflexion and visual imagery of a static foot. During motor imagery, subjects were asked to imagine a single dorsiflexion of their right foot. We instructed the subjects to imagine the foot movement as vividly as possible, in a first person perspective, as if their foot was moving, but without making any actual movements. During visual imagery, subjects were asked to imagine seeing their right foot in its current static position. We again instructed the subjects to imagine seeing the static right foot as vividly as possible, without making any actual movements. Subjects performed both imagery tasks with the eyes closed. This was done in order to optimize imagery performance, as was done in several previous studies (Hashimoto and Rothwell, 1999; Fourkas et al., 2006b; Mercier et al., 2008). Furthermore, an accompanying advantage of eye closure is that motor cortex excitability might be greater with eyes closed than with eyes open (Leon-Sarmiento et al., 2005). The trial time-course was based on two previous studies that examined changes in corticospinal excitability during motor imagery (Fourkas et al., 2006a,b). An auditory cue indicated the onset of a trial. Subjects should start performing the imagery task as soon as they heard the auditory cue, a variable interval of 3–3.5 s elapsed between the beep and the TMS pulse. The TMS pulse indicated the end of a trial (for trial time course see Fig. 1a). A rest period (7 s) elapsed before the next trial.

2.4.3. Experimental procedures

The experiment was divided into two motor imagery blocks and two visual imagery blocks of five trials each (2 blocks \times 2 tasks (motor imagery, visual imagery) \times 5 trials = 20 trials), with a rest period of 7 s in between successive trials, and a rest period of several minutes in between successive blocks. Subjects closed their eyes at the beginning of each block. Subjects were allowed to open their eyes at the end of the block when the experimenter indicated that the block had finished. The motor imagery and visual imagery blocks were performed alternately, and the order was counterbalanced across the subjects. Before we started the experiment, subjects were given written instructions explaining both tasks, followed by actual performance of the foot movement, and a training of both imagery tasks (three trials for each task, with TMS pulses). Prior to each block, subjects were instructed which task they should perform in the next block.

2.5. Tasks and procedures. Experiment II: imagined gait

In the second experiment, we examined the effect of imagined gait on corticospinal excitability.

2.5.1. Experimental set-up

Experiment II was performed directly after Experiment I, and subjects remained seated in the same chair. Therefore, the

experimental set-up of Experiment II was largely similar to that of Experiment I, with two differences. First, subjects did not extend their right leg during Experiment II. Second, button presses with the left thumb were recorded to measure behavioral responses.

2.5.2. Tasks

We used the same protocol as in our previous fMRI study (Bakker et al., 2008), which is a validated protocol that allows for quantifying motor imagery of gait performance by recording imagery times (Bakker et al., 2007a). We asked subjects to imagine walking along visually presented paths of two different widths and three different distances that evoked either normal walking (broad path) or exact foot placement and increased postural control (narrow path). This manipulation allowed us to isolate the effects of movement distance and movement difficulty on imagined walking times. During a matched visual imagery task, subjects imagined a disk moving along the same paths and distances used in the motor imagery task. Both tasks started with the presentation of a photograph showing a corridor with a path in the middle (see Fig. 1c – the stimuli have been described in detail previously, see also Bakker et al., 2007a). During motor imagery trials, a green square marked the beginning of the path in the photograph. Subjects were asked to inspect the photograph on display, to close their eyes, and to imagine walking along the path, starting from the green square and stopping at the green pillar. We instructed the subjects to imagine the walking movement as vividly as possible, in a first person perspective, as if their legs were moving, but without making any actual movements. During visual imagery trials, a black disk was present at the beginning of the path in the photograph. Subjects were asked to inspect the photograph, to close their eyes, and to imagine seeing the black disc moving along the path, from its starting position until the green pillar. We again instructed subjects to imagine the movement as vividly as possible, without making any actual movements. During both tasks, the path could have two different widths (narrow, broad). In addition, the green pillar could be placed at three different distances from the green square or the black disc (6, 8 and 10 m). During each trial, subjects signalled that they had started and stopped the imagery by pressing a button. The time between the two button presses was taken as imagery time (see Fig. 1b for trial time course). A TMS pulse was delivered at 1.7–3 s after the first button press in each trial. This time interval was chosen to make sure that the TMS pulse would be delivered before the end of the trial in all subjects. The time-interval was based on behavioural results of our previous fMRI experiment (Bakker et al., 2008). Subjects were instructed to continue with the imagery task after the TMS pulse had been delivered (this was necessary to be able to record imagery times).

2.5.3. Experimental procedures

The experiment was divided into two motor imagery blocks and two visual imagery blocks of 10 trials each (2 blocks \times 2 tasks (motor imagery, visual imagery) \times 2 path widths (narrow, broad) \times 5 trials = 40 trials), with breaks of several minutes between successive blocks. The motor imagery and visual imagery blocks were performed alternately, and the order was counterbalanced across subjects. Prior to each block, subjects were instructed which task they should perform in the next block. In between trials a fixation cross was presented on the screen (inter-trial interval, ITI: 7.0–7.5 s).

Prior to the first and second blocks, subjects were given written instructions about the task they would perform in the next session, followed by training in the relevant task (15 trials, no TMS pulses during training). Prior to the beginning of Experiment I subjects

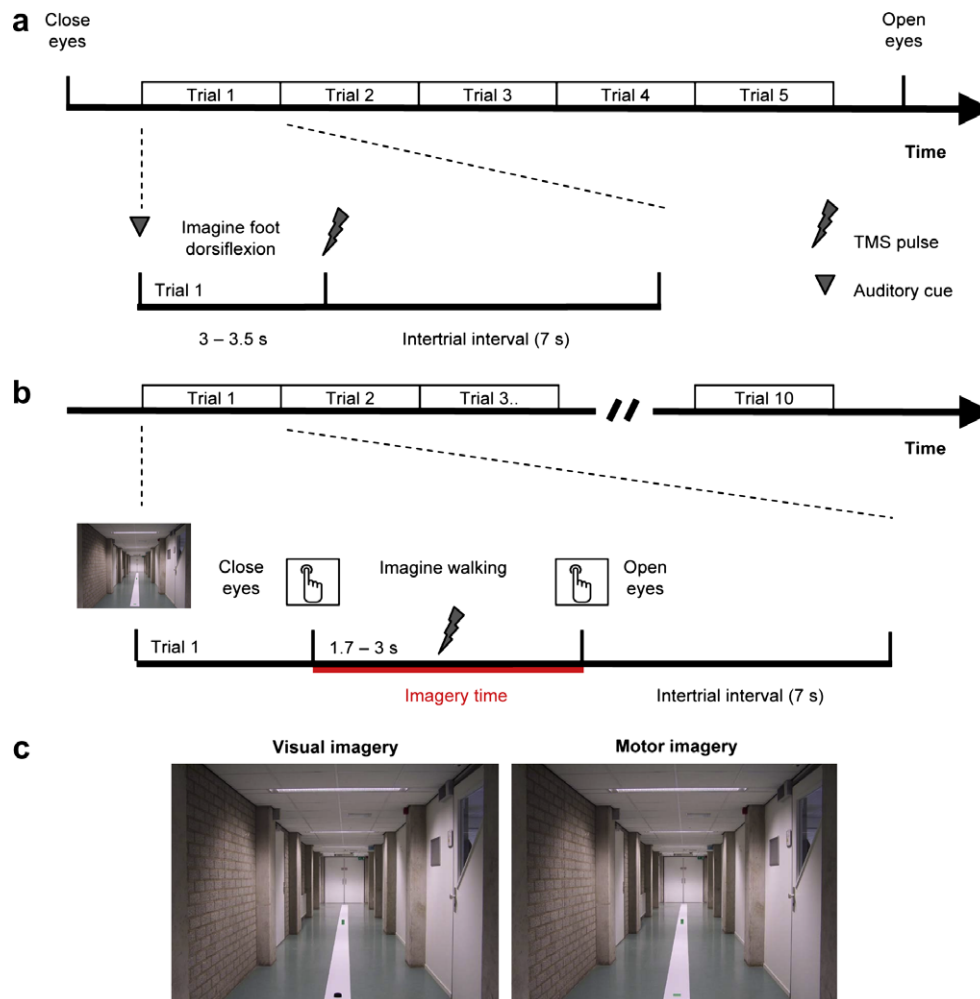


Fig. 1. Experimental set-up. (a) Example of a motor imagery block in Experiment I. Each block consisted of five trials. Subjects closed their eyes at the beginning of the block. Each trial started with an auditory cue indicating that subjects should start performing the imagery task. After a variable interval of 3–3.5 s, a TMS pulse was delivered. Subjects were instructed to stop performing the imagery task after the TMS pulse had been delivered. A rest period of 7 s elapsed before the onset of the next trial. After five trials, the block was finished, and the experimenter indicated that subjects could open their eyes. (b) Example of a motor imagery block in Experiment II. Each block consisted of 10 imagery trials. During each trial, after a short inspection of the photograph on display, the subjects closed their eyes and imagined standing on the left side of the path, next to the green square. The subjects were asked to press a button with the index finger of their right hand to signal that they had started imagining to step onto the path and walking along the path. The subjects were also instructed to press the button again when they imagined that they had reached the end of the walking trajectory. A TMS pulse was delivered at 1.7–3 s after the first button press in each trial. Following the second button press, subjects could open their eyes, and a fixation cross was presented on the screen (inter-trial interval, ITI: 7 s). (c) Examples of photographs of walking trajectories presented to the subjects during the motor imagery, and visual imagery tasks of Experiment II. The photos show a corridor with a white path in the middle and a green pillar positioned on the path. During motor imagery trials, a green square is present at the beginning of the path. During visual imagery trials, a black disc is presented at the beginning of the path. During both tasks, the path width could be either broad (27 cm) or narrow (9 cm). In addition, the green pillar could be positioned at 6, 8 or 10 m from the green square or black disc (6 m in the photos presented in this figure). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

physically walked along short versions (three meters) of both the broad and the narrow paths (three times for each path width), at a comfortable pace, avoiding to place their feet outside the path. This was done to make subjects familiar with the kinaesthetic feeling of walking along the different paths. The broad path allowed for walking over the path with a normal gait, whereas the narrow path required the subjects to carefully position their feet one in front of the other. We instructed subjects to pay attention to the feeling of walking along the different path widths, and to imagine walking in a similar way along the two different paths during the imagery trials. To make subjects familiar with the movement of the disc, they were made to see a video of the disc moving through the same corridor as in the photographs, but without a linoleum path in the middle of the corridor. The disc moved for 6 m, in a straight line, at a uniform speed of about 0.8 m/s. We instructed subjects to imagine seeing the disc moving in a similar way along the two different paths during the imagery trials.

2.6. Behavioral data analysis

In Experiment I, we did not record any behavioural data. In Experiment II, we examined the effects of our experimental manipulations on imagery times in order to quantify task performance. We measured the time between the two button presses that marked the start and the end of the imagined visual or walking movements (imagery time, see Fig. 1b). We used a Mixed Model to analyze the effects of our experimental manipulations on imagery times. We included imagery time as the dependent variable, and SUBJECT as a random factor. As fixed covariates, we included TASK (*motor imagery and visual imagery*), PATH WIDTH (*broad and narrow*), PATH LENGTH (6, 8 and 10 m), TASK \times PATH WIDTH, and TASK \times PATH LENGTH. In addition, we performed a Mixed Model analysis for each task separately. Imagery time was again included as a dependent variable, SUBJECT as a random factor, and PATH WIDTH and PATH LENGTH as fixed covariates. All inde-

pendent variables were rescaled in such a way that their mean value was 0. Because of this, the coefficient of the main effect estimated the mean differences between the various conditions, even if interactions were included in the model.

2.7. EMG data analysis

We used MEP area as our primary outcome measure, because TA MEPs were predominantly polyphasic. MEP area was quantified for each trial as the area on rectified EMG responses in a fixed time interval of 15–80 ms after the TMS trigger (see Fig. 2). As a secondary research question we examined whether the target muscle was at rest at the time of TMS. Background EMG activity was calculated for each TMS trial as the root-mean-square (RMS) amplitude of the 105 to 5 ms pre-TMS EMG trace.

2.7.1. Statistical analysis. Experiment I: imagined foot dorsiflexion

For the statistical analysis of MEP areas, all MEP areas were transformed (natural log) to address non-normality. We used a Mixed Model to analyze the effects of our experimental manipulations on MEP area. We included MEP area as the dependent variable, and SUBJECT as a random factor. As fixed covariates we included TASK (*motor imagery and visual imagery*), MUSCLE (TA

and FDI), TASK \times MUSCLE, BACKGROUND EMG and BACKGROUND EMG \times MUSCLE. We included background EMG in the Mixed Model, because muscle contraction increases MEP areas (Hess et al., 1986). Including background EMG in the mixed model allowed us to correct for possible differences in background EMG levels (Bloem et al., 1993). In addition to the overall analysis, we also performed a Mixed Model analysis for each muscle separately, using the same variables. For all analyses, independent variables were rescaled in such a way that they had mean 0. The alpha-level of all statistical analyses was set at $p < 0.05$.

The statistical analysis of background EMG was largely similar to that of MEP areas with the only difference that background EMG was set as the dependent variable, and we did not include BACKGROUND EMG, and BACKGROUND EMG \times MUSCLE as fixed covariates in the model.

2.7.2. Statistical analysis. Experiment II: imagined gait

The statistical analysis of Experiment II was largely similar to that of Experiment I, with the following differences. For the overall Mixed Model, we also included the factors PATH WIDTH (*broad and narrow*), TASK \times PATH WIDTH and TASK \times PATH WIDTH \times MUSCLE as fixed covariates. For the muscle specific Mixed Models, we also included the factors PATH WIDTH (*broad and narrow*) and TASK \times PATH WIDTH as fixed covariates. Path length was solely varied to have a behavioral control of whether subjects accurately performed imagery (Bakker et al., 2007a). Therefore, we pooled across the factor path length for the EMG analysis.

2.7.3. Statistical analysis. Experiment I versus II: imagined foot dorsiflexion versus imagined gait

Finally, we examined the relationship between the effects of imagined foot dorsiflexion (Experiment I) and imagined walking (Experiment II) on MEP areas. First, we used a Mixed Model to calculate the effect sizes of imagined foot dorsiflexion and imagined walking on MEP area in each subject and muscle separately. In this mixed model analysis, we included MEP area as the dependent variable, and TASK (*motor imagery and visual imagery*) and BACKGROUND EMG as fixed covariates. Afterwards, we used a linear regression analysis to examine for each muscle (TA and FDI) the relationship between effect sizes of imagined foot dorsiflexion and imagined walking. We included single-subject effect sizes of imagined foot dorsiflexion on MEP areas as independent variable in the linear regression, and single-subject effect sizes of imagined walking on MEP areas as dependent variable.

3. Results

3.1. Experiment I: motor imagery of foot dorsiflexion

3.1.1. MEP area

The mean MEP areas for each task and muscle are presented in Table 1. MEP areas were larger during imagined foot dorsiflexion compared to visual imagery (effect size [95% confidence interval] = 38% [19–60%], $p < 0.001$). Interestingly, this effect was observed in both muscles (Fig. 3). In the TA, imagined foot dorsiflexion resulted in 57% [37–80%] larger MEP areas ($p < 0.001$). In the FDI, imagined foot dorsiflexion resulted in a relatively smaller increase in MEP areas of 18% [4–34%], but this was still significant ($p = 0.01$). The effect of task on MEP areas was 26% [0–45%] larger for the TA than for the FDI (TASK \times MUSCLE interaction: $p = 0.05$). These findings suggest that motor imagery of foot dorsiflexion increased corticospinal excitability in both a task-related muscle (TA), and a task-unrelated muscle (FDI). However, the increase in the task-related muscle was larger than the effect in the task-unrelated muscle.

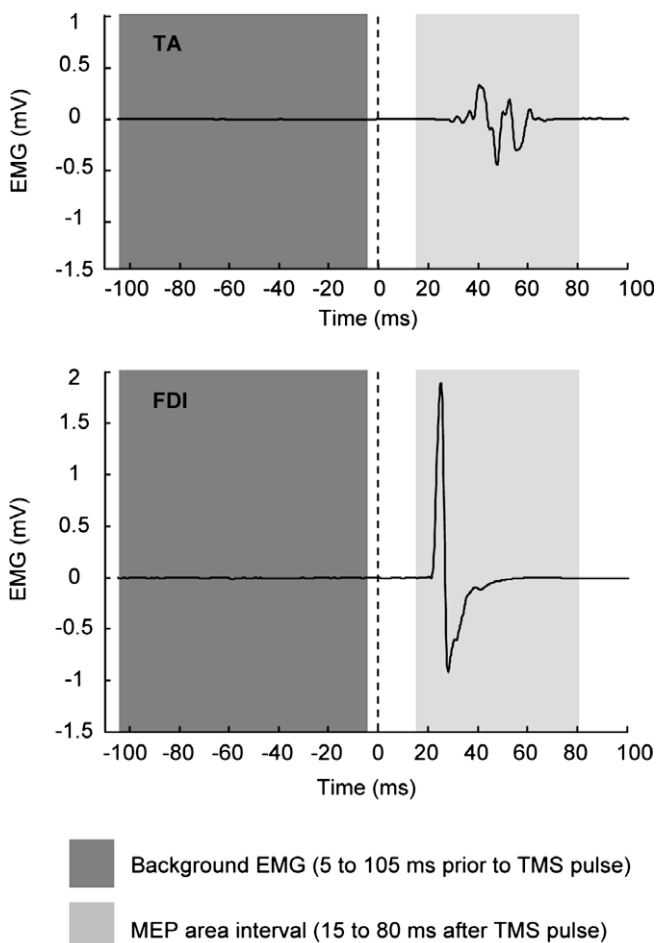


Fig. 2. Motor-evoked potentials. Examples of motor-evoked potentials (MEPs) recorded in the first dorsal interosseus (FDI) and tibialis anterior (TA) in a single subject during a single trial. The dashed line indicates the moment at which the TMS pulse was given (the TMS artifact has been removed from the EMG trace as reported in Section 2). The dark grey block indicates the 100-ms interval that was used to calculate the background electromyography (EMG) activity. The light grey block indicates the 65-ms interval that was used to calculate the MEP area.

Table 1
MEP areas and background EMG

Experiment	Muscle	Task	MEP area (mV ms)		Background EMG (μ V)	
			Mean	SEM	Mean	SEM
I	TA	Motor imagery of foot dorsiflexion	5.22	1.17	1.72	0.11
		Visual imagery of static foot	2.84	0.51	1.68	0.14
	FDI	Motor imagery of foot dorsiflexion	6.34	1.62	1.73	0.17
		Visual imagery of static foot	5.50	1.33	1.93	0.29
II	TA	Motor imagery of gait	3.61	0.59	1.69	0.13
		Visual imagery of disc	3.18	0.47	1.71	0.11
	FDI	Motor imagery of gait	5.25	1.29	2.03	0.22
		Visual imagery of disc	4.76	1.22	1.79	0.15

EMG, electromyography; FDI, first dorsal interosseus; SEM, standard error of mean; TA, tibialis anterior.

3.1.2. Background EMG

Background EMG activity was low in both muscles (Table 1). Imagined foot dorsiflexion did not significantly influence background EMG activity compared to visual imagery (0% [–5% to 7%], $p = 0.89$). In addition, the effect of imagined foot dorsiflexion on background EMG was not different for the different muscles (TASK \times MUSCLE interaction: 8% [–4% to 18%], $p = 0.22$).

3.2. Experiment II: motor imagery of gait

3.2.1. Behavior

We recorded imagery times in order to quantify imagery performance (Bakker et al., 2007a). Imagery times were longer with increasing path length (effect size [95% confidence interval] = 0.7 s [0.6–0.8 s], $p < 0.001$ – Fig. 4), and this effect was not different for the different tasks (TASK \times PATH LENGTH interaction: $p = 0.42$). Furthermore, the effect of path width on imagery times differed for the different tasks (TASK \times PATH WIDTH interaction: 0.9 s [0.4–1.4 s], $p < 0.01$). During imagined walking a smaller path width increased imagery times with 1.2 s ([1.5 to 0.9 s], $p < 0.001$, Fig. 4a), whereas during visual imagery, a smaller path width tended to increase imagery times with only 0.3 s ([0–0.7 s], $p = 0.06$, Fig. 4b). These results indicate that motor imagery was sensitive to the environmental constraints imposed by a narrow walking path that allows only for positioning one foot at a time on the path, whereas visual imagery only tended to be affected. These data suggest that subjects complied with the imagery tasks.

3.2.2. MEP area

The mean MEP areas for each task and muscle are presented in Table 1. Overall, imagined walking did not significantly influence MEP areas compared to visual imagery (6% [–4% to 17%],

$p = 0.25$). Furthermore, there was no significant difference between the effect of imagined walking on MEP areas in TA versus FDI (TASK \times MUSCLE interaction: 2% [–16% to 25%], $p = 0.83$). Finally, there was no effect of path width on MEP areas during imagined walking (PATH WIDTH: $p = 0.17$; TASK \times PATH WIDTH: $p = 0.77$; TASK \times PATH WIDTH \times MUSCLE: $p = 0.73$). These findings suggest that motor imagery of walking did not influence corticospinal excitability compared to visual imagery.

3.2.3. Background EMG

Background EMG activity was low in both muscles (Table 1). The effect of imagined walking on background EMG activity was different for the two muscles (TASK \times MUSCLE interaction, 13% [3–24%], $p = 0.01$). In the TA, imagined walking had no significant effect on background EMG activity (0% [–6% to 4%] ($p = 0.70$)). In the FDI, imagined walking did significantly increase background EMG activity (12% [5–20%] ($p < 0.01$)). We found no effects of path width on background EMG during imagined walking (PATH WIDTH: $p = 0.88$; TASK \times PATH WIDTH: $p = 0.20$; TASK \times PATH WIDTH \times MUSCLE: $p = 0.36$).

3.3. Foot dorsiflexion versus gait

For each individual and each muscle, we calculated the effect size of imagined foot dorsiflexion and imagined gait on MEP areas. We examined whether there was a linear relationship between the effect sizes of imagined gait and the effect sizes of imagined foot dorsiflexion. The effect of imagined gait on TA MEP areas was positively correlated with the effect of imagined foot dorsiflexion on TA MEP areas ($r = 0.56$, $p = 0.024$) (Fig. 5). In other words, subjects with larger effects of imagined foot dorsiflexion on TA MEP areas also showed larger effects of imagined gait. The correlation was specific for the TA, as we found no correlations between (a) the effects of imagined gait on FDI MEP areas and the effect of imagined foot dorsiflexion on FDI MEP areas ($r = -0.09$), and (b) the effect of imagined gait on FDI MEP areas and the effects of imagined foot dorsiflexion on TA MEP areas ($r = 0.01$). We found no relationship between vividness of motor imagery (determined by questionnaire) and the effect of imagined foot dorsiflexion on TA MEP areas ($r = 0.39$, $p = 0.14$). We did find a trend for a positive relationship between the average MEP area per subject and the effect of imagery of foot dorsiflexion on TA MEP areas ($r = 0.47$, $p = 0.07$).

We performed a post-hoc analysis on those five subjects in which the effect sizes of imagined foot dorsiflexion on TA MEP areas were larger than 0.75. In those subjects, imagined walking increased MEP areas by 29% [8–52%] ($p < 0.01$). Although the effect size of imagined walking was larger for TA (38%) than for FDI (14%), this difference was not significant, as we found no significant TASK \times MUSCLE interaction ($p = 0.10$). These findings show that, contrary to the whole group of subjects, this selection of subjects did show an effect of imagined walking on corticospinal excit-

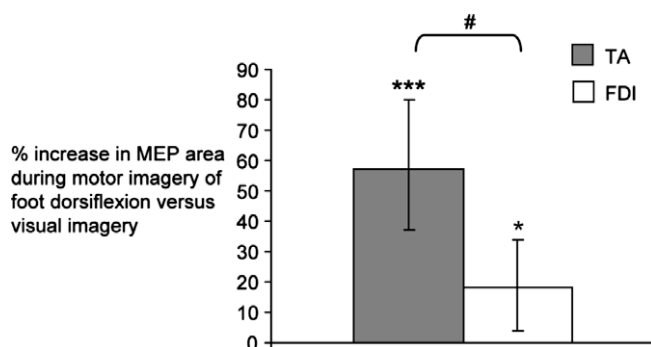


Fig. 3. Effects of imagined foot dorsiflexion on MEP area. Percentage increase of MEP area during motor imagery of foot dorsiflexion compared to visual imagery of a static foot in the TA and FDI. Data represent effect size \pm 95% confidence intervals. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

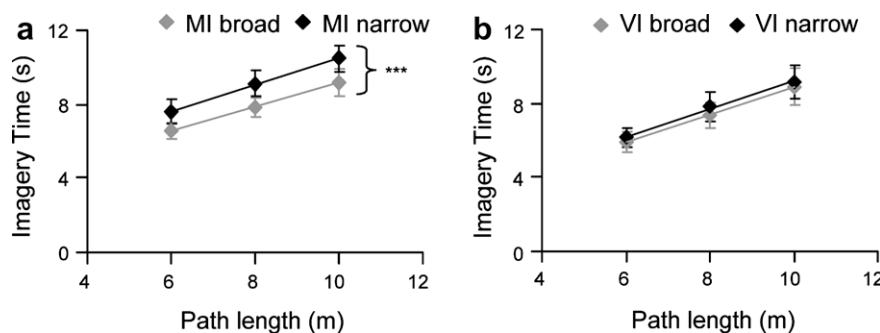


Fig. 4. Behavioral results of Experiment II. Imagery times (IT) are shown for each of the three different path lengths (6, 8, and 10 m), and the two different path widths [Broad (27 cm), and Narrow (9 cm)], separately for each of the two tasks [(a) motor imagery of gait (MI) and (b) visual imagery of a moving disc (VI)]. Data represent means \pm SEM. *** $p < 0.001$. It can be seen that the effect of path width on imagery times differed for the different tasks (TASK \times PATH WIDTH interaction: $p < 0.01$). These results indicate that motor imagery was sensitive to the environmental constraints imposed by a narrow walking path, whereas visual imagery was not. These findings suggest that subjects complied with the imagery tasks.

ability. However, it remains to be seen whether this effect is specific for the TA.

4. Discussion

In this study, we examined the effects of motor imagery of foot dorsiflexion and motor imagery of gait on corticospinal excitability. There were two main findings. First, imagined foot dorsiflexion increased corticospinal excitability in both the TA and the FDI, with a larger effect in the TA. This result indicates that motor imagery of a straightforward lower limb movement (foot dorsiflexion) increases corticospinal excitability in both a task-related muscle (TA) and a task-unrelated muscle (FDI), with larger increases in the task-related muscle. Second, when taking all subjects together, imagined walking did not change MEP areas. However, the size of increment of corticospinal excitability in the TA during imagined foot dorsiflexion predicted the size of the increment of corticospinal excitability in the TA during imagined gait (i.e. subjects with a larger increment of corticospinal excitability in the TA during imagined foot dorsiflexion also showed a larger increment of corticospinal excitability in the TA during imagined walking). This observation suggests that corticospinal effects of a simple imagery task can predict corticospinal effects of a more complex motor imagery task involving the same muscle. We will next discuss these findings in more detail.

4.1. Motor imagery of foot dorsiflexion

Motor imagery of foot dorsiflexion increased corticospinal excitability in both the TA and FDI, with larger effects in the TA. The finding of a larger gain in corticospinal excitability in the TA is in agreement with previous work showing that corticospinal excitability specifically increases within muscles involved in the imagined movement. This was shown during motor imagery of upper limb movements (Facchini et al., 2002; Kuhtz-Buschbeck et al., 2003; Stinear and Byblow, 2004; Fourkas et al., 2006a) and upper leg movements (Tremblay et al., 2001). Our study extends these findings by showing that corticospinal excitability is also increased during motor imagery of movements involving the lower leg. The increase in corticospinal excitability could not be explained by overall changes in background muscle activity. However, since we did not measure concurrent changes in H-reflexes, we cannot rule out the possibility that changes in spinal excitability may have contributed to the results. Note that other investigators found no H-reflex changes with motor imagery (Abbruzzese et al., 1996; Kasai et al., 1997; Hashimoto and Rothwell, 1999).

The finding of increased corticospinal excitability in the FDI during imagined foot dorsiflexion conflicts with previous studies showing that motor imagery only modulates corticospinal excitability of muscles specifically involved in the imagined movement, and does not modulate corticospinal excitability of muscles not involved in the imagined movement (Hashimoto and Rothwell,

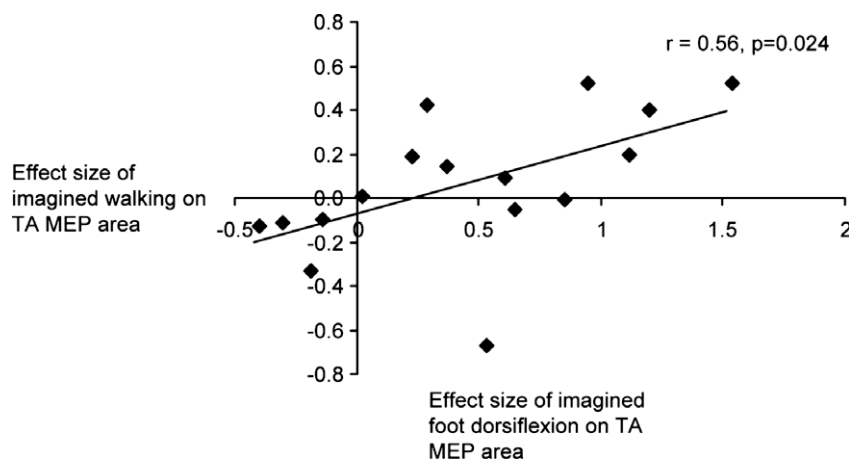


Fig. 5. Relationship between effects of imagined foot dorsiflexion and imagined gait on MEP area in the TA. Effect size of imagined gait on MEP area in the TA is plotted against the effect size of imagined foot dorsiflexion on MEP area in the TA for each subject. Line represents linear regression curve. It can be seen that subjects with larger effects of imagined foot dorsiflexion on MEP areas in the TA also showed larger effects of imagined gait.

1999; Fourkas et al., 2006a). For example, motor imagery of wrist flexion–extension movements modulates MEP areas in flexor carpi radialis and extensor carpi radialis muscles, but does not modulate MEP areas in the FDI (Hashimoto and Rothwell, 1999). Our results show that motor imagery of simple lower leg movements does not only influence corticospinal excitability of a task-related muscle (TA), but also influences corticospinal excitability of a task-unrelated muscle (FDI). One might argue that the effect in the task-unrelated upper limb muscle might be related to interlimb coordination. However, changes in corticospinal excitability of upper limb muscles during lower limb movements have been demonstrated mainly for wrist flexors and extensors (see for example Borroni et al., 2004). In our study, we found changes in corticospinal excitability in the FDI, which is an intrinsic hand muscle. One previous study has also found that imagined foot dorsiflexion can specifically modulate corticospinal excitability of intrinsic hand muscles (Marconi et al., 2007). However, whereas we found *increased* corticospinal excitability of hand muscles during imagined foot dorsiflexion, Marconi et al. (2007) found *reduced* corticospinal excitability. One possible explanation for this discrepancy might be differences in the TMS protocol used. Whereas we stimulated at the TA hotspot using a non-focal double cone coil, Marconi et al. (2007) stimulated at the hotspot of a hand muscle using a more focal figure-of-eight coil. Another possible explanation might be differences in the examined hand muscles. Whereas we examined the FDI, Marconi et al. (2007) examined the opponens pollicis and the abductor digiti minimi. This discrepancy remains to be explained, but both studies do suggest that motor imagery of lower limb movements can influence corticospinal excitability of intrinsic hand muscles.

4.2. Motor imagery of gait: behavioural performance

The procedures used in this study were designed to isolate specific effects of first person kinesthetic motor imagery of gait. We recorded imagery times on a trial by trial basis, showing that imagery times increased as a function of path length during both imagined gait and visual imagery. In addition, we showed that imagery times increased as a function of path width during the imagined gait trials, but not during the visual imagery trials. This result indicates that motor imagery was sensitive to the environmental constraints imposed by a narrow walking path that allows only for positioning one foot at a time on the path. Furthermore, the motor imagery of gait task was adapted from a previous study showing that performance of motor imagery, but not visual imagery, was influenced by subjects' body posture (Stevens, 2005). Taken together, these findings provide evidence that subjects solved the task by using first person kinaesthetic imagery.

4.3. Motor imagery of gait: corticospinal excitability

Motor imagery of walking did not result in an overall increase in corticospinal excitability as we had expected based on our previous fMRI study (Bakker et al., 2008). In that fMRI experiment, we found that motor imagery of walking increased cerebral activity in the caudal part of the dorsal premotor cortex, and that this activity was anatomically distinct from that observed in the premotor cortex during motor imagery of hand rotations. Accordingly, we expected that this increased activity would result in a specific increase in corticospinal excitability of the TA. There might be several reasons for the fact that we did not find this increase in corticospinal excitability when taking all subjects together.

First, the activations found in the premotor cortex during motor imagery of gait in our previous fMRI study might be an epiphenomenon, rather than being functionally relevant for that task. However, this possibility appears unlikely, given the large body

of evidence supporting the involvement of premotor cortices in motor imagery processes (for a recent review, see de Lange et al., 2008).

Second, imagery performance may have been better in our fMRI study compared to our TMS study. During the TMS experiment, imagined walking was performed in a sitting posture, which – because of the flexed knees – might be less suitable for motor imagery of gait than the recumbent posture that was used during the fMRI experiment. Previous work showed that motor imagery increases corticospinal excitability when body posture is compatible with the imagined movement, but not when body posture is incompatible with the imagined posture (Vargas et al., 2004; Fourkas et al., 2006a). Furthermore, the TMS pulses may have been perceived as uncomfortable, rendering it more difficult for subjects to remain focused on the imagery task during the TMS experiment. However, we recorded behavioral data to quantify task performance that suggest that subjects were able to perform the imagery tasks during both the TMS and fMRI experiment.

Third, the timing of our TMS pulses may not have been optimal to detect changes in corticospinal excitability. During actual walking, the TA is mainly activated during the swing phase and landing phase of walking, and the most convincing evidence for involvement of the motor cortex in controlling the TA during walking was obtained for the swing phase of walking (Petersen et al., 2001). Our motor imagery of gait protocol did not allow for keeping track of the phases of the imagined walking movements. Therefore, the delivery of the TMS pulses was not linked to a particular phase of the gait cycle.

Finally, the increases in cerebral activity in the premotor cortex as recorded during the fMRI experiment may have not been strong enough to result in detectable changes in TA corticospinal excitability. TMS was applied over the primary motor cortex, whereas the changes in cerebral activity were located in the premotor cortex.

4.4. Relationship between foot dorsiflexion and walking

The experimental set-up was not designed to directly compare the effects of imagined foot dorsiflexion and imagined walking on corticospinal excitability. This would have required the tasks to be more adequately matched (e.g. for differences in trial time-course see Fig. 1), and the task order to be counterbalanced across subjects. However, because the two tasks were performed by the same subjects, the set-up did allow for examining the relationship between the effects of the two different tasks on corticospinal excitability. We found a positive relationship between the effect of imagined foot dorsiflexion and the effect of imagined walking on TA corticospinal excitability (i.e. subjects with larger increases in corticospinal excitability in the TA during imagined foot dorsiflexion also showed larger increases in corticospinal excitability in the TA during imagined walking). This relationship is interesting, since it suggests that imagined walking only influences corticospinal excitability in those subjects with the largest increment of corticospinal excitability in the TA during imagined foot dorsiflexion. The nature of this relationship remains to be determined. One possibility could be differences in general increases in corticospinal excitability across subjects. However, this is not likely given that the relationship was only found for the TA, and not for the FDI. A second possibility could be differences in imagery ability across subjects. However, there were no significant relationships between vividness of motor imagery (determined by questionnaire) and the effects of imagined foot dorsiflexion or imagined walking on TA MEP areas. A third possible explanation might be differences in MEP areas in TA across subjects. We indeed found a trend for a positive relationship between the average MEP area per subject and the effect of imagined foot dorsiflexion on MEP areas in TA

($r = 0.47$, $p = 0.07$). A similar relationship was not found for the FDI. This would suggest that subjects with greater TA MEP areas tend to show greater effects of motor imagery of lower leg movements on corticospinal excitability. However, this might only partially explain the relationship between the effects of imagined foot dorsiflexion and imagined walking. An additional explanation might involve differences in the extent to which subjects specifically focused on movements of the TA during imagery. In our study imagined foot dorsiflexion was always performed prior to imagined walking. Therefore, only those subjects who could specifically focus on the TA during the simple foot dorsiflexion task may have been able to also focus on this muscle during imagined walking. This would be in agreement with the fMRI finding that activity in bilateral cortical motor areas during motor imagery of gait is expanded when subjects are trained to focus their attention on the leg movements involved in walking (Sacco et al., 2006).

5. Conclusions

Our results show that imagery of a simple lower extremity movement (foot dorsiflexion) can increase corticospinal excitability in both a task-related muscle (TA) and a task-unrelated muscle (FDI), with greater increases in the task-related muscle. These results provide further evidence for the effect of motor imagery of lower limb movements on corticospinal excitability. Furthermore, we show that imagined gait only increases corticospinal excitability in those subjects with the largest increases in corticospinal excitability during imagined foot dorsiflexion. These results suggest that corticospinal effects of a simple imagery task can predict corticospinal effects of a more complex imagery task involving the same muscle.

Acknowledgements

This research was supported by the Stichting Internationaal Parkinson Fonds (to M.B. and B.B.). B.B., I.T., G.v.E. and S.O. were supported by The Netherlands Organization for Scientific Research (NWO) (B.B.: VIDI Grant No. 91776352; I.T.: VIDI Grant No. 45203339; G.v.E.: Grant No. 051.02.050; and S.O.: VENI Grant No. 91656103). AS was supported by the Princess Beatrix Fund.

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