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RESEARCH ARTICLE

Control of Movement

Assessing corticospinal excitability and reaching hand choice during whole body motion

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Abstract

Behavioral studies have shown that humans account for inertial acceleration in their decisions of hand choice when reaching during body motion. Physiologically, it is unclear at what stage of movement preparation information about body motion is integrated with the process of hand selection. Here, we addressed this question by applying transcranial magnetic stimulation over left motor cortex (M1) of human participants who performed a preferential reach task while they were sinusoidally translated on a linear motion platform. If M1 only represents a read-out of the final hand choice, we expect the body motion not to affect the motor-evoked potential (MEP) amplitude. If body motion biases the hand selection process before target onset, we expect corticospinal excitability to be influenced by the phase of the motion, with larger MEP amplitudes for phases that show a bias to using the right hand. Behavioral results replicate our earlier findings of a sinusoidal modulation of hand choice bias with motion phase. MEP amplitudes also show a sinusoidal modulation with motion phase, suggesting that body motion influences corticospinal excitability, which may ultimately reflect changes of hand preference. The modulation being present before target onset suggests that competition between hands is represented throughout the corticospinal tract. Its phase relationship with the motion profile indicates that other processes after target onset take up time until the hand selection process has been completely resolved, and the reach is initiated.

NEW & NOTEWORTHY Full body-motion biases decisions of hand choice. We examined the signatures of this bias in hand preference in corticospinal excitability before a reach target was presented. Our results show that behavior and corticospinal excitability modulate depending on the state of the body in motion. This suggests that information about body motion penetrates deeply within the motor system.

corticospinal excitability; hand choice; motor control; self-motion; vestibular system

INTRODUCTION

We frequently encounter tasks that can be performed with either hand, for example, moving papers on a desk, picking up a key from the table, or opening a door. Whether we use our left or right hand is known to depend on various factors, including handedness, recent choice success, and eye and head position (1–3). Biomechanical factors also play a role; participants prefer to move the hand that is closest to the target (4, 5), and for two equidistant targets, participants choose to move to the target that can be reached with the lowest biomechanical cost (6, 7).

Recently, Bakker et al. (8, 9) studied hand choice when participants are in motion. In such a dynamic situation, not only do vision and proprioception provide information about the state of the body and the environment but also information about whole body motion is registered by the vestibular organ (10). Full-body rotation or acceleration differentially modulates the biomechanical costs of left- and right-hand movements due to Coriolis or inertial shear forces working on the arm requiring muscle activity to counteract these

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forces (8, 11–14). Consequently, hand preferences are modulated by the current dynamic situation (8, 9). The physiological basis of this motion-related modulation of hand preference is unknown.

It has been proposed that decision-making and movement generation processes are tightly connected in the sensorimotor areas of the brain (15, 16). For hand selection, this implies that motor plans for both hands are generated in parallel, while these two plans compete for execution. It is unclear at what level this competition between the two motor plans is resolved.

On the one hand, studies suggest that competition for hand selection is resolved before movement preparation reaches dorsal premotor cortex (PMd), possibly in parietal cortex (17–19). On the other hand, it has been observed that areas closer to movement execution, up to primary motor cortex (M1), represent evidence for multiple concurrent movements (20–23).

Transcranial magnetic stimulation (TMS) over the motor cortex can be used to obtain a noninvasive physiological read-out of the state of corticospinal excitability, as evaluated by electromyographic recordings of the motor-evoked potential (MEP) (24, 25). In preferential-reaching tasks, corticospinal excitability is enhanced for the selected hand, whereas it is suppressed for the nonselected hand (26–29). We reasoned that if full-body motion has a modulatory effect on hand preference, this modulation might be affecting the preparatory state of motor cortex, even if no target is presented yet. We expected enhanced excitability of left M1 for phases where hand choice was biased toward the right hand and suppressed excitability of left M1 for phases where hand choice was biased toward the left hand. Here, we examine if this modulation of hand preference with full-body motion is present in M1, by applying a single TMS pulse over left M1 to quantify corticospinal excitability at the moment a reach target would have been presented. In this way, we learn how full-body motion affects hand preference.

We hypothesized that if M1 only represents a read-out of an already made decision for which the competition was resolved in upstream areas, corticospinal excitability would not be modulated by the whole body motion if no target is presented. However, if body motion affects hand preference before target onset, we expected corticospinal excitability to modulate dependent on the whole body motion, even before a target is presented.

METHODS

Participants

Twenty self-reported right-handed healthy volunteers (15 females) aged 19–47 (mean age 25 yr) took part in this study, consisting of an intake session and two experimental sessions. Participants had normal or corrected-to-normal visual acuity and had no history or presence of neurological or psychiatric disorders by self-report. Due to technical problems, data of one female participant had to be discarded. Participants received written and verbal information about the study before providing written informed consent, whereby they remained naïve as to the research question. Participants refrained from taking psychotropic substances within 2 h before experimentation and from taking alcohol within 24 h before experimentation. This study was approved by the medical research ethics committee of the Radboud University Medical Center Nijmegen (NL59818.091.16).

Apparatus

Participants were seated on a vestibular sled in a darkened room (Fig. 1A). The sled was powered by a linear motor (TB15N; Technotion, Almelo, The Netherlands) and controlled by a Kollmorgen S700 drive (Danaher, Washington, DC). Participants were securely fastened with a five-point seat belt. Their head was immobilized with a personalized thermoplastic mask (Posicast). Visual stimuli were presented on a 27-in. touch screen that also registered touch of the two index fingers (ProLite; Iiyama, Tokyo, Japan). The position of both index finger tips and the sled was measured at 500 Hz using an Optotrak Certus system (Northern Digital, Waterloo, Canada). Electromyographic activity of six right arm muscles was recorded using a Trigno Wireless EMG system (Delsys, Boston): first dorsal interosseous, brachioradialis, biceps long head, biceps short head, triceps lateral head (TLAT), and triceps long head. EMG data were band-pass filtered (30–450 Hz), amplified (1,000), and sampled at 1,111 Hz.

For the MEP measurements, we targeted the TLAT muscle, as this is the primary actor of the reaching movement. To elicit MEPs, a figure-of-8 coil (Cool-B65, MagVenture A/S) was placed over left M1 to target the right arm TLAT. The coil was oriented posterolaterally at an angle of ~45° to the midline and fixed to the sled. The coil was securely fastened to the sled. Together with the mask, this configuration ensured that there was minimal motion between the coil and the head within a session. Stimulation parameters were in agreement with the International Federation of Clinical Neurophysiology safety guidelines (30). There were no serious adverse events and participants had no issues tolerating the TMS. As TLAT is the primary actor of the reaching movement and this was the targeted muscle, only data from TLAT will be reported.

Experiment

The intake session and two experimental sessions took place on different days and all started with localizing the right arm TLAT hotspot and determining the resting motor threshold for this muscle (31). During this procedure, the arms were flexed while the full lower arm and hand were resting relaxed on the table and armrests. If we could not elicit a MEP at a stimulation intensity of 83% (as a percentage of the maximum machine output), or if the participant did not feel comfortable with the experimental setup, volunteers were not invited to take part in the experimental sessions. Therefore, we saw about three times as many volunteers in the intake session than volunteers who took part in the full experiment. The mean resting motor thresholds in the experimental sessions of the participants who completed the experiment was 70.2% (SD = 11.3) of the maximum machine output. These relatively high motor thresholds are likely related to the location of the somatotopic representation of the targeted muscle in the primary motor

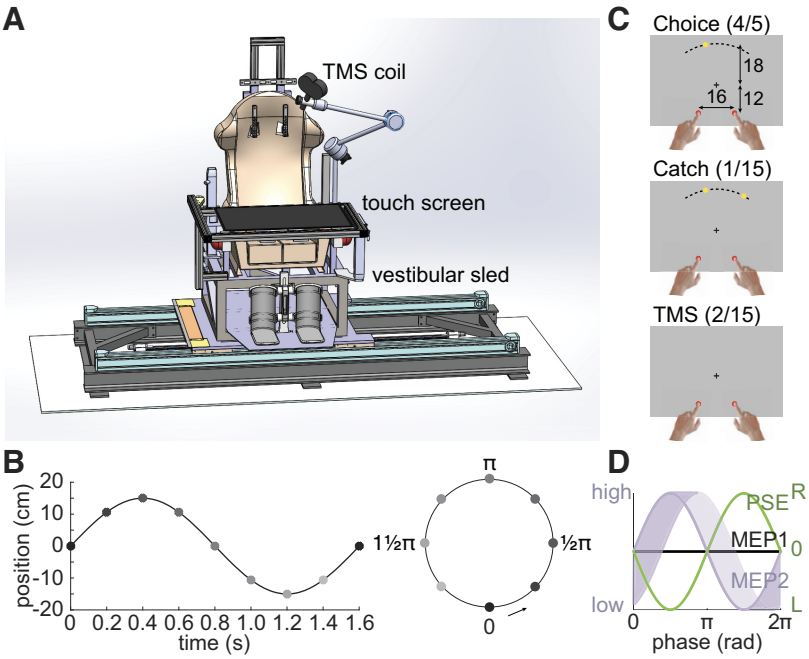

Figure 1. Experimental setup. *A*: illustration of the vestibular sled, touch screen, and TMS coil. *B*: sled position as a function of time. Target stimuli were presented, or TMS stimulation was applied at one of eight phases of whole body motion (gray circles). *C*: start locations of the index fingers (red circles), fixation cross and example target locations (yellow circles) for choice, catch and TMS trials. *D*: predictions for the modulation of hand preference and corticospinal excitability as a function of sled phase. Body acceleration as a function of time is maximally leftward at the right turning point, i.e., at phase ½π. Based on study by Bakker et al. (8), we expect maximum leftward deviation of the PSE, thus making right hand choices over all targets more likely, at this phase (green). MEP may (MEP2, purple) or may not (MEP1; black) modulate as a function of sled phase. In the latter case, as MEPs were evoked over left M1, we expect enhanced MEPs for more right-hand choices. The shaded area for MEP2 indicates the predicted corticospinal excitability for a read-out in the time window from target presentation to movement initiation. MEP, motor-evoked potential; PSE, point of subjective equality; TMS, transcranial magnetic stimulation.

cortex. After the resting motor threshold was determined in the intake session, participants were familiarized with the experimental setup and fitted with the personalized head mask.

During the experimental sessions, the sled translated in a sinusoidal fashion along the interaural axis with an amplitude of 0.15 m and a period of 1.6 s (Fig. 1*B*), resulting in a peak-to-peak amplitude of 0.3 m, a peak velocity of 0.59 m/s, and a peak acceleration of 2.3 m/s^2. Although in motion, participants looked at a fixation cross in the center of the screen and triggered the start of each trial by placing their left and right index fingers on the starting points (red circles, 3.5 cm diameter; Fig. 1*C*). There were three types of trials: choice trials, catch trials, and TMS trials (Fig. 1*C*). In choice trials, a target was presented (yellow circle, 3.5 cm diameter) at one of eight phases of the whole body motion (gray circles in Fig. 1*B*). Targets appeared within 5° of the intended phase of sled motion. In 75% of the trials, the direction of the presented target was determined by a Bayesian adaptive approach to find the target angle for which participants were equally likely to choose their left and right hand (32, 33), whereby possible angles were −40°, −35°, −30° to 30° with steps of 2°, 35°, and 40°. In the other 25% of trials, a peripheral target (−40°, −35°, −30°:2:−22°, 22°:2:30°, 35°, or 40°) was presented, enabling an estimate of the full psychometric curve after data collection. The adaptive estimation was run for each phase of motion separately. Participants were instructed to hit the target as quickly and accurately as possible with either their left or their right index finger. In catch trials, to avoid predetermined hand choices, two targets were presented and participants were instructed to hit both targets with their left and right index fingers.

In TMS trials, a single TMS pulse (~1 ms) at 120% of the participants' resting motor threshold was delivered at one of eight phases of motion (gray circles in Fig. 1*B*). Thus, the pulse was delivered at the time a target would have been presented in a choice trial, but the target remained absent in the TMS trials. After a TMS trial, there was a 3-s break and participants were asked to lift their fingers and replace them at the start locations. Trial type was pseudorandomized whereby there were at least three other trials in between successive TMS or catch trials. Per session, participants performed 6 blocks of 120 trials with short breaks in between the blocks. Each block consisted of 96 choices, 16 TMS, and 8 catch trials, resulting in a total of 1,440 trials per participant. Per phase of motion there were 24 TMS trials. One experimental session tested at the phases of sled motion 0, $\frac{1}{2}\pi$, π, and $1\frac{1}{2}\pi$, and the other session tested at $\frac{1}{4}\pi$, $\frac{3}{4}\pi$, $1\frac{1}{4}\pi$, and $1\frac{3}{4}\pi$.

Analyses

Hand choice was determined by the first index finger leaving the touch screen, as registered online by the screen. Optotrak data confirmed the choices determined based on touch screen data. For each sled phase, the target angle for which participants were equally likely to choose their left and right hand was estimated by a cumulative Gaussian distribution fit using a maximum likelihood approach with a lapse rate (34):

$$P(x) = \lambda + (1 - 2\lambda)\frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{-(y-\mu)^2/2\sigma^2}dy \qquad (1)$$

Here, x represents the target angle, μ represents the target angle for which participants were equally likely to choose their left and right hand, i.e., the point of subjective equality (PSE), σ represents the standard deviation of the choice distribution, and λ represents the lapse rate.

Based on Bakker et al. (8), PSE was expected to modulate with phase (Fig. 1*D*; green). To determine the phase modulation of the sled on the PSE, two sinusoids with a coupled phase (θ_{PSE}) and two independent amplitudes (A1 and A2) and offsets (B1 and B2) were fit to each participants' PSEs of the two sessions:

$$PSE_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} = A1 \times \sin\left(sled_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} - \theta_{PSE}\right) + B1 \quad (2)$$

$$PSE_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} = A2 \times \sin\left(sled_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} - \theta_{PSE}\right) + B2$$

Corticospinal excitability was determined by measuring the MEP amplitude caused by the single pulse TMS. For each trial, the difference between the maximum and minimum EMG activity in TLAT 15–35 ms after the TMS pulse was calculated (7). Trials were excluded if the maximum EMG activity in a window 200 ms before the TMS pulse exceeded 0.1 mV (28), if the trigger was missing, or if sensor connection was lost. The trigger happened to be missing in one full session of *participant 11*. Of all other trials of all participants, 9% was excluded. MEP was determined as the mean potential per participant per phase.

Similar to the hand choice data, two sinusoids with a coupled phase (θ_{MEP}) and two independent amplitudes (C1 and C2) and offsets (D1 and D2) were fit to each participants' MEPs of the two sessions:

$$MEP_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} = C1 \times \sin\left(sled_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} - \theta_{MEP}\right) + D1 \quad (3)$$

$$MEP_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} = C2 \times \sin\left(sled_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} - \theta_{MEP}\right) + D2$$

This ensured that differences in amplitude and offset, that may occur due to differences in coil position and stimulation intensity on different testing days, were accounted for.

As MEP is a noisy measure, the sinusoid fits were also performed on all single trial MEPs per participant instead of the mean MEP per phase per participant. Also, a single sinusoid phase was fit to all participants' mean MEPs with session- and participant-dependent amplitudes and offsets. All of these fits resulted in a similar estimation of the mean phase, suggesting that the measure is robust. Therefore, we only report results of the individual fits to the mean MEPs.

To test if there was a sinusoidal modulation of the PSEs and MEPs, or if a constant offset per session could better explain the behavioral and physiological data (see Fig. 1*D*), a constant model was also fit to the data of each participant:

$$PSE_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} = mean\left(PSE_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi}\right) \quad (4)$$

$$PSE_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} = mean\left(PSE_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi}\right) \quad (5)$$

$$MEP_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi} = mean\left(MEP_{phase\ 0,\frac{1}{2}\pi,\pi,1\frac{1}{2}\pi}\right) \quad (6)$$

$$MEP_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi} = mean\left(MEP_{phase\ \frac{1}{4}\pi,\frac{3}{4}\pi,1\frac{1}{4}\pi,1\frac{3}{4}\pi}\right) \quad (7)$$

For every participant, the fits of the two models were compared by computing the Bayesian information criterion (BIC), which accounts for the difference in the number of parameters:

$$BIC = N \cdot \ln\left(\sigma_e^2\right) + k \cdot \ln(N) \quad (8)$$

Where N is the number of fitted data points (N = 8 for all participants except for participant 11 N = 4), σ_e^2 is the mean squared error of the fit, and k is the number of model parameters, i.e., 1 for the constant model and 3 for the sinusoid model. The BIC value is smaller if the model has fewer parameters and hence provides a more parsimonious description of the data. To compare the two models, a difference value was computed:

$$\Delta BIC = BIC_{constant} - BIC_{sinusoid} \quad (9)$$

A BIC value difference of 2–6 indicates positive evidence for the model with the lower value, 6–10 indicates strong evidence, and >10 very strong evidence (35).

As MEPs were induced by stimulating left M1, we expected that MEPs would be enhanced for phases where a right-hand choice was more likely. Behaviorally, a more likely right-hand choice corresponds to a PSE shift toward the left (Fig. 1*D*, green). If the modulation of MEP is aligned with the presentation of the target, we therefore expect a π phase difference between PSE and MEP (Fig. 1*D*, purple). However, the modulation of MEP may not be aligned with target presentation, because information about the target may take some time to process in the brain, i.e., nondecision time (36). Maximally, this process would last as long as the reaction time, which is ~300 ms in this task (8). With a sled period of 1.6 s, this would result in a $\frac{5}{8}$ π phase difference between PSE and MEP (Fig. 1*D*, shaded purple). Thus, we hypothesize that the phase difference between PSE and MEP will be in between $\frac{5}{8}$ π and π (Fig. 1*D*). To test if the MEP phases were distributed uniformly around the circle, or were in the mean direction of the fitted PSE phase minus $\frac{5}{8}\pi$, we performed a V-test for nonuniformity (37, 38).

To be able to get a phase estimate across participants in which the reliability of the individual participants' estimate is taken into account, we implemented a full Bayesian version of the MEP modulation model in Stan (39) and pystan (40, 41). We used a hyper-prior on the phase, but left amplitude and offset free across participants and sessions. The same approach was used on the PSE data.

RESULTS

We investigated if corticospinal excitability, before a target is presented, reflects biases in hand preference induced by whole body motion. In most trials, participants were free to choose with which hand they preferred to move to the target. Figure 2*A* shows hand choice behavior of *participant 9*, separately for the different sled phases. Cumulative Gaussian fits were used to estimate the target angle for which participants were equally likely to choose their left and right hand, i.e., the PSE, indicated by the vertical black line. Figure 2*B* shows the PSE as a function of the sled's motion phase at which the target was presented for the individual participants. Data from the two sessions are indicated by dark and light blue. To determine the phase relationship between sled motion and hand preference, the PSEs of each participant were fitted by two sinusoids with a single-phase and session-dependent amplitudes and offsets (Eq. *3*). Consistent with previous work from our laboratory, the PSE was shifted mostly to the left, thus indicating a preference for using the right hand, around maximum leftward acceleration, i.e., sled phase $\frac{1}{2}\pi$. Similarly, the PSE was shifted most strongly to the right around maximum rightward acceleration, i.e., sled phase $1\frac{1}{2}\pi$ (8, 9).

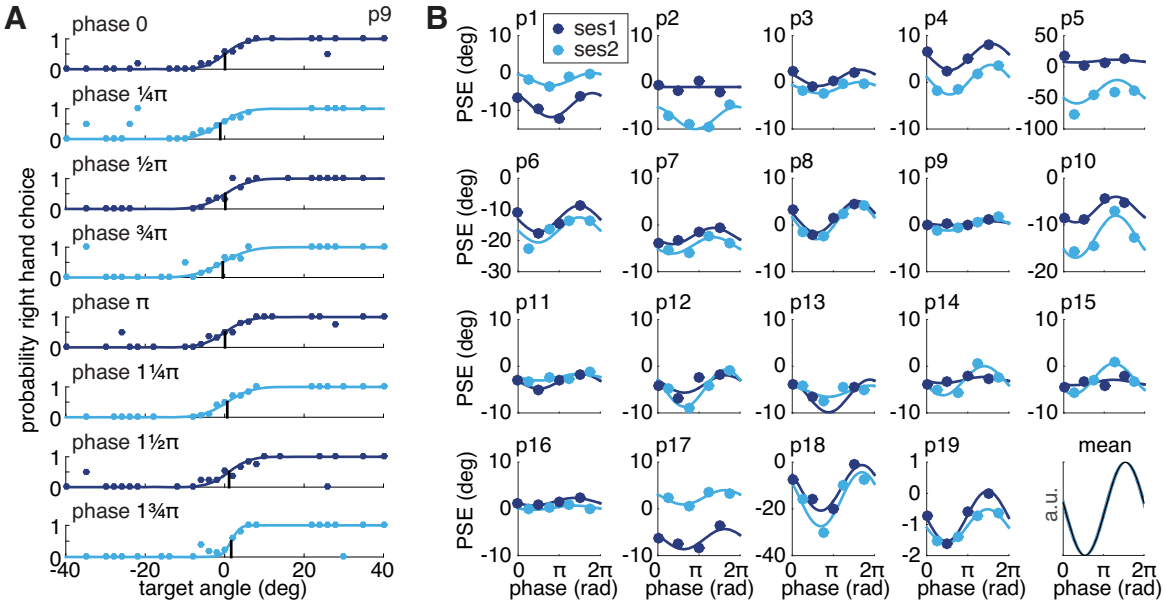

Figure 2. Choice behavior. *A*: probability of right-hand choice as a function of target angle (dots) fit by a cumulative Gaussian distribution (lines) for *participant 9*. The vertical black line indicates the PSE angle. Each panel shows a different sled phase. *B*: PSE as a function of sled phase for all participants (p1 to p19) and the circular mean phase with SE of the mean phase (*bottom right*; amplitude in a.u.). PSEs were tested in two different sessions (dark blue: 0, ½π, π, and 1½π; light blue: ¼π, ¾π, 1¼π, and 1¾π). Lines show sinusoidal fits with a within-participant coupled phase and session-dependent amplitudes and offsets (*Eq. 2*). PSE, point of subjective equality.

To test if the PSE data are better represented by a sinusoid than by a constant offset, we calculated the difference in BIC between the two models, thereby accounting for the difference in number of free parameters. As illustrated in Fig. 3, *left*, 16 out of 19 participants show strong to very strong evidence ($\Delta BIC > 6$) for a sinusoidal modulation, whereas no participant shows positive evidence for a constant offset ($\Delta BIC < -2$). This again confirms that hand choice is modulated by sinusoidal body motion in a sinusoidal fashion. The modulation is thought to reflect the influence of bottom-up acceleration signals on hand choice (8, 9).

In selected trials, a single TMS pulse was delivered. Figure 4*A* shows the mean TLAT EMG response (MEP) to this pulse for each sled phase for *participant 9*. Figure 4*B* shows the resulting MEP amplitudes as a function of sled phase for all participants. Compared with the PSEs, MEPs were more variable between sessions and between participants. As for the PSEs, a sinusoidal model with a single-phase and session-dependent amplitudes and offsets was fit to the MEPs for each participant (*Eq. 3*). Across participants, the circular mean phase seems to peak around π (*bottom right*).

To test if the MEP data, similar to the PSE data, also support a sinusoidal model over a constant offset, the difference in BIC value between the two models was calculated (Fig. 3, *right*). Here, 15 out of 19 participants show positive to very strong evidence ($\Delta BIC > 2$) for a sinusoidal modulation, whereas no participant showed positive evidence for a constant offset ($\Delta BIC < -2$). This suggests that the MEPs were modulated by the full body motion in a sinusoidal fashion.

We hypothesized that if corticospinal excitability reflects biases in hand preference, there would be a $\frac{5}{8}\pi$ to π phase difference between the PSE and MEP phases (Fig. 1*D*). Figure 5, *A* and *C*, shows polar plots of the PSE and MEP phases for all participants. With a V-test for nonuniformity, we tested if the MEP phases were distributed uniformly around the circle or were in the mean direction of the fitted PSE phase $-\frac{5}{8}\pi$ (37, 38). We found that the MEP phase distribution was in the direction of the PSE phase $-\frac{5}{8}\pi$ distribution ($V = 5.57$, $P = 0.0353$). This suggests that the modulation in corticospinal excitability that we found may be related to hand preference.

As the elicited MEPs were noisy, also the fitted MEP phase varied across participants. Figure 5, *B* and *D*, depicts the phase distribution across the group for sinusoid in the PSE model and sinusoid in the MEP model.

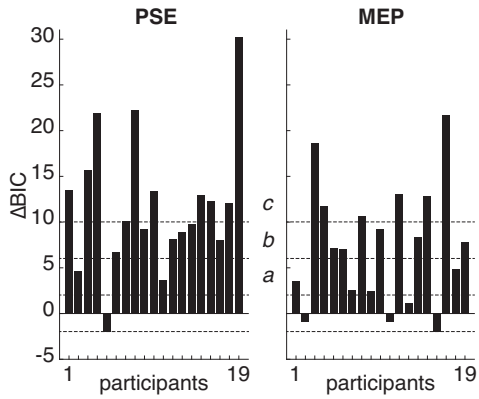

Figure 3. BIC model comparisons for the PSE (*left*) and MEP data (*right*). ΔBIC values per participant. A positive value indicates support for the sinusoidal model over the constant model. A BIC value difference of 2–6 indicates positive evidence for the model with the lower value (*a*), 6–10 indicates strong evidence (*b*), and >10 very strong evidence (*c*). BIC, Bayesian information criterion; MEP, motor-evoked potential; PSE, point of subjective equality.

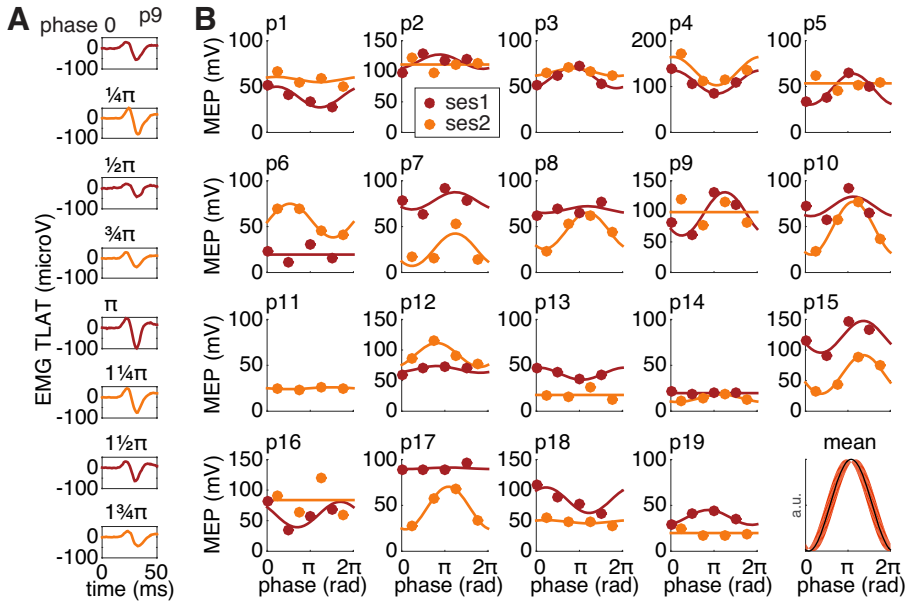

Figure 4. Corticospinal excitability. *A*: average EMG response of TLAT as a function of time since the TMS pulse for *participant 9*. Each panel shows a different sled phase. *B*: mean MEP amplitude as a function of sled phase for all participants (panels 1:19) and the circular mean phase with SE (*bottom right*). MEPs for each phase were tested in two different sessions (dark red: 0, ½π, π, and 1½π; orange: ¼π, ¾π, 1¼π, and 1¾π). Lines show the sinusoid fits with a within-participant coupled phase and session-dependent amplitudes and offsets. MEP, motor-evoked potential; TLAT, triceps lateral head; TMS, transcranial magnetic stimulation.

Comparing the width of the estimated group distribution for PSE and MEP (Fig. 5, *B* and *D*), across participants the estimate of the PSE phase is more reliable than the estimate of the MEP phase.

DISCUSSION

We examined if corticospinal excitability reflects hand choice preference due to whole body motion before the hand is selected. Choice behavior confirms previous observations from our laboratory: sinusoidal whole body motion modulates hand choice bias. Specifically, the target for which both hands are equally likely to be selected shifts maximally to the left (indicating a preference for using the right hand) at maximum leftward body acceleration (Fig. 2*B*) and maximally to the right at maximum rightward body acceleration (8, 9). Corticospinal excitability also modulates sinusoidally with body motion. Stimulation over left M1 resulted in maximum excitability around phase π (maximum leftward body velocity, Fig. 4*B*). The sinusoidal modulation of corticospinal excitability suggests that biased competition between hands is deeply ingrained within the motor system. This fits within a framework of multiple concurrently prepared actions, even before a target is presented (20, 22, 23).

The fact that both the hand choice bias and MEP amplitude are sinusoidally modulated by whole body motion, raises the question whether the MEP modulation is predictive of hand preference. MEPs were elicited at the same phases of body motion as the target would have been presented. If hand preference is reflected in the corticospinal state at the moment of target presentation, we would have expected a phase difference between PSE and MEP of π: a maximum shift of the PSE to the left (negative) corresponds to a maximum MEP amplitude (Fig. 1*D*). However, if behavioral choice is influenced by the corticospinal state somewhere in the reaction time window, the phase of the MEP modulation would shift further along the sled motion (to the right in Fig. 1*D*; sled motion period is 1.6 s), resulting in a smaller phase difference between PSE and MEP. This MEP phase shift would maximally last as long as reaction time (~300 ms), resulting in a phase difference between PSE and MEP of $\frac{5}{8}\pi$. The mean phase difference that we found was even slightly smaller than the hypothesized window. This might suggest that hand preference is not fully predictable by corticospinal excitability before a target is presented and warrants further investigation.

It has been shown that vestibular information is taken into account in movement planning and online control of reaching movements. Vestibular stimulation by means of full-body rotation or by means of artificial stimulation of the vestibular organ with galvanic stimulation, which induces the illusion of a body rotation, results in immediate corrections of the reaching movement to account for the perceived rotation (42–45). Also, visuomotor feedback gains for online corrections are modulated by vestibular information (46). In addition, a proprioceptively deafferented patient showed reach corrections only if the head moved with the body, stimulating the vestibular system, but not if the head remained fixed in space while the body moved. This suggests that vestibular information contributes to the control of reaching movements (47).

In hand choice tasks with a stationary body, biomechanical costs in terms of required effort have been shown to influence hand selection (2). The relative effort associated with moving either arm changes continuously under whole body motion, which we have hypothesized might alter hand choice during passive body motion (8). Bakker et al. (8) found that a model that computes future movement effort based on a constant whole body acceleration from the moment of target presentation best describes the observed choice biases. Behaviorally, we confirm previous results, but the phase shift between behavior and corticospinal excitability in the current study suggests that the exact moment at which the body acceleration is registered by M1 might be later than the moment of target presentation.

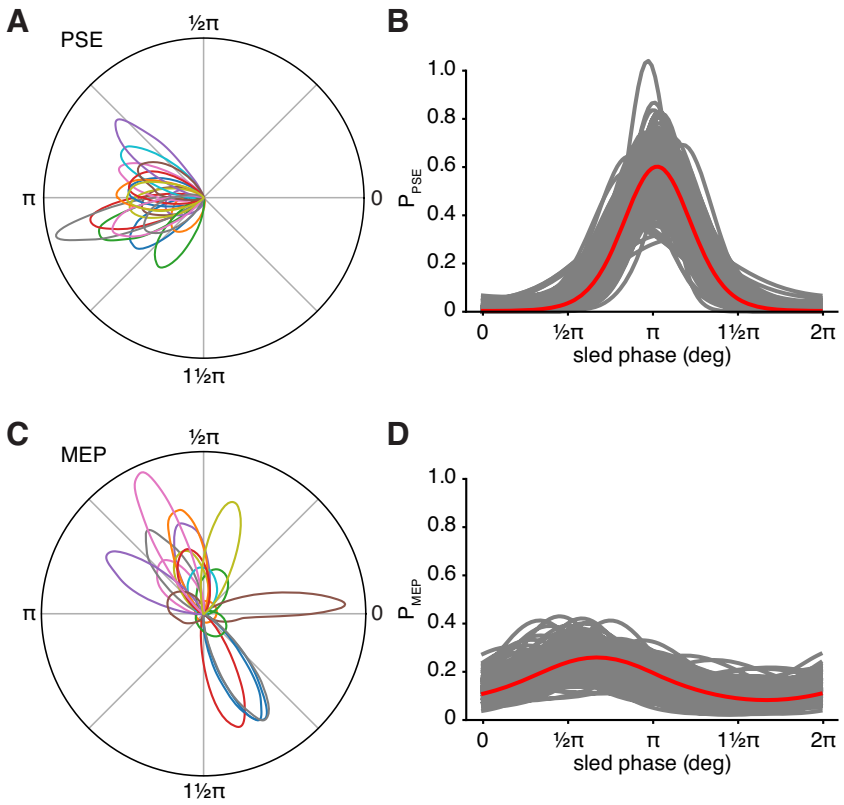

Figure 5. Phase distributions and their reliability. *A*: phase distributions for the individual participants for the PSE. *B*: phase distribution across participants for individual draws from the posterior distribution (gray) of the Bayesian model fit and the average (red). *C*: same as *A*, but for the MEP phase distributions. Colors in panel *A* and *C* are matched for same participant. *D*: same as *B*, but for the MEP phase. MEP, motor-evoked potential; PSE, point of subjective equality.

From previous work, we know that reaching under whole body linear acceleration requires adaptation of an internal model (48), but we were unable to show signs of learning in choice behavior in the current paradigm (8). This raises the question whether the modulation of the MEP with sled phase is developing over the course of the experiment or that this coupling is the result of a more direct modulation of body motion-related signals on the corticospinal tract. We aimed to post hoc examine the possibility of a development of the MEP amplitude due to learning by comparing the MEPs of the first half of the experiment to the second half, whereby MEP amplitude was computed for each half separately according to the methods applied to the full data set. However, the small number of trials did not provide us with enough power to prove or disprove a change in MEP over the course of the experiment. Future research, with more TMS trials, might examine if corticospinal excitability slowly adapts as a function of the passive body motion.

The observed modulation in corticospinal excitability may find its origin in not only cortical areas related to hand selection and movement preparation but also the spinal part of the circuit (25). Possibly postural responses anticipating the passive full-body motion modulated the MEP amplitude (49). To minimize coactivation of antagonistic muscle pairs (50), our setup was designed to enable a relaxed arm and body posture throughout the experiment. If TLAT was unexpectedly more active than during resting state, this trial was excluded. Also, if there would have been coactivation, one may expect that this would result in an overall increase of muscle tension, rather than the sinusoidal pattern observed here. Therefore, we believe that the observed modulation of corticospinal excitability with body motion is not related to increased tension in antagonistic muscles, but rather to the motion itself.

Postural reflexes evoked by the passive body motion may also have modulated the resting state EMG activity (51). To check whether this was the case, we computed the mean TLAT activity in a window from 50 ms before the TMS pulse until the pulse and fitted the same sinusoidal model as to the MEP amplitudes to this prepulse mean. This did not result in a consistent phase estimate across participants, suggesting that the observed modulation of corticospinal excitability with body motion is not related to postural reflexes.

Alternatively, more global effects could have influenced corticospinal activity. For example, it has been reported that attentional focus (external vs. internal) modulates MEPs evoked by motor cortex stimulation (52). Concurrent leg muscle activation results in a prolonged attenuation of EMG activity (i.e., cortical silent period) after TMS pulses targeting finger muscle abduction, whereas the MEP amplitude itself remained unaffected (53). Bestmann et al. (54) demonstrated that uncertainty and surprise influence MEPs in a delayed-response task. Although our TMS pulses were applied over M1, the induced electric field could have resulted in stimulation of corticospinal, intracortical, and transcortical neurons, with activation spreading throughout the cerebral cortex possibly increasing neural excitability (25, 55). We controlled for these effects by means of full body fixation, no target being present in the TMS trials and unpredictable stimuli presentation times.

We manipulated the state of the body with sinusoidal full-body motion. As position, velocity, and acceleration are

inherently related for sinusoids, and the motion may be predictable, it is difficult to infer what information participants used. Congruent with previous findings for eye and hand selection, peak preferences align with acceleration information (8, 9, 56). However, corticospinal excitability peaks around phases of maximum and minimum velocity. Future work could use multiple superimposed sinusoidal sled motions, whereby position, velocity, and acceleration are decoupled, to test what information drives behavior and corticospinal excitability.

To conclude, we show that both choice behavior and corticospinal excitability modulate as a function of passive full body motion. This modulation may be driven by biomechanical costs predicted based on vestibular information, suggesting that body motion information biases hand selection processes even before a target is presented.

DATA AVAILABILITY

All data and code are available from the Donders Institute for Brain, Cognition and Behavior repository at https://doi.org/10.34973/pm0w-wj61.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

L.O.W., B.S.R., D.J.L.G.S., L.P.J.S., and W.P.M. conceived and designed research; L.O.W., S.C.W., B.S.R., and L.P.J.S. performed experiments; L.O.W. and L.P.J.S. analyzed data; L.O.W., L.P.J.S., and W.P.M. interpreted results of experiments; L.O.W. and L.P.J.S prepared figures; L.O.W. drafted manuscript; L.O.W., S.C.W., D.J.L.G.S., L.P.J.S., and W.P.M. edited and revised manuscript; L.O.W., S.C.W., D.J.L.G.S., L.P.J.S., and W.P.M. approved final version of manuscript.

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