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Similar scaling of contralateral and ipsilateral cortical responses during graded unimanual force generation

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ABSTRACT

Hemibody movements are strongly considered as being under the control of the contralateral hemisphere of the cerebral cortex. However, some neuroimaging studies have found a bilateral activation of either the primary sensori-motor (SM1) areas or the rostral prefrontal cortex (PFC), during unimanual tasks. More than just bilateral, the activation of these areas was found to be symmetrical in some studies. However, the symmetrical response remains strongly controversial notably for handgrip force generations. We therefore aimed to examine the bilateral SM1 and rostral PFC area activations in response to graded submaximal force generation during a unilateral handgrip task. Fifteen healthy subjects performed 6 levels of force (ranging from 5 to 50% of MVC) during a handgrip task. We concomitantly measured the activation of bilateral SM1 and rostral PFC areas through near-infrared spectroscopy (NIRS) and the electromyographic (EMG) activity of the bilateral flexor digitorum superficialis (FDS) muscles. Symmetrical activation was found over the SM1 areas for all the investigated levels of force. At the highest level of force (i.e., 50% of MVC), the EMG of the passive FDS increased significantly and the ipsilateral rostral PFC activation was found more intense than the corresponding contralateral rostral PFC activation. We suggest that the visuo-guided control of force levels during a handgrip task requires the cross-talk from ipsi- to contralateral SM1 to cope for the relative complexity of the task, similar to that which occurs during complex sequential finger movement. We also propose alternative explanations for the observed symmetrical SM1 activation including (i) the ipsilateral corticospinal tract and (ii) interhemispheric inhibition (IHI) mechanism. The increase in EMG activity over the passive FDS could be associated with a release of IHI at 50% of MVC. Finally, our results suggest that the greater ipsilateral (right) rostral PFC activation may reflect the greater demand of attention required to control the motor output at high levels of force.

Introduction

The corticospinal tract (CST) is classically depicted as a crossed pathway and subsequently hemibody movements are often considered as emanating from under the control of the contralateral hemisphere of the cerebral cortex. However, the true nature of the CST is more complex, this structure not being a fully crossed pathway (Kuypers, 1985). Those nervous fibers not crossing constitute the ipsilateral CST. Numerous authors have described the role of the latter in the control of unilateral hand tasks (Bawa et al., 2004; Brus-Ramer et al., 2009; Wassermann et al., 1991, 1994; Ziemann et al., 1999) and have implicated ipsilateral cortical activation in unimanual control through neuroimaging methods. For instance, Wriessnegger et al. (2008) reported, using the near-infrared spectroscopy (NIRS) technique, a bilateral activation over the primary sensorimotor (SM1) areas during a unilateral finger tapping task, as revealed by an increase in oxyhemoglobin (O_2Hb) and a slight decrease in deoxyhemoglobin (HHb). Similarly, Pfurtscheller et al. (2000) found a bilateral electroencephalography (EEG)-measured event-related desynchronization in the lower mu-rhythm during unimanual movement compared to rest.

Whereas the presence of ipsilateral cortical involvement in unimanual tasks is clearly supported through previous studies the extent or magnitude of this relation has still not been definitively established. On the one hand, numerous studies describe the response of the SM1 areas as asymmetric (Catalan et al., 1998; Ehrsson et al., 2000; Kawashima et al., 1996; Tanji et al., 1988), and favor a higher contralateral activation for a large panel of hand tasks. On the other hand, no significant difference between the ipsilateral and the contralateral

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activations of these areas were found during complex sequential finger movements (Verstynen et al., 2005). The high magnitude of the ipsilateral SM1 area activation was related to the role of this area in "shaping precisely" the muscular command originating from the contralateral hemisphere (Davare et al., 2007; Ehrsson et al., 2000) when fine finger control is required. Indeed, according to the transcranial magnetic stimulation study performed by Davare et al. (2007), during unimanual fine finger movements the ipsilateral M1 strongly contributes to the setting of muscle recruitment timing, either through facilitatory or inhibitory mechanisms. In summary, traditional neuroimaging data show that tasks involving a higher complexity in the sequencing of finger movements elicit stronger and less asymmetric activation pattern in motor areas. Nevertheless, similar results were found with functional magnetic resonance imaging (fMRI) for the production of various submaximal levels of force in power-handgrip tasks (Dai et al., 2001), a task which does not require much precision according to phylogenetic and functional considerations (Ehrsson et al., 2000; Napier, 1956). Indeed, based on the findings from Dai et al. (2001), albeit not highlighted by the authors, one may observe a symmetrical activation of the SM1 areas from 20 to 65% of maximal voluntary contraction (MVC) during a handgrip task. Further, Shibuya et al. (2008) found a NIRS-measured symmetrical M1 activation during the course of a low-intensity fatiguing handgrip task.

It is possible that this symmetrical activation pattern may not be limited to the SM1 areas only. The rostral prefrontal cortex (PFC) areas for example, are ipsilaterally connected to the motor areas through cortico-cortical pathways (Krieghoff et al., 2011) and are involved in the initiation and the control of voluntary movements (Miller and Cohen, 2001). A bilateral activation of the rostral PFC areas has been observed during fatiguing unilateral handgrip tasks (Liu et al., 2003; Mottola et al., 2006). However, the involvement of processes associated with fatigue in these studies and in Shibuya et al. (2008) may obscure the true extent of such bilateral activation. Finally, while previous studies have reported a symmetrical activation of the SM1 areas during various submaximal levels of force (Dai et al., 2001), the corresponding result for the rostral PFC has not been reported to date.

Therefore, we aim to examine the ipsilateral and contralateral activation responses of SM1 and rostral PFC areas to graded levels of force production during a unilateral handgrip task. We suggest that the symmetrical activation observed is not a property of the complex sequential finger movements only. Rather, in accordance with the results of Dai et al. (2001), we hypothesize that contralateral and ipsilateral rostral PFC and SM1 changes operate in a similar way with graded submaximal force generation during a unilateral handgrip task. The new insight revealed by this study may be relevant for the diagnostic evaluation of neurological hand motor assessments. Such a NIRS method could be used to examine the cortical activation during the assessment and at the same time monitor treatment progress with less strenuous procedures than traditional neuroimaging methods (fMRI and EEG).

Materials and methods

Participants

Fifteen healthy volunteers took part in the study (aged 28.0 ± 7.5 years; height 175.5 ± 5.9 cm; body weight 69.4 ± 8.9 kg). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971). None had any sign of neurological, respiratory, and cardiovascular disease or used medication, which might affect brain and muscle functions. Each subject provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentation.

Protocol and task procedure

The experiments were conducted in a quiet and dimly lit room. Each subject performed the entire protocol once. The subjects were asked to sit comfortably at a table. They were facing a computer screen with the left forearm resting upon the surface and held in place with straps to prevent extraneous movements during isometric contractions of the right forearm. The dominant hand was held in neutral position in the sagittal plane. The angle of the elbow was set to 110° for each subject (with 0° corresponding to the full extension of the arm). The protocol began with a familiarization and warm-up phase with the handgrip task. After individual set-up, the subjects were requested to perform during 5 min a few static submaximal contractions of the finger flexors in an intermittent mode. Foremost, the subjects produced three MVCs of a 5-s duration followed by 90 s of passive recovery. Second, each subject underwent an experimental block-paradigm design containing six conditions of static submaximal force levels repeated three times. The target levels of force were set at 5%, 10%, 20%, 30%, 40% and 50% of MVC. The subjects matched their force with a target force for 30 s followed by 60 s of rest. Applying such intervals in the set-up was determined following pilot trials to both maximize NIRS-evoked responses and minimize the occurrence of neuromuscular fatigue. The block paradigms were pseudo-randomized to avoid order and fatigue effects as well. The pseudo-random order prevented immediate repetition of relatively high force levels between conditions and blocks. Immediately after each block, a MVC was carried out to ensure that no neuromuscular fatigue was induced by the successive muscle contractions. To reduce artifacts, the subjects were asked throughout the experimental protocol to minimize head and body movements as well as to breathe as gently and as regularly as possible.

Measurements

Force

The levels of force were recorded using a handgrip dynamometer (Captels, Saint-Mathieu de Tréviers, France). The force signals were recorded at 1000 samples per second using a data acquisition system (Biopac MP30, System Inc., Santa Barbara, CA). To maintain the level of force correctly, visual feedback was displayed on the computer screen facing the subjects.

Electromyography

The surface electromyogram (sEMG) of the flexor digitorum superficialis (FDS) muscle of the hand actively involved in the task (right) and the passive (left) hand were recorded using bipolar Ag/AgCl electrodes (Contrôle Graphique Medical, Brie-Comte-Robert, France) with a 9-mm diameter at an inter-electrode distance of 20 mm. The skin was shaved, abraded and washed with emery paper and cleaned with 70° alcohol in order to obtain low impedance between the two bipolar electrodes (<3 kΩ). The reference electrode was positioned on the styloid process of the left ulna. The EMG cables were strapped to the chair to prevent movement artifacts. The EMG signals were amplified (×1000), measured at a sample rate of 1000 samples per second and synchronized with the force signals using the Biopac MP30 data acquisition system (Biopac System, Inc., Santa Barbara, CA).

Near infrared spectroscopy

The NIRS technique has been described elsewhere (Elwell et al., 1994) and has been demonstrated previously as relevant for investigating cortical activity during movement generation (Perrey, 2008). NIRS measurements were performed using a continuous wave (CW) multichannel NIRS system (Oxymon Mk III, Artinis, The Netherlands). The sampling rate was set at 10 Hz. This system allowed measurement of changes in optical density at two different wavelengths in the near-infrared range (nominal wavelengths 760 and 850 nm)