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CORTICAL CURRENT DENSITY OSCILLATIONS IN THE MOTOR CORTEX ARE CORRELATED WITH MUSCULAR ACTIVITY DURING PEDALING EXERCISE

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Abstract—Despite modern imaging techniques, assessing and localizing changes in brain activity during whole-body exercise is still challenging. Using an active electroencephalography (EEG) system in combination with source localization algorithms, this study aimed to localize brain cortical oscillations patterns in the motor cortex and to correlate these with surface electromyography (EMG)-detected muscular activity during pedaling exercise. Eight subjects performed 2-min isokinetic (90 rpm) cycling bouts at intensities ranging from 1 to 5 W kg^{-1} body mass on a cycle ergometer. These bouts were interspersed by a minimum of 2 min of passive rest to limit to development of peripheral muscle fatigue. Brain cortical activity within the motor cortex was analyzed using a 32-channel active EEG system combined with source localization algorithms. EMG activity was recorded from seven muscles on each lower limb. EEG and EMG activity revealed comparatively stable oscillations across the different exercise intensities. More importantly, the oscillations in cortical activity within the motor cortex were significantly correlated with EMG activity during the high-intensity cycling bouts. This study demonstrates that it is possible to localize oscillations in brain cortical activity during moderate- to high-intensity cycling exercise using EEG in combination with source localization algorithms, and that these oscillations match the activity of the active muscles in time and amplitude. Results of this study might help to further evaluate the effects of central vs. peripheral fatigue during exercise. © 2012 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: EEG, current density, EMG, motor cortex.

INTRODUCTION

Despite modern imaging technologies, to date it has not been possible to clearly display neural changes within the human cortex during whole-body exercise. This is mainly due to the necessity of remaining inactive during positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) for example.

A number of near-infrared spectroscopy (NIRS) studies have reported hemodynamic changes in the cortex during varied whole-body exercises (Thomas and Stephane, 2008; Ekkekakis, 2009; Billaut et al., 2010; Rooks et al., 2010; Smith and Billaut, 2010). Nevertheless, these studies were simply able to show changes in brain hemodynamics with exercise intensity and/or fatigue that were limited to the prefrontal cortex. Further the NIRS signal may be contaminated by changes in blood circulation caused by exercise, and it has proved difficult to infer about changes in neural activity. Finally, it remains unclear to what degree changes in the NIRS signal are affected by possible interference of extracranial tissue (Canova et al., 2011).

So far the number of studies displaying exercise related neural changes within the cortex are rare. Beside a PET study by Tashiro et al. (2001) and a fMRI study by Mehta et al. (2009), proofing the possibility to localize plausible brain activity patterns in primary and secondary motor cortices during exercise by taking advantage of the delayed nature of the BOLD signal, most of these studies describe changes in cortical activity by using electroencephalography (EEG) (Crabbe and Dishman, 2004; Thompson et al., 2008) and EEG integrating source localization algorithms (Schneider et al., 2010a) after but not during exercise. Changes in brain cortical activity after exercise, as well as the effects of exercise on neurocognition and mood, seem to be dependent upon three parameters: exercise intensity, duration and mode (Ekkekakis, 2009). However, recent studies have highlighted that these parameters have to be considered on a very individualized and personal basis (Schneider et al., 2009a; Brummer et al., 2011a).

Our group has recently shown that motor cortex (M1) activity increases with exercise intensity on a cycle ergometer (Brummer et al., 2011b). This is in good agreement with the fact that an increasing muscular activity during pedaling exercise requires additional motor units, which is reflected by an increase in M1 activity. In contrast, a small decrease of activity in the sensory cortex has been reported after exercise and no

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Abbreviations: BA4, Brodman area 4; EEG, electroencephalography; EMG, electromyography; fMRI, functional magnetic resonance imaging; M1, motor cortex; NIRS, near-infrared spectroscopy; PET, positron emission tomography; sLORETA, standardized low resolution brain electromagnetic tomography.

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changes in (pre-) frontal cortex activity with increasing exercise intensity could be noticed (Schneider et al., 2009b). Beside the expected increase in M1 activity with increasing exercise intensity, this study (Schneider et al., 2009b) particularly demonstrated that using newly developed active electrodes in conjunction with source localization algorithms (sLORETA) allows to record and localize brain cortical activity during whole-body maximal exercise. Moreover, this study presented robust evidence that relying on changes in electrical current density caused by neural activity is a new and promising way to analyze brain cortical activity far beyond common but incongruent frequency analysis (Schneider et al., 2009b).

The aim of the present study, therefore, was to identify the time course of M1 activation patterns and its correlation to muscle activation patterns during whole-body exercise. We hypothesized that (i) EEG could be powerful enough to detect local oscillations in cortical activity that are dependent upon muscle activity, and (ii) the M1 activity patterns would track the changes in muscular activity.

EXPERIMENTAL PROCEDURES

Subjects

Eight subjects (3 female aged 24 ± 2 and 5 male aged 27 ± 4) volunteered to participate in this experiment after reading and signing an informed consent form. They were informed of the possible risk and discomfort associated with the experimental procedures before they gave their written consent. The experimental design of the study was approved by the Research Ethics Committee of Victoria University and German Sport University, in accordance with the Declaration of Helsinki.

Methods

Subjects exercised on an electronically braked cycle ergometer (Excalibur Sport, Lode®, Groningen, the Netherlands) equipped with standard cranks (length = 165 mm). Before each session, vertical and horizontal positions of the saddle and handlebar were set so that the participants could pedal in a comfortable position. During the experimental session, subjects were asked, after a standardized warm-up (i.e. 5 min at 1 W/kg, 2 min at 3 W/kg, and 1 min at 5 W/kg) and a 5-min recovery period, to perform five pedaling exercises at constant pedaling cadence (90 rpm) and at different power outputs, which were related to the participants' individual body weight (1 W/kg, 2 W/kg, 3 W/kg, 4 W/kg and 5 W/kg). The pedaling exercises lasted ~2 min and were interspersed by at least 2 min of recovery to limit the occurrence of muscle fatigue. Surface electromyography (EMG) and EEG signals were recorded continuously for at least 100 consecutive pedaling cycles for each pedaling condition (see Supplementary Video 1). Two of the subjects were able to perform just up to an intensity of 4 W/kg, therefore we decided to perform further statistical analysis based on the data obtained during each individual's four last stages (Brummer et al., 2011b).

EEG data collection and analysis

A head-size adapted 32-channel electroencephalography (EEG) cap was mounted on the participants' head. Electrodes were organized in the international 10–20 system around the motor cortex on electrode positions F1, F2, FC3, Fz, F3, F4, FC4, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, C5, CP5, CP1, CP2, CP6, C1, P7, P3, Pz, P4, P8, C2, C6, CP3, CPz, CP4, Electrode FCz was used as reference, AFz as ground. The cap, fixed with a chin strip to prevent shifting during the exercise trials, was permeable to air in order to prevent an increase in heat during exercise. Distances between electrodes were approximately 5 cm to prevent possible cross talk between electrodes due to salt bridges caused by sweat. Each electrode was filled with SuperVisc electrode gel (EasyCap GmbH, Herrsching. D) for signal transduction. The use of active EEG electrodes developed by Brain Products (Gilching, Germany) allows recording electro-cortical activity even during high-intensity exercise free of movement artifacts (Brummer et al., 2011b).

EEG data were processed by Brain Vision Analyzer 2 (Brain Products, Gilching, Germany). A systematic protocol for excluding artifacts was performed that included careful visual inspection of all EEG data and automated exclusion procedures, which were set to gradient threshold > 60 μV. An individual component analysis (ICA) was run on the data to check for eye movement, jaw movement as well as facial and neck muscle artifacts. If applicable those were subtracted from the original data. If necessary individual channels were replaced by topographical interpolation (spline; Order: 4; Degree: 10; Lambda: 1E-05). High and low-pass filters were applied so that a frequency range from 0.5 to 60 Hz remained for analysis (time constant 0.0318 s; 48 dB/octave). Data were segmented using the top-dead-center (TDC) trigger signal. This resulted in approximately 100 segments of 660 ms duration (i.e. one pedaling cycle at 90RPM), which were averaged over all cycles and baseline corrected for source localization.

The motor cortex, also known as M1, is located in Brodman area 4 (BA4). As shown by Kiviniemi et al. (2009) it is subdivided into two areas representing the hand areas (located lateral) and the feet areas (located along the hemispherical

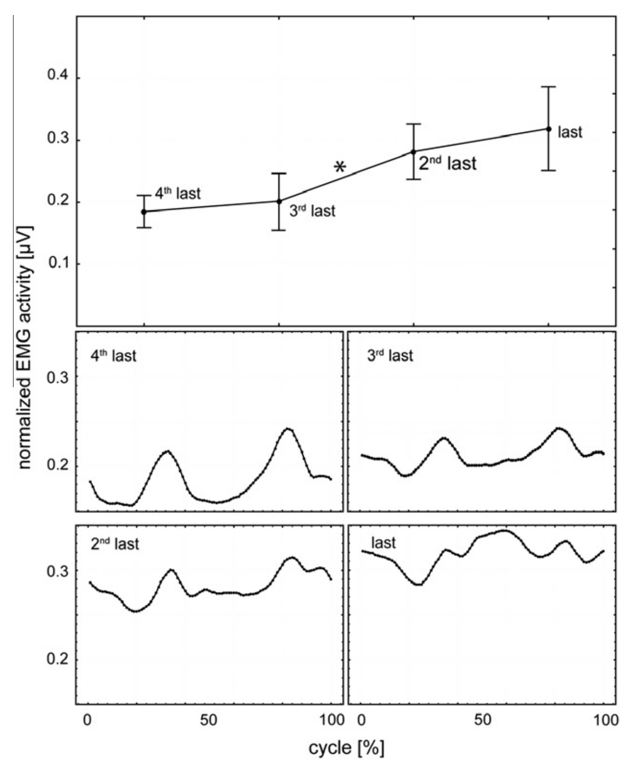

Fig. 1. *Top*: Changes in average EMG_{sum} values resulting from controlled manipulation of power output. *Bottom:* Changes in the EMG_{sum} activity during the pedaling cycle resulting from controlled manipulation of power output.