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DOES SENSORIMOTOR CORTEX ACTIVITY CHANGE WITH QUADRICEPS FEMORIS TORQUE OUTPUT? A HUMAN ELECTROENCEPHALOGRAPHY STUDY

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Abstract—Encoding muscular force output during voluntary contractions is widely perceived to result, at least in part, from modulations in neuronal activity within the sensorimotor cortex. However the underlying electrophysiological phenomena associated with increased force output remains unclear. This study directly assessed sensorimotor cortex activity using electroencephalography (EEG) in humans performing isometric knee-extensions at a range of discrete torque levels. Fifteen healthy males (age 24 ($s = 5$) years) completed one familiarization and one experimental trial. Participants performed a cyclic series of 60 isometric knee-extension contractions with the right leg, including 15 contractions of a 5-s duration at each of four discrete torque levels: 15%, 30%, 45% and 60% of maximal voluntary torque (MVT). Isometric knee-extension torque, quadriceps electromyography and EEG were recorded at rest and throughout all the contractions. EEG (0.5–50 Hz) was collected using a 32-channel active-electrode cap. A voxel-based low-resolution brain electromagnetic tomography (LORETA) analysis calculated cortical activation within the sensorimotor cortex (one of 27 MNI coordinates) for the entire 0.5–50-Hz range (cortical current density (CCD)), as well as for each constituent frequency band in this range (delta, theta, alpha, beta and gamma). Gamma band (30–50 Hz) cortical activity increased with contraction torque (analysis of variance [ANOVA], $P = 0.03$). Conversely, activity within the other frequency bands was not modulated by torque ($P \geqslant 0.09$), nor was overall CCD ($P = 0.11$). Peripheral neuromuscular activation (quadriceps electromyography (EMG) amplitude) demonstrated distinct increases between each torque level ($P < 0.01$). In conclusion, sensorimotor cortical activity within the gamma band demonstrated an overall increase with contraction torque, whereas both CCD and each of the other constituent frequency bands were not modulated by increments in torque magnitude during isometric knee-extension contractions up to 60%MVT.

Key words: motor control, force production, motor cortex, sensory cortex.

INTRODUCTION

Understanding the cortical encoding of skeletal muscle contractions, including the force of contractions, is of wide relevance to human function and health; including neurological disorders, brain computer interfacing, healthy aging and the responses to physical training/ rehabilitation. Several studies on non-human primates have suggested that a number of cells within the motor cortex modulate their activity in relation to the isometric contraction force of an active muscle (Evarts, 1968; Cheney and Fetz, 1980; Evarts et al., 1983; Hepp-Reymond et al., 1999). However, animal investigations have typically been limited to studying relatively low-force amplitudes, and it is difficult to detect changes in the number of participating cells or modifications in whole populations of cells.

In humans, studies utilizing positron emission tomography (PET; Dettmers et al., 1995) and functional magnetic resonance imaging (fMRI; Thickbroom et al., 1998; Dai et al., 2001; Cramer et al., 2002; Ward and Frackowiak, 2003; van Duinen et al., 2008; Keisker et al., 2009) have found cortical activation in sensorimotor regions of the brain to increase with increments in force during isometric or near-isometric contractions of the fingers/hand. However, findings are not unequivocal; Ludman et al. (1996) found no difference in fMRI BOLD signal during cyclic finger flexion of light and heavy loads, and Christensen et al. (2000) found no correlation between bipedal recumbent cycling load and cerebral blood flow-related activation within the motor cortex. Moreover, both PET and fMRI techniques measure hemodynamic responses within localized regions of the brain as an indirect surrogate of neuronal activity. In contrast, measuring cortical electrical activity provides a direct index of neuronal activation as this is the method of communication within the central nervous system.

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Abbreviations: ANOVA, analysis of variance; CCD, cortical current density; EEG, electroencephalography; EMG, electromyography; EMG_{RMS}, electromyography root mean square; fMRI, functional magnetic resonance imaging; LORETA, low-resolution brain electromagnetic tomography; MVCs, maximal voluntary contractions; MVT, maximal voluntary torque; PET, positron emission tomography.

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Decreases in surface electroencephalography (EEG) amplitude have been observed within the alpha frequency band with increments in force during isometric 'pinching' using the thumb and little finger (Mima et al., 1999). Similarly, Dal Maso et al. (2012) found beta band activity to decrease with increments in isometric knee flexion force in strength-trained individuals. However, findings to date have been inconsistent; both isometric elbow flexion force (Cremoux et al., 2013) and the magnitude of a resistive load applied against index finger extensions (Stančák et al., 1997) were found to have no effect on the amplitude of EEG recorded during contractions. All these studies have related contraction force to changes in EEG recordings as they appear at the scalp. In contrast, source localization of EEG signals represents an increasingly viable technique for the measurement of neuronal activity within sensorimotor cortex regions of interest during motor tasks.

Recent investigations (Brümmer et al., 2011; Schneider et al., 2013) have evaluated the source-localized EEG signal originating within the motor cortex during the performance of incremental ergometer cycling, and have reported an increased cortical activation to accompany greater cycling loads. However, cycling is a complex movement, with multiple joints involved and numerous muscles each producing a constantly changing amount of force at different times throughout the movement. Analysis of constant torque isometric contractions of a single large muscle (e.g. the quadriceps), over a range of discrete force levels may provide a more experimentally controlled situation in order to observe the cortical encoding of skeletal muscle force production. Moreover, these studies (Brümmer et al., 2011; Schneider et al., 2013) only reported the power of the EEG signal for the entire 0.5–50-Hz recording (known as cortical current density (CCD)), which does not enable examination of activity patterns in the narrower constituent frequency bands.

The aim of this study was to examine cortical activity within the sensorimotor cortex as determined by source-localized EEG measurements during constant torque isometric contractions of the quadriceps muscle group at a range of discrete torque levels. Sensorimotor activity within the delta, theta, alpha, beta and gamma bands was determined, in addition to overall CCD.

EXPERIMENTAL PROCEDURES

Participants

The data for one participant included a high-amplitude noise component in the recorded EEG signals during almost all of the submaximal contractions performed and was therefore excluded from further analysis. Subsequently, participants were fifteen healthy, injury-free, recreationally active males with no known history of neuromuscular or skeletal disorders (mean ± *s*: age 24 ± 5 years, stature 1.80 ± 0.06 m, body mass 76.7 ± 9.9 kg). The experimental procedures were approved by the Loughborough University Ethics Advisory Committee, and each participant provided written informed consent prior to their involvement.

Experimental protocol

A familiarization session was completed 5–14 days prior to the experimental trial, during which participants rehearsed performing maximal and submaximal isometric knee-extension contractions. The experimental trial involved the determination of maximal voluntary torque, and a cyclic series of 60 submaximal isometric knee extension contractions; 15 contractions at each of four distinct torque levels (15%, 30%, 45% and 60% of maximal torque) (Fig. 1). Electromyography (EMG), EEG and torque were measured simultaneously during submaximal contractions, and real-time graphical feedback of contraction torque was displayed on a computer monitor positioned in front of the participant. All contractions were performed with the right leg. Participants were advised to abstain from strenuous or atypical exercise for 36 h prior to the experimental trial, and to avoid the intake of nutritional stimulants (e.g. caffeine) on the day of the trial.

Maximal voluntary contractions (MVCs): Following a prescribed warm-up of submaximal isometric knee extensor contractions, participants performed four MVCs, with a 40-s rest between contractions. Participants were instructed to exert a maximum effort of knee-extension torque continuously for 3–5 s, with visual biofeedback and verbal encouragement provided. Maximal voluntary torque (MVT) was determined as the highest torque over a 500-ms epoch during the four repetitions, and amplitude of the quadriceps signal (EMG_{MVT}) was also calculated for this time window. Participants rested for 10-min following the MVCs, allowing for the EEG cap to be fitted and the EEG signals to be visually inspected.

Submaximal contractions: For each contraction, in response to a verbal cue, participants increased knee-extensor torque to the required level and maintained this torque until instructed to relax (after ~5 s). Horizontal lines representing 15%, 30%, 45% and 60%MVT were displayed on the monitor to facilitate accurate maintenance of these target torques. Each contraction torque was performed three times, before proceeding to the next torque level in ascending order, with this sequence of 12 contractions cycled through five times (Fig. 1A). The time interval between successive contractions increased with torque level to minimize fatigue (20, 30, 40 and 50 s, respectively; Fig. 1B). Two minutes after the completion of the submaximal contractions, two further MVCs were performed to assess whether any fatigue-related decrement in MVT had occurred.

Six 60-s segments of resting EEG data were also collected; one prior to the submaximal contractions, and after every set of 12 contractions. During resting collections, participants were instructed to keep their eyes closed, refrain from moving/talking and focus on themselves in order to minimize shifts in cognitive activity Brümmer et al. (2011).

Torque measurements

Isometric knee-extensor torque of the right leg was measured with participants seated in a dynamometer