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Preparatory band specific premotor cortical activity differentiates upper and lower extremity movement

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Abstract

Event related desynchronization (ERD) allows evaluation of brain signals in multiple frequency dimensions. The purpose of this study was to determine left hemispheric non-primary motor cortex differences at varying frequencies of premovement ERD for similar movements by end-effectors of the upper and lower extremities. We recorded 32-channel electroencephalography (EEG) while subjects performed self-paced right ankle dorsiflexion and wrist extension. Electromyography (EMG) was recorded over the tibialis anterior and extensor carpi ulnaris. EEG was analyzed for premovement ERD within the alpha (8–12 Hz), low beta (13–18 Hz) and high beta (18–22 Hz) frequencies over the premotor, motor, and sensory areas of the left and mesial cortex from –1.5 to 0 s before movement. Within the alpha and high beta bands, wrist movements showed limited topography, but greater ERD over posterior premotor cortex areas. Alpha ERD was also significantly greater over the lateral motor cortex for wrist movements. In the low beta band, wrist movements provided extensive ERD differences to include the left motor and mesial/lateral premotor areas, whereas ankle movements showed only limited ERD activity. Overall, alpha and high beta activity demonstrated distinctions that are consistent with mapping of wrist

and ankle representations over the sensorimotor strip, whereas the low beta representation demonstrated the clearest distinctions between the limbs over widespread brain areas, particularly the lateral premotor cortex. This suggests limited leg premovement activity at the dorsolateral premotor cortex. Low beta ERD may be reflect joint or limb specific preparatory activity in the premotor area. Further work is required to better evaluate the extent of this low beta activity for multiple comparative joints.

Keywords

EEG; Event related desynchronization; Premotor cortex; Upper extremity; Lower extremity

Introduction

Synchronized oscillations, which can be measured by electroencephalography (EEG), are a form of communication within local and between widespread neuronal assemblies (Bressler 1995; Pfurtscheller et al. 2000; Momjian et al. 2003). Analytical techniques which evaluate EEG signals in the frequency domain are able to capture this aspect of brain function, allowing the sensorimotor areas to be viewed as a dynamic network (Serrien et al. 2004; Wheaton et al. 2005a, b). As well, EEG provides high temporal resolution, which increases confidence in relating scalp-recorded brain activity with resultant behavior or movement (Pfurtscheller and Andrew 1999).

Event related desynchronization (ERD), reduced power at local cortical areas at particular frequencies of the EEG signal, is thought to reflect electrophysiological change in cortical areas actively involved in movement-related sensory and motor information processing (Pfurtscheller and Aranibar 1979; Steriade and Llinas 1988). Most commonly, premovement ERD within the alpha (8–12 Hz) and beta (13–22 Hz) frequency bands is seen at electrodes over primary sensorimotor areas, and generally differs in spatial focus and timing based on the motor task. Alpha band ERD is traditionally seen over extensive cortical areas, and may relate to presetting of sensorimotor regions involved with a subsequent motor task (Crone et al. 1998; Pfurtscheller and Lopes da Silva 1999). Beta ERD is often more restricted to the corresponding motor somatotopy, and is thought to reflect information processing within localized neuronal assemblies related to specific aspects of motor processing (Neuper and Pfurtscheller 2001). Beta band activity seems to be a composition of multiple narrow frequency components, which may differ in movement-related temporal and spatial properties (Pfurtscheller et al. 1997, 1998). As well, changes in beta oscillations are capable of discriminating movement execution between upper and lower extremities (Neuper and Pfurtscheller 2001) and of proximal and distal movements within the upper extremity (Stancak Jr et al. 2000b).

Outside of the primary motor regions, power decreases in the alpha and beta frequency spectra have been reported for lateral premotor and supplemental motor areas in simple movements of the upper extremity (Ohara et al. 2001; Sochurkova et al. 2006), as well as mesial and lateral premotor areas in complex upper extremity movements (Wheaton et al. 2005b). Premovement ERD at non-primary motor regions highlights the importance of these structures in motor planning and execution (Kurata and Wise 1988; Rizzolatti et al. 1998; Tanji 2001).

Similar mechanisms may generate ERD at primary as well as non-primary motor structures in both upper and lower extremity movement. However, differences in ERD at motor and non-primary motor areas for upper and lower extremity movements can suggest cortical regional specificity for similar motor commands. As well, further spatial descriptions of

premovement ERD bandwidths can suggest frequency specificity and relevance on cortical planning activity differences in upper and lower extremity movements. This in turn may have an impact on hypotheses related to cortical planning activity outcomes in motor learning studies in patients with brain pathologies, such as stroke. While post-movement onset ERD has been evaluated between foot and finger movements (Neuper and Pfurtscheller 2001), ERD related to premovement planning has not been investigated in non-primary motor structures for similar movements of distal joint end-effectors between the lower versus upper extremities. As well, the premovement discriminative capacity of discrete frequency bands within the composite beta band has not been evaluated in non-primary motor structures for similar upper and lower extremity movements. This may be useful in better elaborating on motor planning, as non-primary motor cortical areas that have long been thought to have a role in the organization of movement and may form part of a larger network for motor planning and execution differently for different types of movement (Wise et al. 1997).

This study aims to determine differences in left hemispheric activity at non-primary motor areas in the production of similar movements by homologous end effectors of the arm and leg. The focus of this work is premovement ERD of left hemisphere and mesial premotor and sensory cortices within alpha (8–12 Hz), low beta (13–18 Hz), and high beta (18–22 Hz) frequency bands for right ankle and wrist movements. We hypothesized that the low and high beta bands would provide the most distinguishing characteristics, with greater ERD for wrist than ankle movements over left hemisphere premotor and sensory areas.

Methods

Subjects

Eight right-handed healthy volunteers (five males, three females, mean = 32.5 ± 7.8) with no history of neurological disorders or musculoskeletal problems limiting repeated joint movement participated in the studies. The University of Maryland School of Medicine Institutional Review Board and Baltimore VAMC Research and Development Committee approved these experimental procedures. Subjects were notified of the testing protocols before the study, and informed consent was obtained.

Procedure

A brief training session was performed to ensure familiarity with the experimental design. The movement tasks took place in six 5-min blocks. Subjects sat comfortably in a reclining chair and were asked to perform motor tasks with the right hand and right foot only, in a self-paced manner.

Experimental sessions consisted of three blocks of wrist extension, and three blocks of ankle dorsiflexion. The wrist movement was initiated with the palm facing downwards on the armrest at a neutral joint angle, then extending the wrist against gravity. The foot movement was performed by placing the foot on the floor (with shoe removed), then dorsiflexing the ankle while maintaining heel contact with the ground. Subjects were instructed to make a series of single, brisk movements followed by a 10–15-s interval between each movement. As well, the subjects were instructed to reach their comfortable maximal joint movement extent for each repetition. Blocks of wrist extension and ankle dorsiflexion were alternated during the session. Analysis was made on the differences in preparatory activity of each of the movement types across alpha (8–12 Hz) and low (13–18 Hz) and high (18–22 Hz) beta bands. Thirty-two channel EEG was recorded (1 kHz sampling rate, DC–500 Hz) with a Synamps2 amplifier using a linked ear reference recorded in the Acquire module of Scan 4.2 (Neuro Scan Labs, El Paso, TX). Surface electromyography (EMG) was recorded from the

right flexor carpi ulnaris and tibialis anterior muscles (1 kHz sampling rate, 1–200 Hz). EMG onset was identified in each trial, and epochs were made from 4.0 s before to 2.0 s after EMG onset. Approximately 600 artifact free trials per condition were collected. Based on our hypothesis, the signal from electrodes over the left and mesial premotor (F3, FC3, FZ, and FCZ), motor (C3, CZ), and sensory (CP3, CPZ) areas were individually evaluated as electrodes of interest.

Data analysis

Analysis was performed using Neuroscan (Compumedics, El Paso, TX) and MATLAB (Mathworks Inc., Natick, MA). All trials containing large drifts, ocular activity, muscle artifact, swallowing, or other artifacts were manually excluded.

Band specific power analysis

Movement related activity was calculated in the alpha (8–12 Hz), low (13–18 Hz), and high (18–22 Hz) beta bands. The continuous EEG signal was bandpass filtered (–48 dB/octave) within each frequency range and rectified, then epoched and averaged across trials. The magnitude of power was normalized by expressing the change as a ratio of the absolute power at baseline period from –4.0 to –3.5 s before EMG. The magnitude was expressed as the percentage of increase (positive percentage) or decrease (negative percentage) from a baseline period, as previously described (Pfurtscheller and Aranibar 1977). As the present work evaluated ERD, we expected that we would only be limited to negative percentage changes. Epochs were divided up into three non-overlapping 500 ms segments and analyzed for statistically significant differences within an electrode of interest. Specifically, all analysis procedures were conducted between the two movement types during the pre-movement phase from –1.5 to –1 s, –1 to –0.5 s and –0.5 to 0 s. Repeated measures ANOVAs were performed for each electrode and frequency individually, with time (3) $\times$ movement type (2) as factors. Specific to the a priori hypothesis, we assessed significant differences between the movement conditions within the same time bin and electrode using a paired *t*-test (e.g., C3, time 1, wrist versus C3, time 1 ankle). Bonferroni corrected *P*-values for three comparisons (corrected $\alpha = 0.0167$) were used as a threshold for significance.

Results

Movement duration

On average, the wrist extension and ankle dorsiflexion movements were performed for similar durations, as specified in the experimental protocol. Consistency of movement between the wrist and ankle was verified by similar mean durations of rectified EMG traces for the flexor carpi ulnaris (421 ms) and the tibialis anterior (413 ms).

Wrist versus ankle ERD

For each frequency and time bin, any significant differences in ERD were always greater for wrist than ankle movements. Further description of the ERD differences within each frequency is described below.

Alpha frequency band

Within the alpha band, ANOVAs revealed a significant difference ($F = 6.45$ and $P = 0.015$) in ERD activity between wrist and ankle movement in the left lateral motor area (C3), and *t*-test showed a difference at –1.5 to –1 s with a significant trend ($P = 0.026$) after the Bonferroni correction (Fig. 1). There was a significant difference in ERD over the left posterior premotor area (FC3, $F = 6.09$, and $P = 0.0185$) at –1.5 to –1 s prior to movement

onset ($P < 0.0167$). No significant differences were found over other cortical areas in the alpha band.

Low beta frequency band

The low beta frequency band demonstrated widespread distinctions in ERD prior to wrist and ankle movement. ANOVAs revealed significant differences over the left premotor area (F3, $F = 10.62$, and $P = 0.0024$), left posterior premotor area (FC3, $F = 15.54$, and $P = 0.0004$), mesial premotor (FZ, $F = 4.86$, and $P = 0.034$), posterior mesial premotor (FCZ, $F = 4.78$, and $P = 0.036$), and left motor area (C3, $F = 7.69$, and $P = 0.0087$) (Fig. 1). At each time bin within an electrode, paired t -tests revealed significantly greater ERD for wrist movements at the mesial and left premotor and left posterior premotor areas ($P < 0.0167$, all comparisons). Significant trends showed greater ERD at the left motor area at all time intervals prior to wrist movements (time 1, $P = 0.024$; time 2, $P = 0.018$; time 3, $P = 0.019$). There were no significant differences between ERD activity prior to wrist and ankle movement onset in the mesial motor (CZ, $F = 0.68$, and $P = 0.4123$) or mesial sensory (CPZ, $F = 0.48$, and $P = 0.4922$) areas.

High beta frequency band

Wrist movement ERD activity was significantly different from ankle only in the left posterior premotor area (FC3, $F = 7.12$, and $P = 0.0114$) in the high beta frequency band, which was significantly different at each point in the analysis (Fig. 1). No significant between-limb differences in ERD activity were found at any other cortical areas sampled at this frequency band.

Discussion

We aimed to assess differences in premovement ERD for simple end-effector movements at the upper (wrist) and lower (ankle) extremities. Overall, wrist ERD was always greater than ankle ERD for each time bin, frequency and electrode analyzed. Alpha and high beta showed limited activity and differential ERD, confined to the left motor and posterior premotor areas. Low beta ERD was seen across more widespread areas, including mesial and lateral anterior/posterior premotor areas and the left motor cortex. A summary of the results is illustrated in Fig. 2.

While our aim was to address premovement ERD in homologous joints across the upper and lower extremity, we could not certify that the movements were performed the same kinematically. However, our EMG data verify that the durations of muscle activation to each limb were quite similar. One potential confound of prescribing the same angular displacements or velocities between limbs is that inherent differences in the inertial loads of the moving segments, and the sizes and numbers of motor units in agonist muscles for each, may elicit different cortical demands to achieve the same kinematic outcome. Hence, there may be no perfect way to generate such comparisons other than seeking a task-based approach as we have chosen here. Given these methodological constraints, this work does provide insights on neural planning differences between these two joints.

Beta ERD has been shown in previous studies to reflect motor planning. Different patterns of post-movement/stimulation onset ERD showed lower peak beta activity over the hand area for finger movements (<20 Hz) and higher peak beta activity at the foot area for ankle movements (>20 Hz) (Neuper and Pfurtscheller 2001). In the present work, greater ERD was seen at each frequency band but optimally at 13–18 Hz, and overall with more lateralization for wrist movements than ankle movements for each task, similar to previous findings (Pfurtscheller et al. 1997). This difference was particularly evident over the lateral

premotor cortex. We were unable to statistically distinguish between wrist and ankle movements from sensory and mesial motor areas (Fig. 2). This may be due to the extensive ERD patterns seen, likely a result of volume conduction from the cortical source for either movement. This is evident in the spatial maps of both beta bands (Fig. 1).

While effector-specific mapping of sensory and motor cortex is well established (Penfield and Boldrey 1949), similar mapping must be evaluated at the premotor cortex, which demonstrated the clearest activation differences in this study. The rostral ventral premotor cortex is an area that has demonstrated involvement in hand actions (Rizzolatti et al. 2002). Using functional magnetic resonance imaging (fMRI), effector-specific movement observation has demonstrated premotor activation in a topographical map (Buccino et al. 2001). Here, the authors demonstrate hand movement observation evoked activity of the rostral ventral premotor cortex, while foot movement observation evoked activity of dorsal area 6, which is in closer proximity to mesial areas. fMRI studies have shown similar patterns of distinction between knee and elbow movements (Luft et al. 2002). Detailed analysis has also revealed similar premotor mapping in primates (Rizzolatti et al. 1998). This may explain the volume of ERD seen for wrist as opposed to ankle movements over lateral areas, particularly for the low beta band. As well, ERD for foot movements was confined to mesial regions for each frequency studied (Fig. 1). The correlation of the low beta band to this activity is unclear. However, this has also been shown in a similar positron emission tomography (PET) study with higher activity in the dorsal premotor areas in the execution phase of cyclic wrist compared to cyclic ankle movements (Ehrsson et al. 2000). We suspect that early premovement differences in the low beta band are reflective of precise effector-specific mapping of lateral premotor areas relevant to planning.

High beta, overall, was more confined to the motor cortex than the extensive low beta mapping. Generally, beta ERD may reflect confined mapping based on somatotopy (Crone et al. 1998). Based on the spatial maps it seems likely that high beta demonstrates effector-specific mapping along the relevant motor cortex. Yet, this frequency was only discernable between the two movements over the lateral posterior premotor area, likely because of the shared ERD over cortical regions seen for both effectors. Two explanations may clarify this. One, volume conduction between mesial and lateral motor areas may cause indiscernible statistical difference. Second, it has been suggested that the ventral premotor and supplementary motor areas may have activity that is similar for different limb segments and effectors (Matelli et al. 1993; Ehrsson et al. 2000). Unfortunately, because of volume conduction, we cannot be sure that such an effect is real and would have to be evaluated in future work.

There was also limited spatial mapping of the premovement alpha ERD. Previous reports have indicated more widespread distribution of the alpha ERD relative to beta ERD (Crone et al. 1998). However, studies have also demonstrated premovement alpha ERD based on somatotopy (Stancak Jr et al. 2000a), which could have resulted from comparing proximal and distal upper extremity movements with differing alpha band resonance. As both of the movements in this study were distal and involved similar kinematic joints, we suggest that this allows for a consistent mapping based on somatotopy. This has been substantiated by demonstrating somatotopic mapping of ERD activity within the alpha band for finger and toe movements (Pfurtscheller et al. 1997).

In conclusion, this work demonstrates distinctions between upper and lower extremity ERD planning activity of similar movements, chiefly at low beta frequencies over the left and mesial premotor cortex. This specific activity may be optimal for targeting effector-specific planning activity in future studies addressing planning phase of movements in neuropathology and aging. As well, evaluation of frequency specificity across multiple

effectors with similar task demands will help to further illustrate mapping of premotor cortex preparation activity.

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Fig. 1. Head maps of premovement ERD seen for each movement across alpha, low beta, and high beta. Increasing ERD is seen in *blue*. The *red rectangle* identifies areas of analysis

Fig. 2. Overall mapping of electrodes that showed distinctions (significance or trends toward significance) in premovement ERD. Note, for all electrodes, wrist ERD was greater than leg ERD