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Using electroencephalography to study functional coupling between cortical activity and electromyograms during voluntary contractions in humans

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Abstract

Previous studies of neuronal oscillations in sensorimotor cortex in humans and primates have observed rhythmic 15–30 Hz activity, which is correlated with motor output. In humans, this work has been limited to magnetic recordings. In the present study we investigate if similar results can be obtained using electroencephalography (EEG). EEG recordings were made from over the sensorimotor cortex of five adult subjects who performed repeated periods of maintained wrist extension and flexion. Coherence analysis between EEG and electromyogram (EMG) recordings from these muscles revealed correlation in the 15–30 Hz range, with a synchronous correlation structure which matches that previously observed in humans and in paired cortical recordings from primates. We conclude that EEG is equally efficient at investigating functional aspects of these cortical rhythms during voluntary movement in humans. © 1998 Elsevier Science Ireland Ltd.

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The presence of rhythmic neuronal activity in human motor cortex associated with voluntary movements has been well documented, e.g. [8]. One component of these cortical rhythms, often referred to as the β rhythm and observed in the frequency range 15–30 Hz, has been found to undergo systematic changes in its magnitude prior to and during voluntary movements in humans [9]. In addition, studies in primates have revealed the presence of similar oscillations in local field potentials (LFP) recorded from the sensorimotor cortex during motor activity [6,11]. These studies suggested that 15–30 Hz rhythms are associated with attentive mechanisms or preparation for movement. However, it was recently established through simultaneous magnetic recordings from sensorimotor cortex and electromyograms (EMG) in humans that localised cortical activity and motor unit firing are correlated in this frequency range during maintained voluntary contractions [3]. This demonstration provides a link between the generation of these cortical oscillations and maintained voluntary motor output in man, with functional consequences affecting features of motor unit firing and physiological tremor [3]. Similar results have been reported using LFP recordings in primates [1,7]. To date, studies reporting a correlation between cortical activity and EMG in humans have been restricted to magnetic recordings obtained from single [3] or multiple channel [10] magnetoencephalogram (MEG) systems. MEG facilities are expensive to install and maintain. However electroencephalography (EEG) facilities are widely available. In this study we investigate if similar results to those obtained with MEG can be observed using EEG.

Five normal subjects participated. Surface EMGs were recorded from the Extensor digitorum and Flexor carpi radialis muscles of the dominant forearm which was supported in a rigid cast with the fingers extended and taped.

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Two bipolar EEGs were recorded from the contralateral hemisphere, with an electrode spacing of 2.5 cm (first pair: 1.75 cm lateral to the vertex, 0.25 cm posterior and 2.25 cm anterior to interauricular line; Second pair: 2.5 cm lateral to first). Subjects performed repeated periods of maintained wrist extension/flexion, in response to auditory cues presented at random intervals of 2–3 seconds, with a constant 1.5 seconds allowed to move between positions, which were fixed at 75% of maximal wrist angle. Six minutes of data was collected in three sessions from each subject. Fig. 1 illustrates a 10 s segment from one session.

Surface EMG records were full wave rectified, and estimates of the auto spectra and coherence spectra between each EEG and EMG signal were formed for the periods of maintained contraction. The first 200 ms after each auditory cue was omitted to ensure analysis of postural data only. Data relating to the movement phases are not dealt with in the present report. Spectra were estimated according to the method in [4], with the addition of zero padding and a weighting scheme, e.g. see [2], to include data from incomplete segments at the end of each maintained contraction. In the time domain the cumulant density between EEG and EMG was estimated from the inverse Fourier transform of the cross spectrum [4]. Fig. 2 illustrates results from one subject during wrist extension. The EMG spectral estimate (Fig. 2b) has distinct peaks around 10 and 22 Hz, the EEG spectral estimate (Fig. 2a) has most power concentrated below 10 Hz, but also has a distinct component around 22 Hz. The coherence estimate, Fig. 2c, shows a significant correlation between the signals from 16 to 36 Hz, with a peak at 22 Hz. The phase estimate (Fig. 2d) indicates a constant phase difference of approximately π radians over the range of frequencies at which the signals are correlated. Consequently the two signals are phase locked, and approximately out of phase. The cumulant density estimate (Fig. 2e) has a prominent dip around time zero, also indicating that the two signals are synchronized and are out of phase.

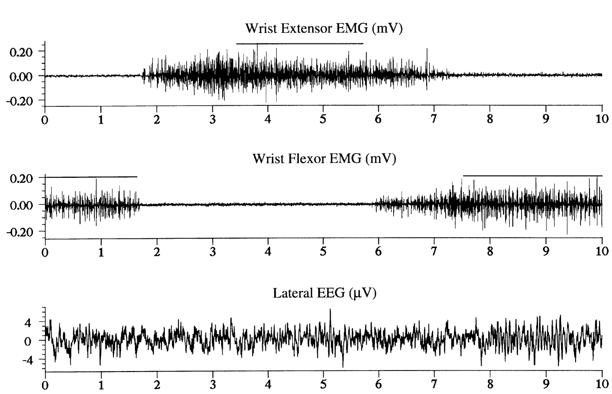

Fig. 1. A 10 s segment of experimental data showing, from top to bottom, wrist flexor EMG, wrist extensor EMG, and the lateral EEG channel. Sections included for analysis are indicated by the solid lines above each EMG trace. This segment illustrates two periods of maintained flexion: 0–1.6 and 7.5–10 s, and one period of maintained extension: 3.4–5.7 s.

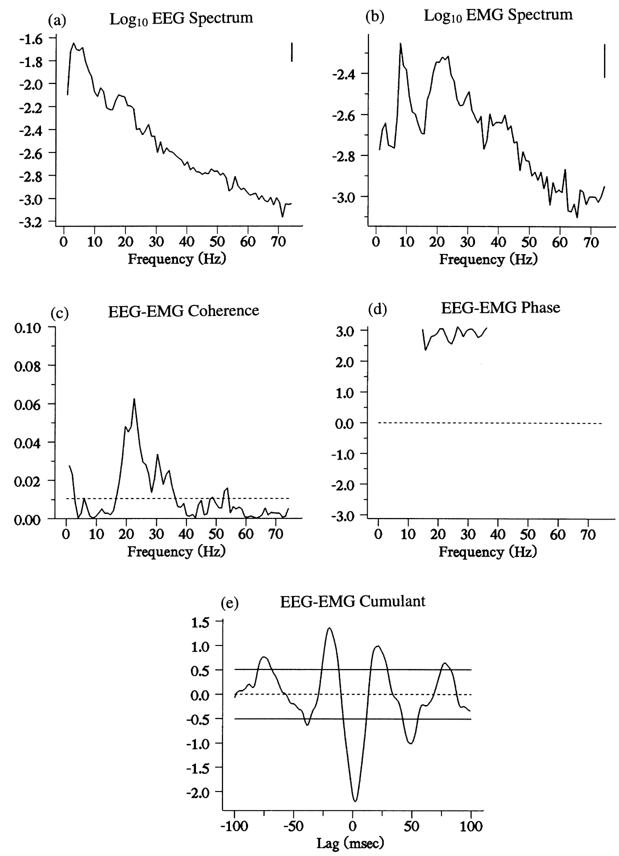

Fig. 2. (a) Log plot of estimated EEG spectrum, (b) log plot of estimated rectified EMG spectrum. Estimated (c) coherence, (d) phase, and (e) cumulant density, between the EEG and EMG signals. The solid vertical lines in (a,b) indicate the magnitude of a 95% confidence interval for the spectral estimates, the horizontal dashed line in (c) indicates the upper 95% significance level based on the assumption of independence, and the horizontal lines in (e) indicate the expected value (dashed line) and upper and lower 95% confidence limits based on the assumption of independence. Analysis of 118 segments, containing 103 000 data samples.

The coherence estimate between this lateral EEG signal and the flexor EMG during periods of maintained flexion is similar, with a maximum of 0.05 at 20 Hz (not shown). Fig. 3 shows the coherence estimates for the four other subjects. These coherence estimates show a similar pattern of correlation, with peak values in the range 11–26 Hz. The estimates for one subject (Fig. 3g,h) have additional peaks at 33 and 42 Hz during extension, and at 27 and 48 Hz during flexion.

These results are similar to those previously observed using non-invasive single [3] and multiple [10] channel magnetic recordings in humans, and invasive microelectrode recordings in primates [1,7]. All three measures of cortical activity exhibit a correlation with motoneurone firing during maintained contractions. Therefore, over this frequency range (centred around 20–25 Hz), these different signals appear to be detecting features of the same rhythmic processes present in cortical activity during maintained contractions. The signals generated using MEG and EEG recording systems reflect current flow in different orientations. MEG systems measure tangential current dipoles, and are therefore more sensitive to activity in cortical neurones which are located in cortical fissures [12]. EEG signals represent a superposition from different current sources which propagate to the surface and disperse radially over the scalp, and are therefore more sensitive to current flow perpendicular to the scalp. In the present study, coherence estimates were consistently stronger from the bipolar electrode pair located 4.25 cm lateral to C_Z, which is consistent with sites overlying the sensorimotor cortex, and corresponds with recording sites used in MEG studies [3,10]. EEG recordings suffer from the drawbacks of current dispersion due to volume conduction and the filtering effects of the skull. However, neither of these factors appear to reduce the efficacy with which EEG can detect these cortical rhythms compared with MEG [3].

Spectral analysis techniques also allow the timing relationship between EEG and EMG to be explored through estimates of the phase (Fig. 2d) and cumulant density function (Fig. 2e). For the example in Fig. 2, the constant phase indicates phase locked signals. The cumulant density estimate has a minimum at +2 ms, and maxima at –20 and +21 ms. These maxima correspond to a period of oscillation of 41 ms or 24 Hz, in agreement with the coherence. The peak at +21 ms matches experimentally measured central latencies from cortex to muscle, via corticospinal pathways, however, this interpretation does not match the phase estimate, and may therefore not accurately describe this data. The phase curve for a pure delay is a straight line, starting from zero radians at zero frequency, with slope equal to the delay. The constant phase curve in Fig. 2d implies a delay which changes with frequency, for example if a delay is fitted to individual points of this phase estimate it gives latencies of EMG leading EEG by 33 ms at 15 Hz and by 14 ms at 36 Hz. If we assume a causal relationship and use an unrestrained version of the phase estimate, this procedure results in latencies of EMG lagging EEG by 35 ms at 15 Hz and by 14 ms at 36 Hz. It is not clear that these figures can be reconciled into a single meaningful latency. The assertion in [10], based on spike triggered averaging, that the timing relationship between MEG and EMG signals can be represented by EMG lagging MEG may over simplify the complex timing relationship between these two signals during periods of maintained voluntary contraction. The phase estimates for the other four subjects also show constant phase over the range of significant coherence. Three subjects produced phase estimates which were out of phase, one gave phase estimates which were in phase (i.e. around zero radians), the corresponding cumulant density estimates for this subject had a positive peak around time zero. Pairs of LPFs recorded in primates, with one reference electrode fixed at a depth of 2 mm, are consistently in phase when the second electrode depth is less than 1 mm, and consistently out of phase when the second electrode depth is below 1 mm [7]. The synchronous EEG-EMG correlation structure which we observe is thus similar to that observed in cortical-cortical correlations in primates, but represents synchronization over a far greater distance (i.e. cortex and spinal cord). In sensory systems synchronization between spatially disparate populations of cortical neurones with zero phase lag is well documented, e.g. [5], these authors further argue that oscillatory activity contributes to synchronization between disparate sites.

Our results indicate that the oscillations are present in EMG records for both wrist extension and flexion, and are correlated with the same gross EEG channel. The strength of correlation appears greater during maintained flexion (Fig. 3, right column compared with left column), however other factors such as EEG electrode position may contribute to this difference. LFP oscillation in primates are observed with equal likelihood during extension and flexion [7].

LFP oscillations in primates are characterized as episodes of variable duration containing clear oscillations in the observed signal [6,7,11]. These periods are quantified by their duration and number of oscillations. In the present EEG recordings, clear oscillatory patterns are not readily

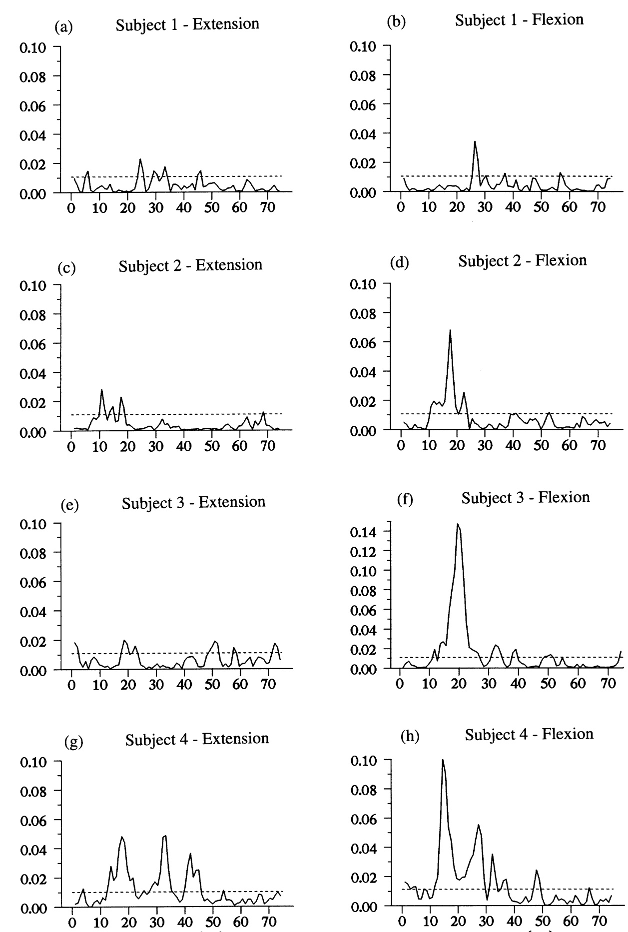

Fig. 3. Estimated coherence functions between the lateral bipolar EEG and wrist extensor EMG (a,c,e,g), and wrist flexor EMG (b,d,f,h) during periods of maintained wrist extension and flexion, respectively, for four different subjects. Horizontal dashed lines represent upper 95% confidence limits as for (c).

identifiable, see Fig. 1. However, a frequency domain approach to analysing stochastic time series [4] will detect the presence of correlated rhythmic components. The spectral estimates show that rhythmic activity is present in EMG signals in the 15–30 Hz band (Fig. 2b) and that it is also present in EEG signals (Fig. 2a), although at a reduced level compared with nearby frequency components.

The functional significance of these rhythmic correlations is unclear. Murthy and Fetz [6,7] concluded that the correlations represent a neural correlate of attention, finding that oscillations were more prevalent during tasks requiring demanding sensorimotor behaviour. Sanes and Donoghue [11] found that the cessation of LFP oscillations was correlated over wide areas with movement onset, and that oscillations were most pronounced during hold and pre-cue periods. Magnetic recordings in humans have revealed a correlation with EMG during periods of maintained contractions [3,10]. In primates, rhythmic correlations between cortical LFPs and EMG have been observed [1,7], which are restricted to periods of maintained contraction [1]. The present results demonstrate similar findings can be observed in humans with EEG recordings, and that rhythmic correlations between cortical activity and different muscle groups can be observed during periods of maintained contraction in a position holding task. A consensus view of these results is that these rhythmic oscillations in the sensorimotor cortex are associated with voluntary motor tasks involving maintained muscle activation, such as position holding.

The present results provide a clear demonstration of the utility of EEG in exploring functional aspects of cortical rhythms during voluntary movement. Along with results from magnetic recordings [3,10] they establish the widespread presence of rhythmic cortical activity which is correlated with motor unit firing during maintained voluntary contractions. The correlation structure, in particular the phase relationship, matches that observed between paired cortical LFP records in primates [7]. It seems reasonable to propose that further studies using EEG in humans will provide a means of exploring task dependent aspects of these cortical rhythms, since, based on the present findings, any changes in the EEG-EMG correlation structure would reflect changes in corresponding patterns of cortical-cortical oscillations.

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