Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man

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1. Simultaneous recordings of cortical activity, recorded as the magnetoencephalogram (MEG), and the electromyogram (EMG) of the ipsilateral and contralateral first dorsal interosseous muscles (1DI) were made during maintained voluntary contractions.

2. The MEG recorded from a localized region of the sensorimotor cortex of the dominant hemisphere was coherent with the EMG from the contralateral 1DI muscle over a limited band of frequencies. The peak coherence was confined largely within the beta range of cortical activity (13–35 Hz). Significant cortical activity at 10 Hz and 40–50 Hz was not correlated with motor output. The MEG and EMG from the ipsilateral 1DI muscle were uncorrelated at all frequencies.

3. Significant coherence between the MEG and the EMG was associated with synchronous behaviour between the MEG and EMG in the time domain.

4. The results demonstrate that synchronized cortical activity contributing to MEG activity within the beta range of frequencies during maintained voluntary contractions is coupled to motor output at frequencies of motor-unit activity associated with motor-unit synchronization. This observation provides further evidence for the involvement of cortical neurones in the generation of motor-unit synchronization.

5. We suggest that the coherence between MEG and contralateral EMG observed during maintained isometric contractions may provide an example of binding within the motor system.

There is currently considerable interest in the functional role of rhythmicity and synchronization within the mammalian central nervous system. In sensory systems it has been proposed that rhythmic activity in spatially separated populations of neurones is related to perceptual binding (Singer, 1993). Although such behaviour, characterized by oscillations in the 40–50 Hz range, has been studied mainly in visual and olfactory systems it also occurs in hippocampus and somatosensory systems (see Gray, 1994). In the motor system, experiments on monkeys have related the occurrence of synchronous high frequency (25–35 Hz) oscillatory activity between separate areas of the sensorimotor cortex with the performance of exploratory movements (Murthy & Fetz, 1992). The widespread presence of rhythmic and synchronous activity has lead some authors to suggest that it represents a fundamental mechanism associated with integration between distant and discrete neural networks (see Gray, 1994).

Rhythmic activity is not only a feature of cortical activity, but is also apparent at other levels within the central nervous system. Short term synchronization, characterized

by a central peak in the cross-correlation histogram, has been observed between pairs of motor-unit spike trains recorded from intrinsic hand muscles in man (e.g. Datta & Stephens, 1990; Farmer, Bremner, Halliday, Rosenberg & Stephens, 1993*a*; Farmer, Swash, Ingrams & Stephens, 1993*b*). A frequency domain analysis of motor-unit synchronization in human hand muscles revealed the presence of a rhythmic 16–32 Hz component (Farmer *et al.* 1993*a*). On the basis of indirect measures Farmer *et al.* (1993*a*,*b*) suggested that this component of motor-unit synchronization arises in part from rhythmic activity in central motor pathways which provide common presynaptic inputs to motoneurone pairs. In the current study, through the use of the magnetoencephalogram (MEG), we provide direct evidence of a relation between localized rhythmic cortical activity and correlated motor-unit activity. A preliminary account of this work has appeared in abstract form (Conway *et al.* 1995*b*).

METHODS

The MEG from the dominant hemisphere was recorded simultaneously with the EMG from the ipsilateral and contralateral first dorsal interosseous muscle (1DI) in six healthy adult subjects (4 male, 2 female) after obtaining written informed consent in accordance with the approval of local ethical committees (Southern General Hospital Trust and West Ethics Committee, Greater Glasgow Health Board, Glasgow).

Recording procedures

The MEG was recorded in a shielded room (environmental field attenuated above 1 Hz) using a single channel (model 601; BTi, San Diego, USA) superconducting quantum interference device (SQUID) fitted with a second-order gradiometer which rejects uniform and first-order ambient fields. The position of the recording probe was aligned with points forming a centimetre grid based on the 10–20 International System of Electrode Placement (Jasper, 1958) marked on a skull cap. Recordings were made from up to twelve grid sites overlying the hand area of the sensorimotor cortex on the lateral surface of the dominant hemisphere. To aid localization of the hand area of the motor cortex, systematic mapping using focal magnetic stimulation (Magstim 200, double 70 mm stimulating coil 9700-00; The Magstim Company, UK) was performed on the first two subjects studied.

The surface EMG was recorded from the right and left 1DI muscles using bipolar Ag–AgCl electrodes placed over the muscle. The MEG and EMG signals were amplified and filtered at 1–100 Hz and 3–500 Hz, respectively. These signals were recorded on magnetic tape for subsequent off-line analysis, at which time they were digitized (1000 Hz per channel).

Experimental protocol

The subjects were instructed to relax or to maintain a constant low-level isometric contraction (< 10% maximal voluntary contraction) of the ipsilateral or contralateral 1DI muscles either separately or together. For each MEG recording site 1–2 min of MEG activity was recorded while relaxed, and with EMG during active contractions of the 1DI muscles.

Statistical methods

The MEG, denoted x, and the rectified EMG, denoted y, were assumed to be realizations of stationary zero mean time series. The principal statistical tool used for data analysis in this study was the discrete Fourier transform and parameters derived from it, all of which were estimated by dividing the records into a number of disjoint sections of equal duration, and estimating spectra by averaging across these discrete sections (Conway, Halliday & Rosenberg, 1993). In the frequency domain estimates of the autospectrum of the MEG, $f_{xx}(\lambda)$ and rectified EMG, $f_{yy}(\lambda)$, were constructed, along with estimates of coherence, $|R_{yx}(\lambda)|^2$, between the MEG and rectified EMG. In the time domain, the cumulant density or covariance function at lag u, $q_{yx}(u)$, with MEG as reference, was estimated from the cross-spectrum via an inverse Fourier transform. The coherence gives an estimate of the magnitude of the correlation between frequency components of the two processes, whereas the cumulant density is a time domain measure of association between two processes similar to a cross-correlation function. Confidence intervals for all parameters were also estimated (for further details see Conway *et al.* 1993; Farmer *et al.* 1993*a*).

RESULTS

Figure 1 provides a schematic representation of the experiment and shows sample records of the MEG from the dominant hemisphere and the EMG from the contralateral 1DI muscle (Fig. 1*A*); the estimated autospectra for the MEG (Fig. 1*B*) and rectified EMG of the contralateral 1DI muscle (Fig. 1*C*) are also shown. The two MEG autospectra shown in Fig. 1*B* correspond to records made while the subject was relaxed (Fig. 1*B*, continuous line) and whilst performing a maintained contraction of the contralateral 1DI muscle (Fig. 1*B*, dotted line). Distinct peaks in these spectra are centred about 10, 20 and 40–50 Hz. In this example the magnitude of these peaks changes during task performance, for example the peak centred about 20 Hz is reduced during contraction of 1DI while the peak in the 40–50 Hz range is enhanced. All subjects showed similar frequency components in the MEG autospectra, although considerable variation in the amplitudes existed between subjects and between recording sites. The autospectrum of the rectified EMG also contains distinct peaks (Fig. 1*C*). The large peak within the frequency range 16–32 Hz is of particular interest, since previous studies on motor-unit synchronization have associated this frequency range with the frequency content of common presynaptic inputs to motoneurones (Farmer *et al.* 1993*a*).

During an experimental trial in which the subject co-contracted both right and left 1DI muscles it was possible to determine whether any correlation existed between the neural activity recorded by the MEG from the dominant hemisphere and both ipsilateral and contralateral EMG recordings. The results of one such experiment are shown in Fig. 2. Figure 2*A* illustrates the autospectrum of the

MEG during a maintained co-contraction of both 1DI muscles. The rectified EMG autospectra are shown in Fig. 2*B* (ipsilateral 1DI) and Fig. 2*C* (contralateral 1DI). In spite of the similarity of these autospectra – both display distinct peaks centred about 10 and 24 Hz – the coherence between the two signals was not significant (not shown).

The estimated coherence between the MEG from the dominant hemisphere and the rectified EMG from the ipsilateral 1DI muscle was not significant (Fig. 2*D*). Likewise the cumulant between the MEG and the ipsilateral EMG failed to reveal any significant correlations (Fig. 2*F*). In contrast, the coherence between the MEG and the rectified EMG from the contralateral 1DI muscle was significant in the range 18–26 Hz (Fig. 2*E*). The cumulant

between these two processes had a large peak centred about a lag u of 0 ms with slowly decaying oscillations for both positive and negative lag values (Fig. 2*G*), indicating that components of the MEG and contralateral 1DI EMG are synchronous. Similar correlations were obtained when the ipsilateral and contralateral 1DI muscles were activated separately. Significant coherence was observed in all subjects and occurred over the frequency range 12–31 Hz, with the peak coherence occurring within the range 14·5–28 Hz. In one subject an additional peak occurred at 7 Hz. Figure 3 provides a summary of the maximal coherence observed between the MEG records from the hand area of the dominant motor cortex and the contralateral EMG for each of the six subjects.
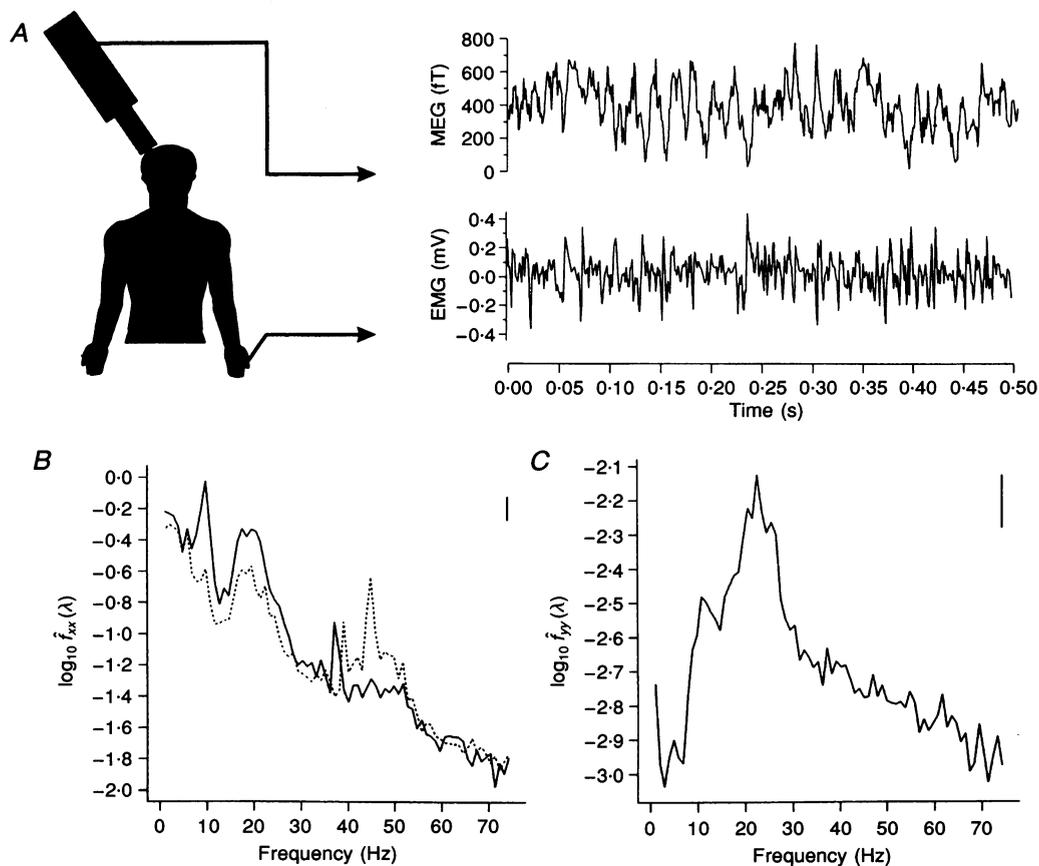

Figure 1

A, schematic of experimental set-up with sample recordings of raw MEG (upper trace) and EMG from the contralateral 1DI muscle (lower trace). *B*, estimated MEG autospectrum, $\hat{f}_{xx}(\lambda)$, obtained with subject relaxed (continuous line) and whilst subject maintained a voluntary contraction of the contralateral 1DI muscle (dotted line). *C*, estimated autospectrum of the rectified contralateral 1DI EMG, $\hat{f}_{yy}(\lambda)$, obtained during a maintained weak contraction of the muscle. All spectra are plotted on a logarithmic scale. The vertical line to the top right of each spectrum represents the magnitude of a 95% confidence interval and provides a scale bar against which to assess the significance of distinct features. ($\hat{f}_{xx}(\lambda)$ is used to denote an estimate of $f_{xx}(\lambda)$.)
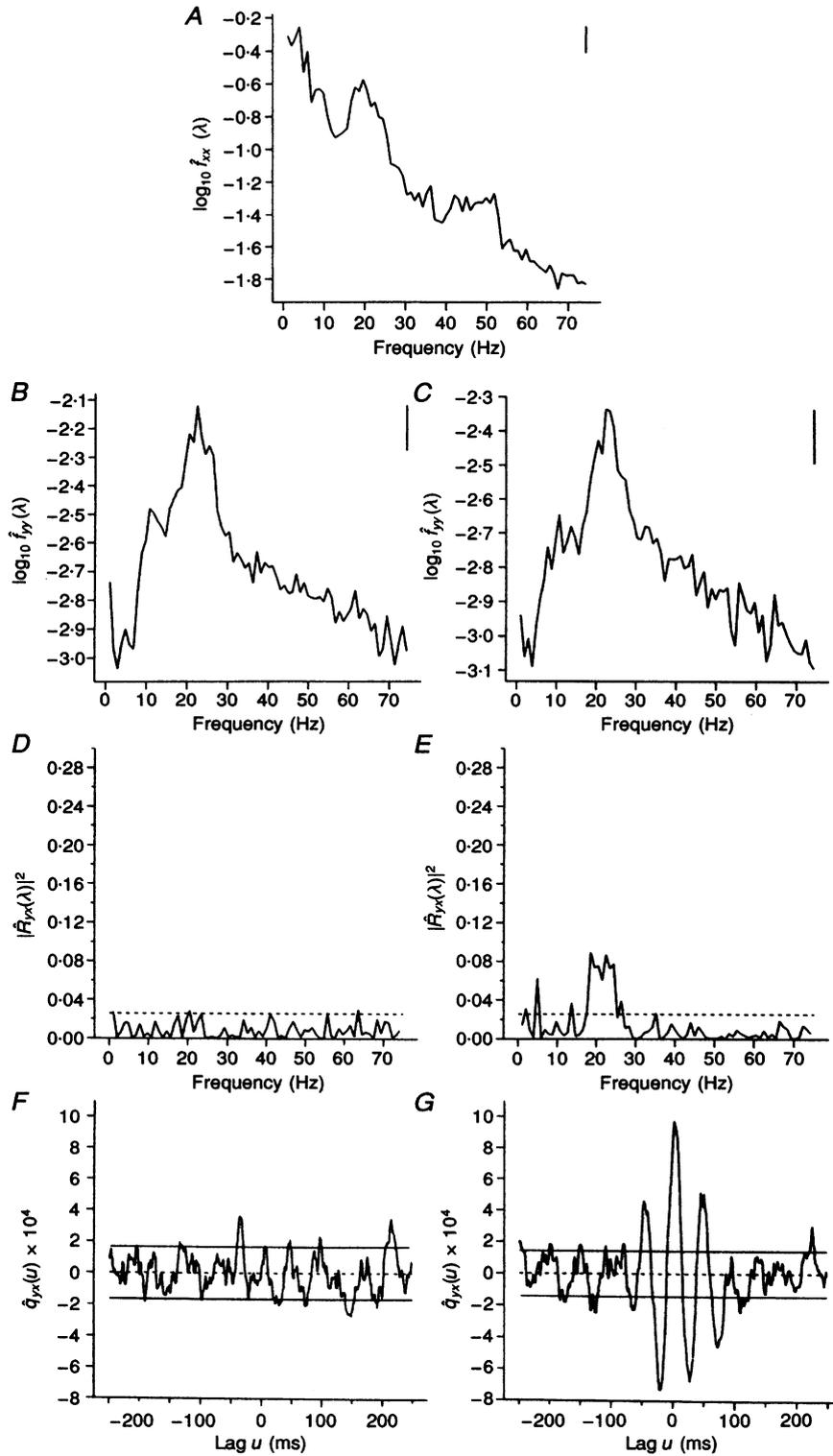
Figure 2. The relation between MEG and EMG during simultaneous contraction of left and right 1DI muscles

A, estimated autospectrum of the MEG. Estimated autospectra of ipsilateral (B) and contralateral (C) rectified 1DI EMGs. Estimated coherence, $|\hat{R}_{yx}(\lambda)|^2$, between the MEG and the ipsilateral (D) and contralateral (E) EMG recordings. Estimated cumulant density, $\hat{q}_{yx}(u)$, between the MEG and the ipsilateral (F) and contralateral (G) EMG recordings. Vertical bars in plots of the autospectra ($A-C$) represent 95% confidence intervals. Horizontal dotted lines in the coherence plots (D and E) and the parallel continuous lines in the cumulant plots (F and G) represent 95% confidence intervals under the assumption that the two processes are independent. Only correlations between the MEG and the contralateral EMG are significant. No correlation was evident between ipsilateral and contralateral EMG recordings (not illustrated).

Localization of the MEG–EMG coupling was studied by recording the MEG from different cortical sites. For each subject the MEG–EMG coupling was localized to a small area of cortex. Small movements of the MEG probe, away from the area of maximal coupling, resulted in a dramatic reduction in the coherence. This is illustrated by the three MEG–EMG coherence plots shown in Fig. 4.

The MEG recording sites, denoted P1, P2 and P3 (Fig. 4), are separated by approximately 2 cm. In this example the maximal coherence occurs at site P1 and is reduced when the probe is moved to either site P2 or P3 (Fig. 4). For the six subjects studied significant coherence was restricted to sites within an area 0–3 cm anterior to the vertex (Cz) and 2–7 cm lateral to the mid-line with the maximal coherence estimates occurring at sites within an area located 0–2 cm anterior to Cz and 3·5–5 cm lateral to the mid-line.

DISCUSSION

This study provides the first demonstration, in man, of a linear correlation between distinct frequency components of brain activity and EMG during maintained voluntary isometric contractions. These results have a number of implications for our understanding of the role played by the motor cortex in regulating motor behaviour.

Spatial localization of MEG–EMG coherence

Coherence estimates were significant only between the MEG recorded from the cortex contralateral to the hand activated during the contraction (Figs 2 and 3). Furthermore, small movements of the recording probe indicated that maximal MEG–EMG coherence was restricted to a localized area of the lateral surface of the cortex (Fig. 4). With reference to the 10–20 system of electrode placement, the co-ordinates on the skull where
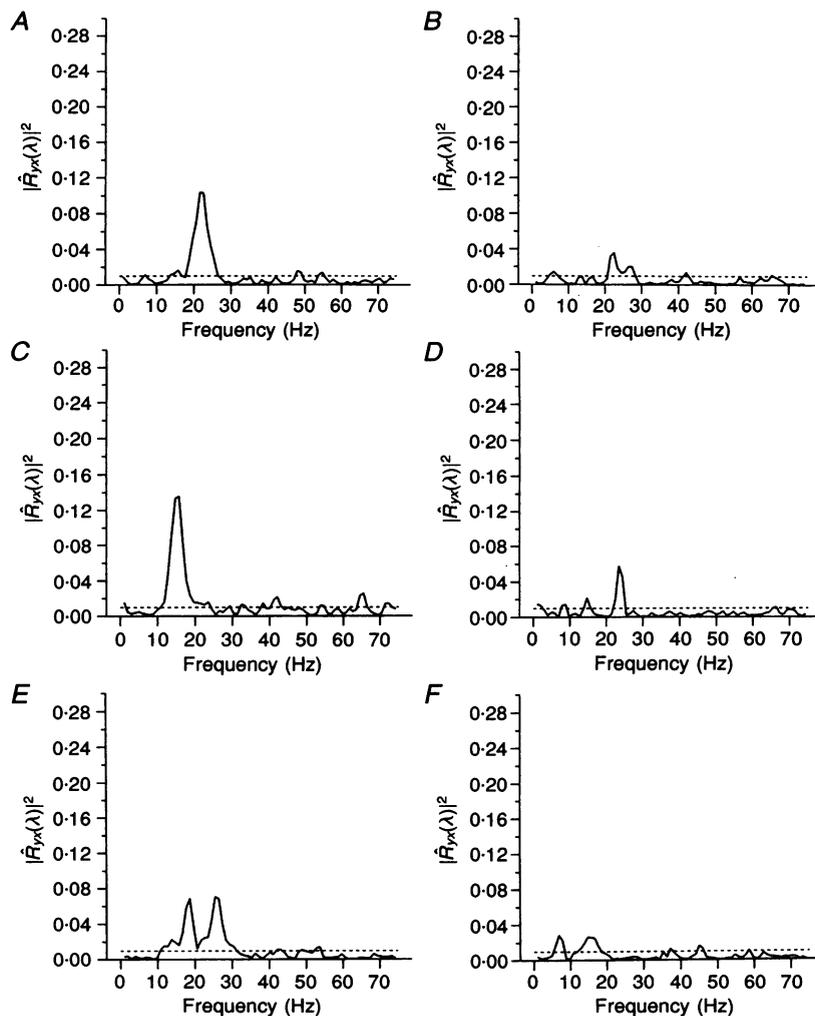

Figure 3. Estimated coherences, $|\hat{R}_{yx}(\lambda)|^2$, between the MEG and the contralateral 1DI EMG from each of the subjects participating in the study

The graphs shown correspond to MEG sites at which the coupling between MEG and EMG was greatest. The horizontal dotted lines in each graph indicate the upper level of the 95% confidence interval for each estimate under the assumption that the two processes are independent.

the MEG–EMG coherence was observed corresponds to sites overlying the primary motor cortex. In mapping experiments using focal magnetic stimulation the areas identified as generating the largest EMG responses in 1DI corresponded with MEG recording sites at which the MEG–EMG coherence was greatest. It is likely, therefore, that the observed correlations between the MEG and the EMG represent coupling between activity of neurones in the hand area of the primary motor cortex and that of motoneurones innervating the contralateral 1DI muscle. Further support for localizing the cortical activity to the primary motor cortex comes from previous multichannel MEG studies which have identified the motor cortex as the most likely source of cortical activity contributing to the beta frequency range (13–35 Hz) (Salmelin & Hari, 1994). However, on the basis of single channel MEG recordings we cannot dismiss the possibility that the somatosensory cortex may also contribute to the coherence.

Functionally distinct MEG rhythms and their relation to EMG activity

Spectral analysis of the MEG identified distinct components in the alpha ($\sim$10 Hz), beta (13–35 Hz), and gamma (40–50 Hz) frequency ranges (Fig. 1B). These components have been described previously in MEG and EEG studies (see Salmelin & Hari, 1994). The component of the MEG autospectrum centred at 10 Hz was not correlated with EMG activity (Fig. 2D and E). Similarly, there was no correlation between MEG in the frequency band 40–50 Hz and the EMG (Fig. 2D and E). In contrast, MEG components contributing to the beta frequency range were coherent with the EMG (Fig. 2E). In sensory systems 40–50 Hz rhythmicity has been associated with perceptual binding (Gray, 1994), and in man activity in this range has been found to be enhanced during selective attention (Naatanen, Ilmoniemi & Alho, 1994). In recordings from the sensorimotor cortex of monkeys performing fine finger
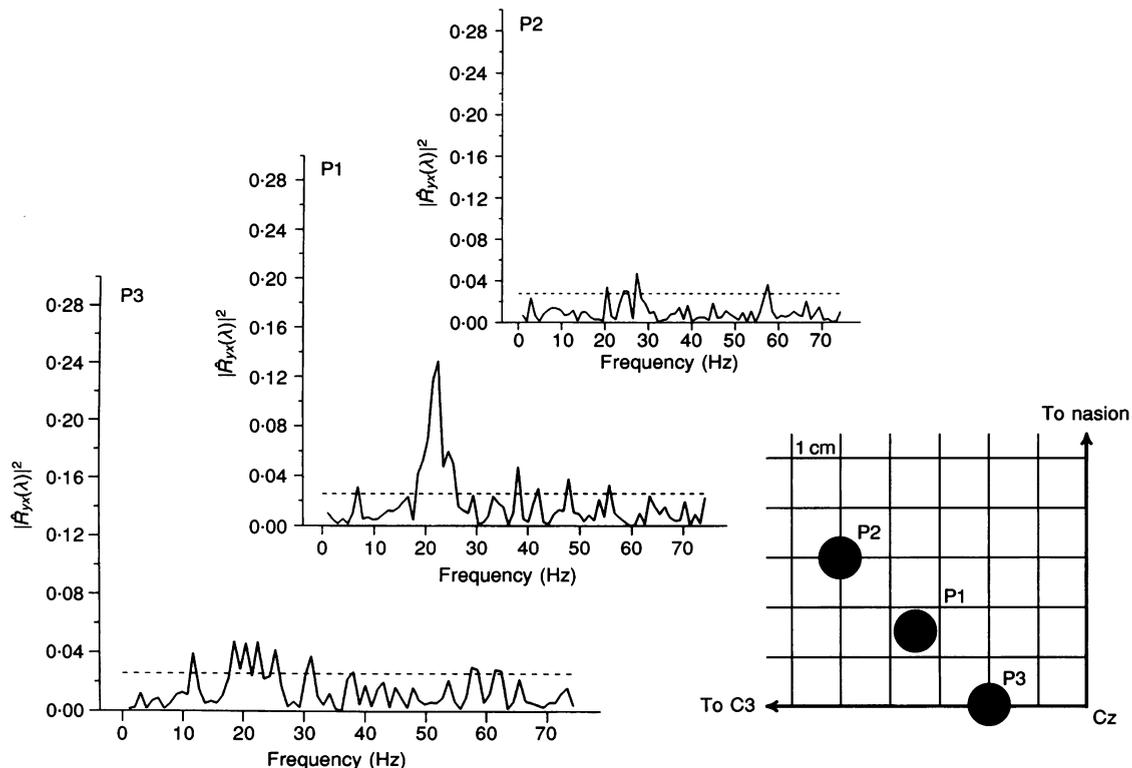

Figure 4. Estimated coherence between EMG and MEG from three skull recording sites P1, P2 and P3

The relative position of the probe at each site to the vertex (Cz) is shown by the centimetre square grid. The coherence plots demonstrate that the largest correlations occur at recording site at P1. Movement of the probe away from this site (e.g. to P2 or P3) results in a dramatic reduction of the coherence and illustrates the high degree of localization of the cortical sites responsible for the observed coupling. The horizontal dotted lines indicate the 95% confidence interval for each estimate under the assumption that the two processes are independent.

movements Murthy & Fetz (1992) have reported the presence of rhythmic activity in the frequency range 25–35 Hz. They postulated that this activity reflected binding functions within the primate sensorimotor system and its presence may relate to the continued sensorimotor integration required during the performance of exploratory movements (Murthy & Fetz, 1992). In experiments associating rhythmic cortical activity with movement in man the beta range of frequencies is suppressed prior to and during repetitive or brief self-paced movements (Penfield, 1954; Pfurtscheller, 1981; Salmelin & Hari, 1994). However, during maintained contractions Penfield (1954) reported that beta activity recorded from the surface of the motor cortex, although initially suppressed, is re-established during the contraction. Although we have not systematically studied alterations in rhythmic MEG activity prior to movement initiation or studied MEG–EMG correlations during rhythmic finger movements, comparison of MEG spectra during rest and during maintained contractions reveal, in agreement with Penfield (1954), that beta activity persists and contributes to the MEG spectra during the period of contraction. There is, however, considerable variation in the magnitude of the MEG components in relation to recording site, task performed and individual. The demonstration that significant coherence between MEG and EMG is restricted to frequencies mainly within the beta range suggests, in relation to motor behaviour, the presence of functionally distinct components of the MEG. For example, 40–50 Hz cortical activity may subserve attentional mechanisms which may be independent of the type of task performed.

MEG–EMG correlations and the relationship to common inputs and afferent feedback

The cumulant between the MEG and the EMG (Fig. 2*G*) illustrates synchronous behaviour of cortical and spinal networks. However, it should be noted that the actual time lag between the discharges of cortical neurones and moto-neurones is unknown. The coherence (Fig. 2*E*) associates the behaviour with rhythmic activity in the beta range of frequencies. Theoretically, there are a number of ways in which this behaviour could occur. The work of Engel, König, Kreiter & Singer (1991) demonstrated that synchronous behaviour between spatially discrete populations of neurones can arise as a consequence of activity within reciprocal connections between the two locations, which in the present case could involve a closed loop incorporating afferent feedback and descending motor activity. Alternatively, this behaviour could also arise from a common input to both sites possibly involving projections from the cerebellum, brainstem, basal ganglia or thalamus. While we cannot at present distinguish between such

mechanisms it is likely that movement related sensory feedback to sites within the central nervous system (including the somatosensory cortex) may play an important role in establishing and maintaining the MEG–EMG coherence. In this context studies on the EMG response to unloading during isometric finger contractions have shown that long loop reflexes involving the primary motor cortex (Matthews, Farmer & Ingram, 1990) play an important role in the maintenance of on-going EMG activity (Matthews & Miles, 1988) raising the possibility that such reflexes may also be important for the generation of MEG–EMG coherence.

Implications for studies of synchronization and coherence between single motor-unit discharges

In the present study cortical activity within the beta range of frequencies was observed to be correlated with the firing behaviour of spinal motoneurones (Fig. 2*E*). This range of frequencies accounts for one of the principal components of the coherence between pairs of single motor-unit spike trains (Farmer *et al.* 1993*a*), and also represents a component of the coherence between single motor units, surface EMG, and physiological tremor (Conway, Farmer, Halliday & Rosenberg, 1994; Conway, Halliday, Rosenberg & Farmer, 1995*a*). Farmer *et al.* (1993*a*), on the basis of indirect evidence, attributed the 16–32 Hz component of the coherence between 1DI motor-unit spike trains to central descending motor activity. The current study, therefore, provides direct evidence that cortical activity contributes to the 16–32 Hz modulation of motor-unit discharges, and also to a component of physiological tremor. The motor-unit coupling observed by Farmer *et al.* (1993*a*) in the 1–12 Hz range was not a feature of the MEG–EMG coherence observed in our studies, and therefore may derive from a process separate from that underlying the coherence observed within the beta range of frequencies and the EMG (Farmer *et al.* 1993*a*; see also Mills & Schubert, 1995).

The findings of the present study are also pertinent to the debate concerning the relative contributions of synchronized presynaptic inputs and last-order branched presynaptic inputs to motor-unit short term synchrony (cf. Datta & Stephens, 1990; Kirkwood, 1991). Rhythmic components of the MEG signal reflect synchronization between the activity of groups of cortical neurones around certain frequencies. Given that the MEG–EMG coherence occurs over a frequency range similar to that found between the discharges of single motor units, it is likely that the motor unit to motor unit 16–32 Hz coherence may in part be attributed to synchronization between cortical presynaptic elements. Farmer *et al.* (1993*a*) demonstrated a relationship between the central peak in the cross-intensity function

and 16–32 Hz motor-unit coherence. It follows, therefore, that the central cross-intensity peak found for pairs of motor-unit discharges in man cannot be attributed to a single process, but may contain contributions from both synchronized presynaptic inputs as well as last-order branched stem axons, with the later only contributing to the very narrowest part of the central peak in the cross-intensity function (for discussion and additional references see Kirkwood, 1991).

General considerations

The finding of MEG–EMG coherence in humans performing steady weak isometric contraction illustrates that cortical rhythms at frequencies in excess of the motor-unit firing rate may influence the timing of motor-unit discharges. The demonstrated relationship between MEG and EMG may represent a process by which binding in the motor system occurs. The expression and gating of coherent behaviour between discrete cortical and spinal networks during co-ordinated motor tasks may be a mechanism used to bind together the discharges of motor units of the different muscle groups necessary for the performance of voluntary movements. The ability of the central nervous system to synchronize and desynchronize populations of neurones during movements requiring different muscle synergies may provide a mechanism which permits the system to behave in a flexible manner. While there is evidence of coherence between motor units of different muscles at frequencies around 20 Hz (Farmer *et al.* 1993*a*) it is limited to studies on 1DI and 2DI, consequently further work examining correlations in the time and frequency domain between different muscle groups and cortical activity is required. Such considerations will form the basis for further studies investigating the relationship between MEG and motor behaviour.

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