Task-and Phase-related Changes in Cortico-muscular Coherence

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Abstract: Cortico-muscular coherence was compared during ramp-and-hold isometric and quasi-isotonic contraction of the ankle joint in human subjects. EEG was recorded from the leg area of the motor cortex. EMG was recorded from the tibialis anterior (TA) muscle. The subjects were requested to maintain a steady low level of dorsiflexion and at intervals of 10 s to increase the contraction level within 1 s, maintain this level for 4 s and then decrease the level of contraction again within another 1 s.

In seven subjects coherence in the 15-35 Hz frequency band was seen between EEG and TA EMG during low-level tonic dorsiflexion. In all subjects coherence disappeared during the ramp phase for both isometric and quasi-isotonic contraction. Coherence at other frequencies was also not observed in any of the subjects during the ramp phase. During the hold phase at the stronger level of contraction coherence reappeared quickly and had the same size as at the low level of contraction. However, a significantly larger level of coherence was found during quasi-isotonic than during the isometric contraction.

This demonstrates that cortico-muscular coherence in the 15-35 Hz frequency band is phase- and task-related. The decrease in 15-35 Hz coherence during the ramp phase may be related to event-related desynchronization of EEG activity. The larger level of coherence during quasi-isotonic contraction may reflect a higher demand of precise control of the joint position. It may also reflect a greater need for binding of functionally related cortical pyramidal tract neurons. (Keio J Med 57 (1): 50–56, March 2008)

Key words: electroencephalography (EEG), electromyography (EMG), coherence, task, phase

Introduction

A number of recent reports have investigated the possible function of synchronous oscillatory synchrony within the sensorimotor cortex of monkeys and humans.1–4 These oscillations can be detected in global measures of cortical activity, including magnetoencephalography (MEG) and EEG in humans, and local field potential (LFP) in monkeys; the dominant characteristic frequency of these oscillations is in the beta range of 15-30 Hz, and they are thought to arise from the synchronous discharge of large numbers of cortical neurones.

Cortical activity in the 15-30 Hz range has been shown to be coherent with oscillatory EMG activity in contralateral hand and forearm muscles in monkeys and humans.1,4–9 However, the functional significance of this corticomuscular coherence is unclear. Kilner et al found that coherence between the cortex and finger muscles was larger when subjects had to squeeze a compliant object rather than a more rigid object.8,9 This suggests that corticomuscular coherence may be related to functional parameters of the performed task. It may also play a functional role in the activation of the muscles.10 Corticomuscular coherence established during prehensile actions has also been shown to vary in a task-dependent manner. It was most prominent during the steady hold period of the precision grip task, but was abolished during digit movement.8,9 Coherence was shown to be
largest when a steady hold period immediately followed movement, and covaried positively with the compliance of the object being gripped; it was smallest during isometric grip of a solid object. This raised the possibility that 15–30 Hz cortico-muscular coherence may encode the ‘motor set’ needed to maintain steady grip of compliant objects.

To further investigate a potential functional role of corticomuscular coherence the purpose of the present study was to investigate whether corticomuscular coherence shows task- and phase specificity for leg movement.

Materials and Methods

Subjects

Experiments were performed on 9 healthy right-handed subjects aged 22–28 years, with approval from the local ethics committee. All the subjects gave their informed written consent to the experimental procedure. All experiments were performed according to the Helsinki declaration.

Experimental procedure

The subjects were seated in an adjustable armchair. Their right leg was semi-flexed in the hip (120°), the knee flexed to 40°, and the ankle in 10° plantar flexion. The foot was mounted to a plate during all measurements. The plate was connected to a torque motor. During quasi-isotonic contraction, the foot was left free to move and an electrical goniometer (SG150, Biometrics, UK) was placed over the right ankle joint for measurement of the position of the joint. “Quasi-isotonic” designates that the movement was performed without any external resistance.

Tasks (Figure 1)

At the beginning of the experiments, the subjects were requested to maintain tonic isometric contraction for 200 seconds in order to measure coherence between the EEG and EMG signals. If there were significant peaks found in EEG-EMG coherence, then the subjects were requested to perform either 1) isometric ramp and hold contraction, 2) quasi-isotonic ramp and hold contraction or slow quasi-isotonic contraction. The ramp and hold task was displayed on the computer screen. To track the displayed target torque or angle, smooth isometric or quasi-isotonic contraction was needed. In the ramp and hold task each trial lasted 10 seconds. With the aid of visual feedback of the torque or the position of the joint, the subjects were requested to maintain a steady low level of dorsiflexion (5%MVC or 0°) and then decrease the level of contraction again within another 1 s. For the slow quasi-isotonic contraction, the subjects were requested to dorsiflex the ankle joint slowly during 4s (from 0° to 10°) and maintain the obtained level for 2 seconds. Each trial was repeated 100 times for performing time-coherence analysis. The torque level of the MVC for each subject was determined prior to the experiment.

Data recording

The EMG activity of the tibialis anterior muscle was recorded by bipolar surface electrodes (inter electrode distance: 2 cm) placed in distal site and proximal site. The amplified EMG signals were filtered (bandpass: 1 Hz to 1 kHz) and sampled at 2 kHz, then stored on a PC for off-line analysis.

EEG was recorded by needle electrodes or surface electrodes between Cz and 2cm anterior to Cz. The amplified EEG signals were filtered (bandpass: 1 Hz to 1 kHz) and sampled at 2 kHz, then also stored on a PC for off-line analysis.

The torque or angle of the ankle joint was also recorded at 2 kHz for off-line analysis.
Analysis

Surface EMG records were full wave rectified, and estimated of the autospectra and coherence spectra between EEG and EMG signal were formed for the periods of maintained tonic contraction.

For the ramp and hold task, the EMG, EEG, torque and position were examined by eye; trials in which the subjects did not perform correctly were rejected. The onset of the ramp phase of the contractions was determined by visual inspection. This was used for subsequent coherence analysis for different segments of data in relation to the onset of contraction. Time-coherence analysis was then performed to determine the modulation of coherence with task performance.

Coherence analysis

Coherence of EEG signal and EMG signal has been described in detail in previous publications\textsuperscript{11–13} and will only be described briefly here.

Coherence is an estimate of the correlation between the frequency components of two spike trains, \( N_1 \) and \( N_2 \), and may be written as

\[
|R_{12}(\lambda)|^2 = \left| f_{12}(\lambda) \right|^2 = \left| f_{11}(\lambda) f_{22}(\lambda) \right|
\]

where \( \lambda \) is the frequency in Herz, \( f(\lambda) \) represents the cross-spectrum and \( f_{11}(\lambda) \) and \( f_{22}(\lambda) \) represent the auto-spectra of the two-component processes.

In the time domain, estimates of the cumulant density function are used to characterize the correlation between the signals. The cumulant density function, denoted by \( q_{xy}(u) \), is defined as the inverse Fourier transform of the cross spectrum

\[
q_{xy}(u) = \int_{-\infty}^{\infty} f_{xy}(\lambda) e^{i\omega u} d\lambda
\]

For two uncorrelated signals, the cumulant has an expected value of zero, deviations from this indicate a correlation between the two signals at a particular time lag, \( u \). Rhythmic inputs will induce symmetrical oscillatory components in the cumulant, the frequency and strength of these components can be quantified from the corresponding coherence estimates. Cumulant density functions are analogous to cross-correlation functions often used to quantify spike train data and have a similar interpretation.\textsuperscript{13}

Time–frequency analysis was then performed to determine the modulation of coherence with task performance. Any trends in the data associated with the ramp phases of the task were first removed using linear regression techniques. Power spectra and estimates of the coherence between all of the EMG signals and the EEG were calculated over a sliding 1.28 sec time window with a 256 point Fast Fourier Transform;\textsuperscript{11} estimates from windows with the same alignment to the task onset were averaged across trials. The time window was moved through the task in 0.1 sec steps to generate a time–frequency map. Differences between tasks were tested using paired \( t \) tests on coherence estimates in the 15–30 Hz range in higher holding phase of the task.

Results

Figure 2 shows representative results for a single subject performing tonic contractions. Figures 2A and B show the power spectra of the TA EMG and the EEG from the leg area during tonic contractions lasting 200 seconds. Both spectra show distinct peaks between 10–12, and 18–25Hz. Figure 2C shows the coherence spectrum between EEG and TA muscle EMG. There was a single peak in the 15–30 Hz range centered around 20 Hz; this peak was statistically significant. Figure 2d shows the cross-correlation analysis. Seven subjects from 9 subjects showed significant coherence during tonic contractions for 200 seconds.
Figure 3 shows the results of time frequency of EMG and EEG and time coherence during isometric ramp and hold contraction in a single subject. Both EEG and EMG power changed in amplitude during the task. Both EEG and EMG power in the 15-30Hz was great during the two hold periods of the task and for the EMG was reduced during the ramp. The below 10 Hz frequency signal in the EEG trace showed no obvious modulation during the task. The EMG power in the 15-30Hz frequency band increased during the second hold phase and also had a higher average frequency. Figures 3 and 4 show time-frequency EEG-EMG coherence maps for the isometric and quasi-isotonic contractions, respectively. For both types of contraction, coherence was confined to the 15-30 Hz range, despite the presence of power at higher and lower frequencies. The coherence showed a marked relationship with the phase of the movement. It was significant during both hold periods, but abolished during the ramp phases. The amount of coherence was similar during the strong contraction (hold phase at high torque level (Fig. 3), or at most dorsiflexed position (Fig. 4) as during the weak contraction (hold phase at low torque level (Fig. 3) and least dorsiflexed position (Fig. 4).

Measurements were also made during a very slow ramp movement without resistance (Fig 5). As can be seen, EEG-EMG coherence was absent when the muscle was at rest, but appeared soon after the onset of the movement and then slowly increased until a maximum when the muscle was maximally activated. There were no changes in the frequency band showing significant coherence during the contraction. Figures 6a and b show data from the same subject as in Figures 2 and 3. As can be seen, the level of coherence in the 15-30 Hz range was greater during 1 second of the upper hold phase of the quasi-isotonic contraction than during the isometric contraction. Figure 6c shows data from all 7 subjects who showed significant coherence. In 5 of the 7 subjects larger coherence was observed in the quasi-isotonic contraction than in the isometric contraction at the higher level holding phase. For the group of subjects there was a significantly higher level of coherence during the quasi-isotonic than during the isometric contraction (paired
t-test: \( p = 0.015 \).

There are some differences in magnitude of coherence between individual subjects, but the phase related changes of coherence in the quasi-isotonic or isometric contraction are basically same between subjects. Task related changes of coherence are described above.

**Discussion**

In this study, we have shown that the 15-35 Hz coherence between the motor cortex and leg muscles is strongly modulated during leg movements. The cortico-muscular coherence was most pronounced during the steady hold period of the task and mostly disappeared during ramp movements. This has similarly been reported for finger muscles in monkey$^4$ and in man.$^8$ The decrease in 15-35 Hz coherence during the ramp phase may be related to event-related desynchronization and the increase in the coherence during hold phase may be related to synchronization of EEG activity.$^{14,15}$ Also the firing pattern of cortico-motoneuronal (CM) cells during the ramp phase a large part of the population of CM neurons might not discharge within the specified frequency band.$^4$

During the ramp phase of both fast and slow contractions, most corticospinal neurons increase their firing rate as the force is increased, but some may show no modulation and others may even decrease (possibly due to recurrent inhibition) their firing rate.$^{16}$ Since discharge of a large part of the population of CM cells at a specific frequency is necessary in order to observe significant corticomuscular coherence at that frequency, it is not surprising that no coherence was observed during the ramp phase.

Recently Baker et al recorded long spike trains simul-
taneously from multiple single neurons in the primary motor cortex (M1) of two conscious macaque monkeys performing a precision grip task. As a population, synchrony was greatest during the steady hold period in striking contrast to the averaged cell firing rate, which was maximal when the animal was moving the levers into target. At the peak of population synchrony during the hold period, about half of the synchronization was within 18-37 Hz frequency range. They concluded that assemblies of neurons were synchronized during specific phases of a complex task with potentially important consequences for both information processing within M1 and for the impact of M1 commands on target motoneurons.

It is likely therefore that the changes in synchrony we have observed during the task reflect changes in the underlying network state between ramp and hold phases. The finding that synchrony is maximal during the hold phase agrees with the finding that 20- to 30-Hz oscillations in LFPs are confined to this period. Ptitsynchell et al. and Donoghue et al. also reported that oscillations in motor cortical field potentials are strongest during steady holding.

We did not observe any significant coherence outside the 15-35 Hz frequency range during either the hold or ramp phases of any of the contractions. It should in particular be noted that significant coherence was not observed outside the 15-35 Hz frequency range even during the slow quasi-isotonic contraction. This is in contrast to several previous studies on finger and hand muscles. Vallbo et al. observed 10Hz oscillation during slow ramp finger movements and Kakuda et al. reported 6-12 Hz coherence between motor units during the movement phase of slow finger movements, which decreased during position holding. Thus they suggested that the 6-12 Hz input is specific for movements and is normally absent or much weaker during steady maintenance of position or force. During phasic movement execution, Feige et al. found a low-frequency (2-14 Hz) synchronization between cortical activity and muscle. Conway et al. also found low frequency coherence during rapid contractions. In pathological state, the 6–15 Hz coherence was found between cortex and EMG in physiological tremor. They conclude that cortical networks are involved in the generation of physiologic tremor. There is thus some evidence that coherence between cortex and muscle may be seen at frequencies around 6-12 Hz especially during the movement phase for both slow and fast finger and hand movements or tremor, but we were unable to confirm that this was also the case for leg muscles. It might be due to the task they used. They use burst contraction as rapid as possible and the coherence is established early in the movement but is short lasting (~100 ms). Therefore the task in this study was different from the studies as above.

The larger level of coherence during quasi-isotonic contraction may reflect a higher demand of precise control of the joint position. The synchronous firing of neurons may be more effective in causing summation at processing. Thus common oscillatory activity may be more necessary for quasi-isotonic contraction than isotonic contraction for the binding together of functionally related cortical elements. Between tasks, the control of the torque and angle might be required especially for quasi-isotonic contraction. Therefore the coherent activity might reflect the combination of these two sources of the information. It may also reflect a greater need for binding of functionally related cortical pyramidal tract neurons in quasi-isotonic than in isotonic contraction as a group.

The results demonstrate a systematic relationship between coherence in the 15-30 Hz range and a specific parameter of the motor task. This relationship was only observed in the degree of coherence between the cortex and the muscles and was not present in the corresponding power spectra from either the MEG or EMG recordings. It is clear that the cortical activity, which is coherent with the leg muscles, represents something much more than just an “idling rhythm”. It is possible that the modulation of coherent oscillatory activity signals and scales these important changes in motor state. Control of both force and displacement is required for quasi-isotonic contraction; information related to both parameters is represented in the primary motor cortex, and it is possible that coherent oscillatory activity reflects the appropriate combination of these two sources of information. The larger level of coherence during quasi-isotonic contraction may reflect a higher demand of precise control of the joint position. It may also reflect a greater need for binding of functionally related cortical pyramidal tract neurons.

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