ORIGINAL ARTICLE

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

Yoshihisa Masakado[1,2] and Jens Bo Nielsen[2]

[1]*Keio University Tsukigase Rehabilitation Center, Shizuoka, Japan*
[2]*Department of Exercise and Sport Sciences & Department of Neuroscience and Pharmacology, Panum Institute, University of Copenhagen, Denmark*

(Received for publication on September 4, 2007)
(Revised for publication on November 7, 2007)
(Accepted for publication on December 3, 2007)

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.[4,8,9] Coherence was shown to be

Corresponding Author: Yoshihisa Masakado, MD Keio University Tsukigase Rehabilitation Center, 3802, Tsukigase, Izu-shi, Shizuoka 410-3293, Japan
Phone: 81-558-85-1701 Fax: 81-558-85-1810 E-mail address: masakado@sc.itc.keio.ac.jp

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.[9] 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 corticomucular 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 at intervals of 10 s to increase the contraction level within 1 s, maintain this level for 4 s

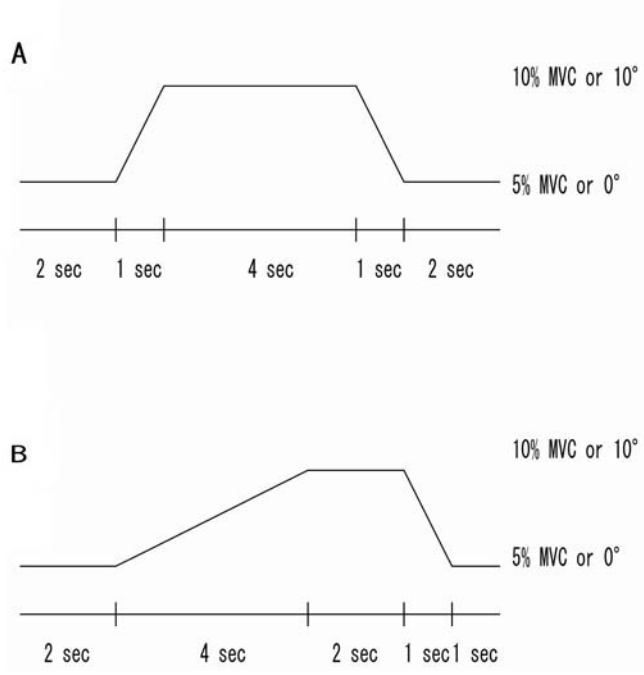

Fig. 1 Task Schematic of the task showing the force or angle required to be exerted on the ankle by the subjects.
A Isometric and quasi-isotonic, ramp and hold contraction
B Slow ramp-and-hold quasi-isotonic contraction

(10%MVC or 10°) 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[11−13] and will only be described briefly here.

Coherence is an estimate of the correlation between the frequency components of two spike trains, N1 and N2, and may be written as

$$|R_{12}(\lambda)|^2 = |f_{12}(\lambda)|^2 / f_{11}(\lambda) f_{11}(\lambda)$$

where λ is the frequency in Herz, $f(\lambda)$ represents the cross-spectrum and $f_{11}(\lambda)$ and $f_{22}(\lambda)$ represent the autospectra 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 $qxy(u)$, is defined as the inverse Fourier transform of the cross spectrum

$$q_{xy}(u) = \int_{-\pi}^{\pi} f_{xy}(\lambda) e^{i\lambda u} d\lambda$$

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.[13]

Time−frequency analysis was then performed to determine the modulation ofcoherence 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;[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.

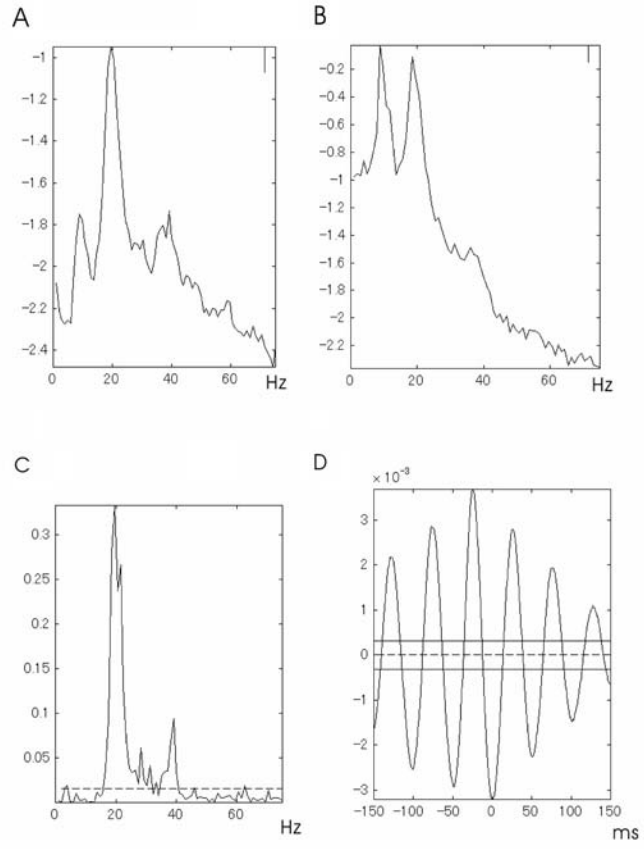

Fig. 2 Coherence analysis during isometric tonic contraction
Single subject data for the isometric tonic contraction.
A. Power spectra of EMG recorded from the tibialis anterior
B. Power spectra for EEG
C. EEG-EMG coherence
D. Cross-correlation analysis

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.

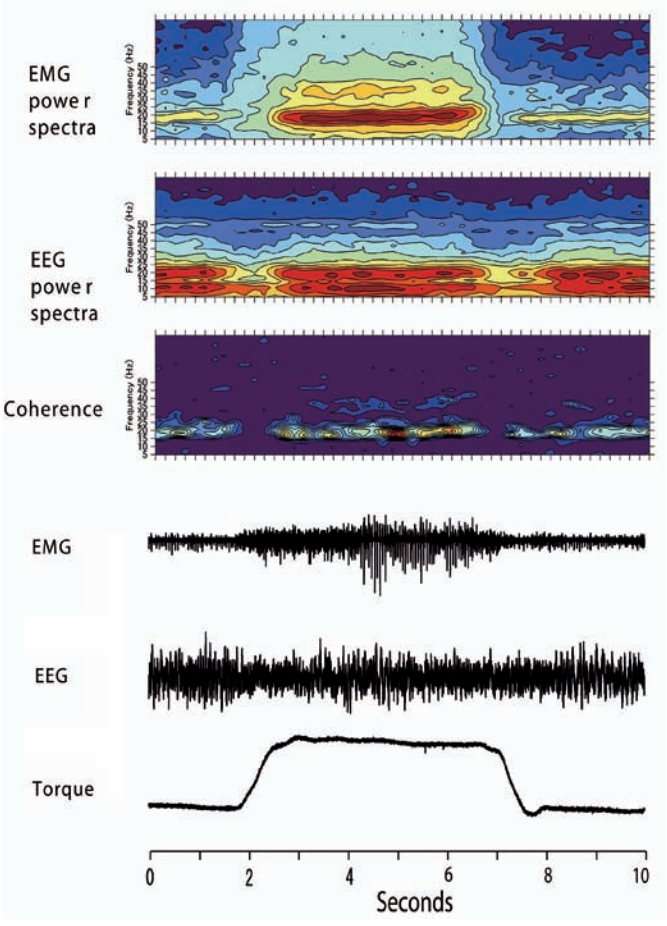

Fig. 3 Time-coherence analysis during isometric ramp and hold contraction (from a single subject)

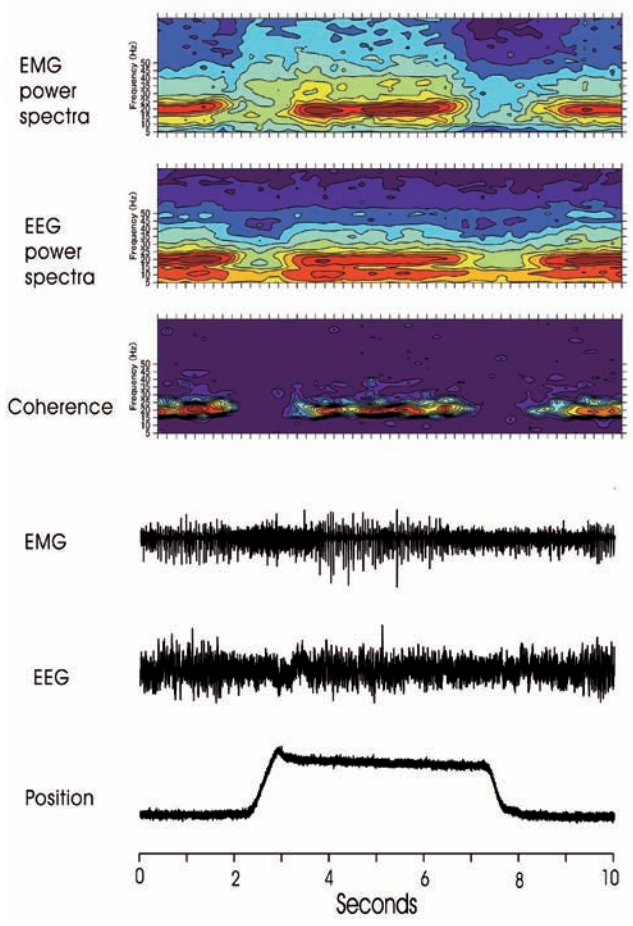

Fig. 4 Time-coherence analysis during ramp and hold quasi-isotonic (from a single subject)

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

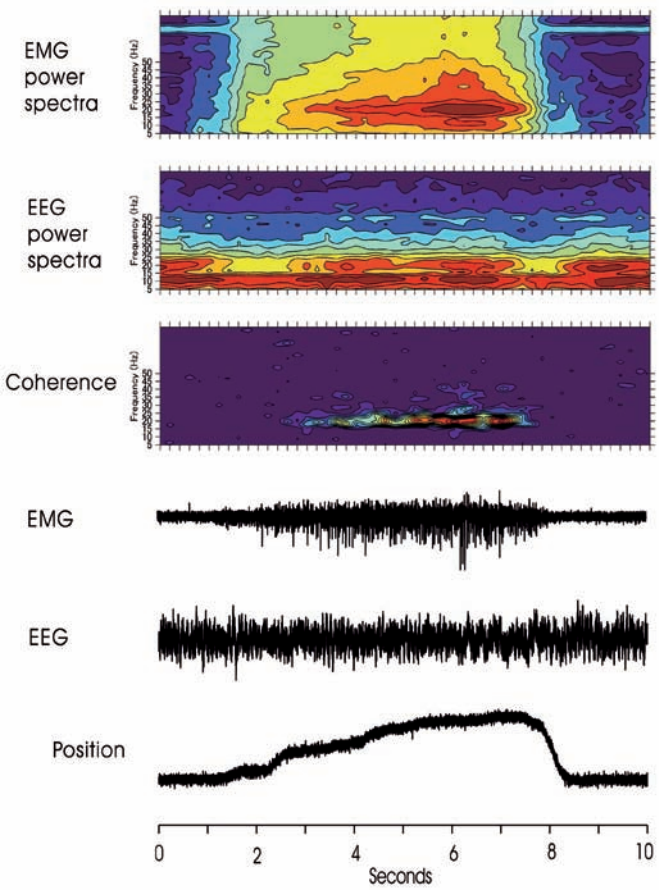

Fig. 5 Time-coherence analysis during slow ramp and hold quasi-isotonic contraction (from a single subject)

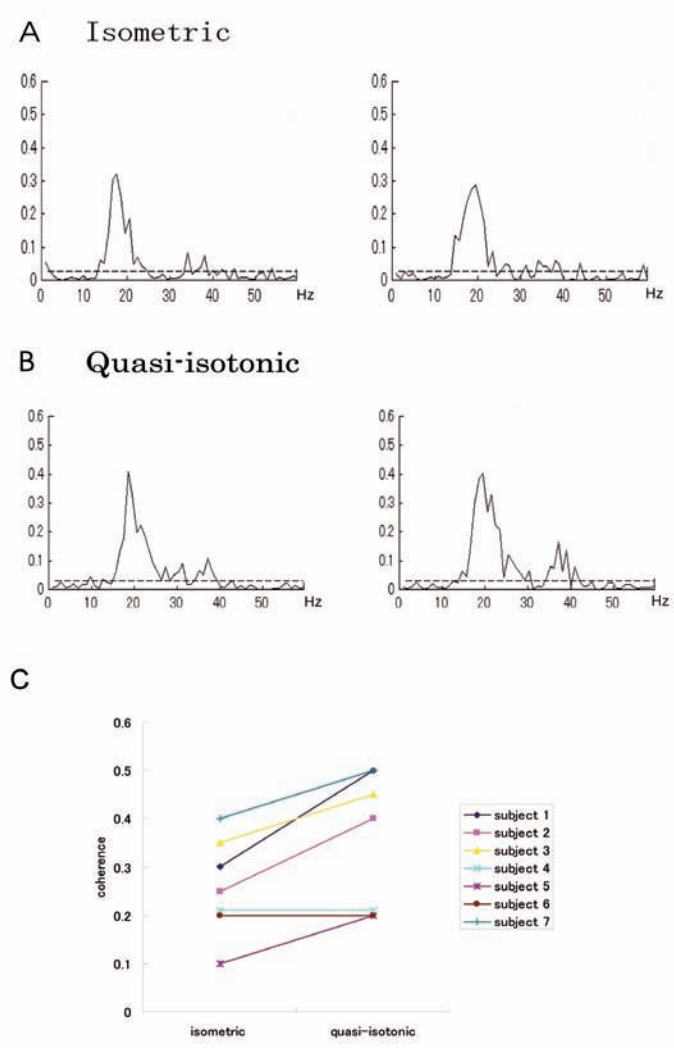

Fig. 6 The coherence data from mid hold phase in a single subject.
A isometric
B quasi-isotonic
Left figure shows the coherence data analyses t the beginning of mid contraction. The right figure shows the coherence data analyses 1 second after the left one.
C The level of coherence is higher in quasi-isotonic contraction than isometric contraction.

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 sychronization 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.[17] 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 motoneurones.

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.[4] Pfurtscheller *et al*[18] and Donoghue *et al*[19] 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.[20–25] Vallbo *et al*[20] observed 10Hz oscillation during slow ramp finger movements and Kakuda *et al*[21] 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*[22] found a low-frequency (2-14 Hz) synchronization between cortical activity and muscle. Conway *et al* also found low frequency coherence during rapid contractions.[23] In pathological state, the 6–15 Hz coherence was found between cortex and EMG in physiological tremor.[24,25] 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 temor, 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 isometric 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 isometric 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".[26–28] 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,[29–32] 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.[1–3] It may also reflect a greater need for binding of functionally related cortical pyramidal tract neurons.

Acknowledgements

Supported by the Danish Research Council, the Elsass Foundation, the Danish Society of Multiple Sclerosis, The Henry Hansen Foundation and the Niels and DesireYdes Foundation

References

1. Murthy VN, Fetz EE: Coherent 25-Hz to 35-Hz oscillations in the sensorimotor cortex of awake behaving monkeys. Proc Natl Acad Sci USA 1992; 89: 5670–74
2. Murthy VN, Fetz EE: Oscillatory activity in sensorimotor cortex of awake monkeys: synchronization of local field potentials and relation to behaviour. J Neurophysiol 1996a;76: 3349–67
3. Murthy VN, Fetz EE: Synchronization of neurons during local field potential oscillations in sensorimotor cortex of awake monkeys. J Neurophysiol 1996b;76: 3968–82
4. Baker SN, Olivier E, Lemon RN: Coherent oscillations in monkey motor cortex and hand muscle EMG show task-dependent modulation. J Physiol 1997;501:225–41
5. Conway BA, Halliday D, Farmer S, Shahani U, Maas P, Weir A, Rosenberg J: Synchronization between motor cortex and spinal

motoneuronal pool during the performance of a maintained motor task. J Physiol 1995; 489: 917–924
6. Salenius S, Portin K, Kajola M, Salmelin R, Hari R: Cortical control of human motoneuron firing during isometric contraction. J Neurophysiol 1997;77:3401–05
7. Hari R, Salenius S: Rhythmical corticomotor communication.Neu roreport 1999;10:R1-10
8. Kilner JM, Baker SN, Salenius S, Jousmaki V, Hari R, Lemon RN: Task–dependent modulation of 15-30Hz coherence between rectified EMGs from human hand and forearm muscles. J Physiol 1999;516:559–70
9. Kilner JM, Baker SN, Salenius S, Hari R, Lemon R: Human cortical muscle coherence is directly related to specific motor parameters. J Neurosci 2000;20:8838–45
10. Baker SN, Kilner JM, Pinches EM, Lemon RN: The role of synchrony and oscillations in the motor output. Exp Brain Res 1999;128:109–17
11. Rosenberg JR Amiad AM, Breeze P Brillinger DR Halliday DM: The Fourier approach to the identification of the functional coupling between neural spike trains. Prog Biophys Mol Biol 1989;53:1–31
12. Farmer SF, Swash M, Ingram DA, Stephens JA: Changes in motor unit synchronization following central nervous lesions in man. J Physiol 1993;463: 83–105
13. Halliday DM, Rosenberg JR, Amjad AM, Breeze P, Conway BA, Farmer SF: A framework for the analysis of mixed time series/point process data--theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. Prog Biophys Mol Biol 1995;64: 237–78
14. Salmelin R, Hari R: Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement. Neuroscience. 1994;60:537–50
15. Pfurtscheller G, Lopes da Silva FH: Event-ralated EEG/MEG synchronization and desynchronization: basic principles. Clin Neurophysiol 1999;110: 1842–57
16. Porter R, Lemon RN: Corticospinal function and voluntary movement. Oxford: Oxford University Press, 1993
17. Baker SN, Spinks R, Jackson A, Lemon RN: Synchronization in monkey motor cortex during a precision grip task. I. Task-dependent modulation in single-unit synchrony. J Neurophysiol 2001;85:869–85
18. Pfurtscheller G, Stancak A, Neuper C: Post-movement beta synchronization. A correlate of an idling motor area? Electroencephalogr Clin Neurophysiol 1996;98:281–293
19. Donoghue JP, Sanes JN, Hatsopoulos NG, Gaal G: Neural discharge and local field potential oscillations in primate motor cortex during voluntary movements. J Neurophysiol 1998;79:159–73
20. Vallbo AB and Wessberg J: Organization of motor output in slow finger movements in man. J Physiol 1993;469: 673–91
21. Kakuda N, Nagaoka M, Wessberg J: Common modulation of motor unit pairs during slow wrist movement in man. J Physiol 1999;520:929–40
22. Feige B, Aertsen A, Kristeva-Feige R: Dynamic Synchronization Between Multiple Cortical Motor Areas and Muscle Activity in Phasic Voluntary Movements. J Neurophysiol 2000;84: 2622–29
23. Conway BA, Reid C, Halliday DM: Low frequency corlico-muscular coherence during voluntary rapid movements of the wrist joint. Brain Topogr 2004;16:221–4
24. Raethjen J, Lindemann M, Dümpelmann M, Wenzelburger R, Stolze H, Pfister G, Elger CE, Timmer J, Deuschl G: Corticomuscular coherence in the 6-15 Hz band: is the cortex involved in the generation of physiologic tremor? Exp Brain Res 2002;142:32–40
25. Raethjen J, Govindan RB, Kopper F, Muthuraman M, Deuschl G. Cortical involvement in the generation of essential tremor. J Neurophysiol 2007;97:3219–28
26. Adrian ED, Matthews BH. The Berger rhythm: potential changes from the occipital lobes in man. Brain 1934;57:355–385
27. Buser P: Thalamocortical mechanisms underlying synchronised EEG activity. In: Halliday AM, Butler SR, Paul R, eds, A textbook of clinical neurophysiology, Chichester, UK: Wiley, 1987;595–621
28. Lopes da Silva F: Neural mechanisms underlying brain waves: from neural membranes to networks. Electroencephalogr Clin Neurophysiol 1991;79:81–93
29. Wannier TMJ, Maier MA, Hepp-Reymond M: Contrasting properties of monkey somatosensory and motor cortex neurons activated during the control of force in precision grip. J Neurophysiol 1991;65:572–589
30. Picard N, Smith AM: Primary motor cortical activity related to the weight and texture of grasped objects in the monkey. J Neurophysiol 1992;68:1868–188
31. Hepp-Reymond M, Kirkpatrick-Tanner M, Gabernet L, Qi HX, Weber B: Context-dependent force coding in motor and premotor cortical areas. Exp Brain Res 1999;128:123–133
32. Kakei S, Hoffman DS, Strick P: Muscle and movement representations in the primary motor cortex. Science 1999;285:2136–2139