Clinical Neurophysiology 113 (2002) 124–131
www.elsevier.com/locate/clinph

Effects of attention and precision of exerted force on beta range EEG-EMG synchronization during a maintained motor contraction task

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Accepted 21 November 2001

Abstract

Objective: The present study was aimed at investigating the effect of attention and precision level of exerted force on beta range EEG-EMG synchronization.

Methods: We simultaneously recorded cortical electrical activity (EEG) in a bipolar manner from the contralateral sensorimotor areas and surface electromyographic (EMG) activity from the flexor digitorum superficialis muscle in 10 healthy subjects during a maintained motor contraction task at 8% of the maximal voluntary contraction (MVC) force level. The coherence between oscillatory processes in the EEG and EMG was calculated. Three different conditions were investigated: (i) performing the task with high precision (HP); (ii) performing the task with high precision and simultaneously performing a mental arithmetic task (HPAT), i.e. attention was divided between the motor task and the mental arithmetic task; and (iii) performing the task with low precision (LP).

Results: We have found that the amount of beta range EEG-EMG synchronization decreases below the 95% confidence level when attention is divided between the motor task and the mental arithmetic task. The results also show that the frequency of beta range synchronization is higher with a higher level of precision but still lies within the beta frequency range (15–30 Hz).

Conclusions: The data indicate that beta range synchronization represents a state of the cortico-muscular network when attention is directed towards the motor task. The frequency of synchronization of this network is associated with, and possibly encodes, precision in force production.

Keywords: EEG-EMG synchronization; Attention; Precision; Maintained motor task; Coherence

1. Introduction

Beta range cortico-muscle synchronization has been observed in the human motor system (Conway et al., 1995; Salenius et al., 1997; Brown et al., 1998; Farmer, 1998; Halliday et al., 1998; Kristeva-Feige et al., 1998; Mima et al., 1998, 2000; Kilner et al., 1999; Mima and Hallett, 1999; Hari and Salenius, 1999; Marsden et al., 2000; Gross et al., 2000; Feige et al., 2000; Schnitzler et al., 2000). Such beta range synchronization was observed also during motor tasks in monkeys (Murthy and Fetz, 1992, 1996; Sanes and Donoghue, 1993; Baker et al., 1997, 1999). It was shown that there is a discrete shift in the frequency of synchronization from ca. 25 Hz to ca. 40 Hz, i.e. from beta to low gamma (Piper) rhythm as the change is made from weak to strong contractions (Brown et al., 1998; Brown, 2000). It was also shown that the beta range cortico-muscular synchronization is directly related to specific motor parameters (Kilner et al., 2000).

Some of the authors investigating the cortico-muscular synchronization (Murthy and Fetz, 1992, 1996; Feige et al., 2000) and the synchronization at cortical level (Sanes and Donoghue, 1993; Kristeva-Feige et al., 1993; Donoghue et al., 1998; Brown and Marsden, 1998) suggest that beta range oscillations could be a correlate of attention during sensorimotor tasks. If this suggestion is true, one could hypothesize that the beta range synchronization would disappear when attention is divided between the motor task and another task performed simultaneously. To test this hypothesis we simultaneously recorded cortical activity from the contralateral sensorimotor cortex and EMG from one of the 'prime movers' in two different experimental conditions. In both conditions subjects maintained a constant isometric force by pressing a force transducer at 8% maximal voluntary contraction (MVC) with their dominant index finger. Visual feedback about the force level was

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1388-2457/02/$ - see front matter
PII: S1388-2457(01)00722-2
CLINPH 2001595

provided to the subject. In one of the conditions the subject directed his attention fully towards the motor task. In the other condition the subject was doing the same but he was also simultaneously performing an arithmetic task. In this way the subject generated in both conditions the same motor outflow, had the same visual input and only the attention varied.

The second aim of this study was to investigate whether EEG-EMG synchronization varies with the level of precision of exerted force. For this purpose the first condition when the subject was performing the task exactly at 8% of the MVC level was compared with a condition with lower precision when the force holding was within a target window.

We studied the effect of precision and attention on EEG-EMG synchronization during a maintained motor contraction task at low force level (at 8% MVC) because in everyday life, the movements of the hand which require most attention and precision are the fine, low-force movements. Evidence from animal studies (Maier et al., 1993) also suggests that the motor cortex is most concerned with coding of weak forces (<10% MVC).

2. Subjects and methods

2.1. Subjects

The experiment was run with 10 healthy subjects (mean age 25.3 years, SD 6; 7 right-handed and 3 left-handed). All subjects participated according to the declaration of Helsinki, with informed consent and the approval of the local ethics committee. The handedness was tested according to a modified Oldfield questionnaire (Oldfield, 1971). The subjects had previous experience with similar experiments.

2.2. Experimental design

During the experimental session, the subject was sitting in an electrically shielded, dimly lit room and was required to maintain a constant isometric force by pressing a force transducer with his dominant index finger starting from complete relaxation. Visual feedback of the force level was provided via an analog display in front of the subject.

The dominant hand and arm were supported in a rigid cast with the index finger positioned on the force transducer. The other fingers were taped. The exerted force was 8% of the MVC for each individual as determined prior to experiment. The mean exerted force for all subjects was 0.54 (SD 0.22) kg.

Three different experimental conditions were investigated in a given recording session:

- High level of precision condition (HP): this condition was defined as maintaining force exactly at 8 % MVC force level. This condition required fine motor control.
- High level of precision with arithmetic task condition (HPAT): this condition was the same as the HP condition but the subject was instructed to perform simultaneously a mental arithmetic task (subtracting 7 sequentially starting from 200, 300 or 400).
- Low level of precision (LP) condition: the low precision condition was defined as maintaining exerted force within a target window representing 20% around the force level of 8% of the MVC. This condition required less fine motor control.

Each condition included 3 trials, each of them lasting 2.5 min. The time between the trials was approximately 3 min. To avoid order effects the trials belonging to the 3 experimental conditions were pseudorandomized. The instruction for the order of trials belonging to the different conditions was given by the experimenter.

Each subject was given several practice trials prior to the experiment until reaching the required force and precision pattern for each of the conditions.

2.3. Recordings

To determine the cortical correlate of the EMG oscillations electric potentials were recorded in a bipolar manner from scalp positions over the contralateral hemisphere overlying the contralateral representation of the hand area: one of the electrodes was positioned at C3 and the other one 2.5 cm anterior to it (bandpass 0–100 Hz; sampling rate 500 Hz; NeuroScan, Herndon, USA). This position of the electrodes was similar to the bipolar electrode position used by Halliday et al. (1998) and Brown et al. (1999). The signal from this bipolar recording results from the joint participation of the contralateral primary motor and premotor areas as shown by source reconstruction (Feige et al., 2000) and by intracortical recordings with epileptic patients (Marsden et al., 2000). The ground electrode was on the forehead.

Bipolar surface EMG (bandpass 1–500 Hz; sampling rate 2500 Hz) was recorded using surface Ag-AgCl electrodes placed over one of the 'prime movers', the flexor digitorum superficialis muscle of the dominant hand.

Electrooculogram (EOG) (the same bandpass as for EEG) was recorded to exclude segments with eye movement artifacts.

Force profiles generated by the subject, EEG, EMG and EOG were digitally stored and analyzed off-line. Fig. 1 illustrates one trial for the HP condition, one trial for the HPAT condition and one trial for LP conditions with the corresponding force, EEG and EMG recordings.

2.4. Data analysis

Artifact rejection was performed off-line by eye to exclude segments with eye movement, muscle artifacts and force profiles not conforming to the force requirements of the experimental condition.

Surface EMG was full wave rectified to maximize information about action potential timing. EEG-, rectified EMG-

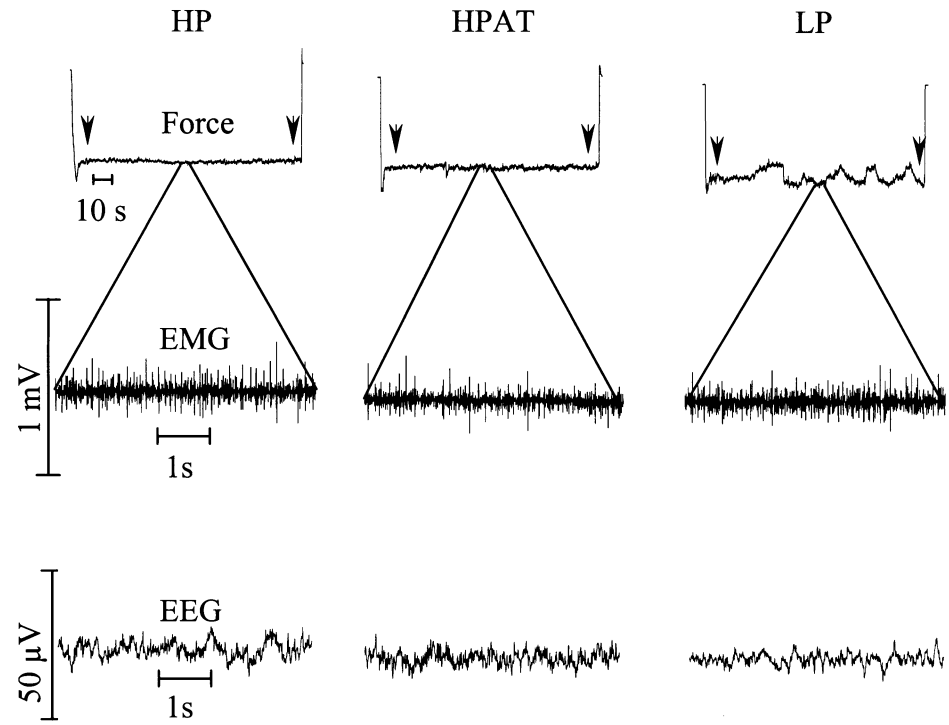

Fig. 1. Force profiles, EEG and EMG from one trial for high precision (HP), high precision with arithmetic task (HPAT) and low precision (LP) conditions for one of the subjects (S1) investigated. The EMG is recorded from pars indicis of the flexor digitorum superficialis muscle of the dominant hand. The EEG is recorded in a bipolar manner from the contralateral motor areas (one electrode placed on C3 and the other one placed 2.5 cm anterior to it). The ordinate for the force profiles represents the force pulse in kilograms. The spectral and coherence analysis was performed only on artifact-free segments marked on the force profiles between both arrows.

and coherence spectra between each EEG and EMG signal were estimated for each trial. Data related to the ramp movement phase are not dealt with in this study.

Spectral analysis of EEG and EMG data were performed by averaging $L = 120$ periodograms of Hanning-tapered artifact-free segments of 2048 data points (Halliday et al., 1998). This yields a frequency resolution of 1.2 Hz. To investigate the stability of the peak frequencies, for each trial, spectra were estimated from 3 non-overlapping pieces of 245760 data points.

Coherence between EEG and EMG was calculated based on cross-spectra f_{xy} and auto spectra f_{xx}, f_{yy} as described in Halliday et al. (1998), e.g. the spectra were estimated from segments and the coherence R_{xy} was estimated from the combined spectra:

$$|R_{xy}(\lambda)|^2 = |f_{xy}(\lambda)|^2 / \left(f_{xx}(\lambda) f_{yy}(\lambda)\right)$$

The significance of coherence can be judged using the test provided by Rosenberg et al. (1989), e.g. the confidence limit **cl** for zero coherence at the α quantile and for **L** the number of applied segments is:

$$\mathrm{cl}(\alpha = 0.95) = 1 - (1 - \alpha)^{1/(L-1)}$$

where $\alpha = \mathbf{0.95}$ and $\mathbf{L = 120}$, $\mathbf{cl \approx 0.025}$.

The hypothesis of non-correlated activity at each frequency is rejected if the estimated coherence at that frequency exceeds this value.

The generality of the individual coherence spectra was analyzed by calculating the histogram of percentage cases showing significant coherence peaks at each frequency. Due to chance interactions alone the incidence of significant coherence was expected to approach the 5% level. In addition, statistical fluctuations of percentage cases of significant coherence around the 5% limit were taken into account by calculating the standard deviation (SD) of the Poisson distribution. The percentage cases of significant coherence beyond the upper confidence limit of $2 \times \mathrm{SD}$ ($\approx 95\%$) are regarded as significant on the group basis following Farmer et al. (1993).

Mean rectified EMG during the analyzed periods was calculated for each subject and condition to check whether there was a consistent difference in the mean rectified EMG with condition.

3. Results

All subjects performed the arithmetic task in the HPAT condition without error. All subjects performed the motor tasks according to the instruction. None of the subjects reported fatigue effects during the experiment. All subjects

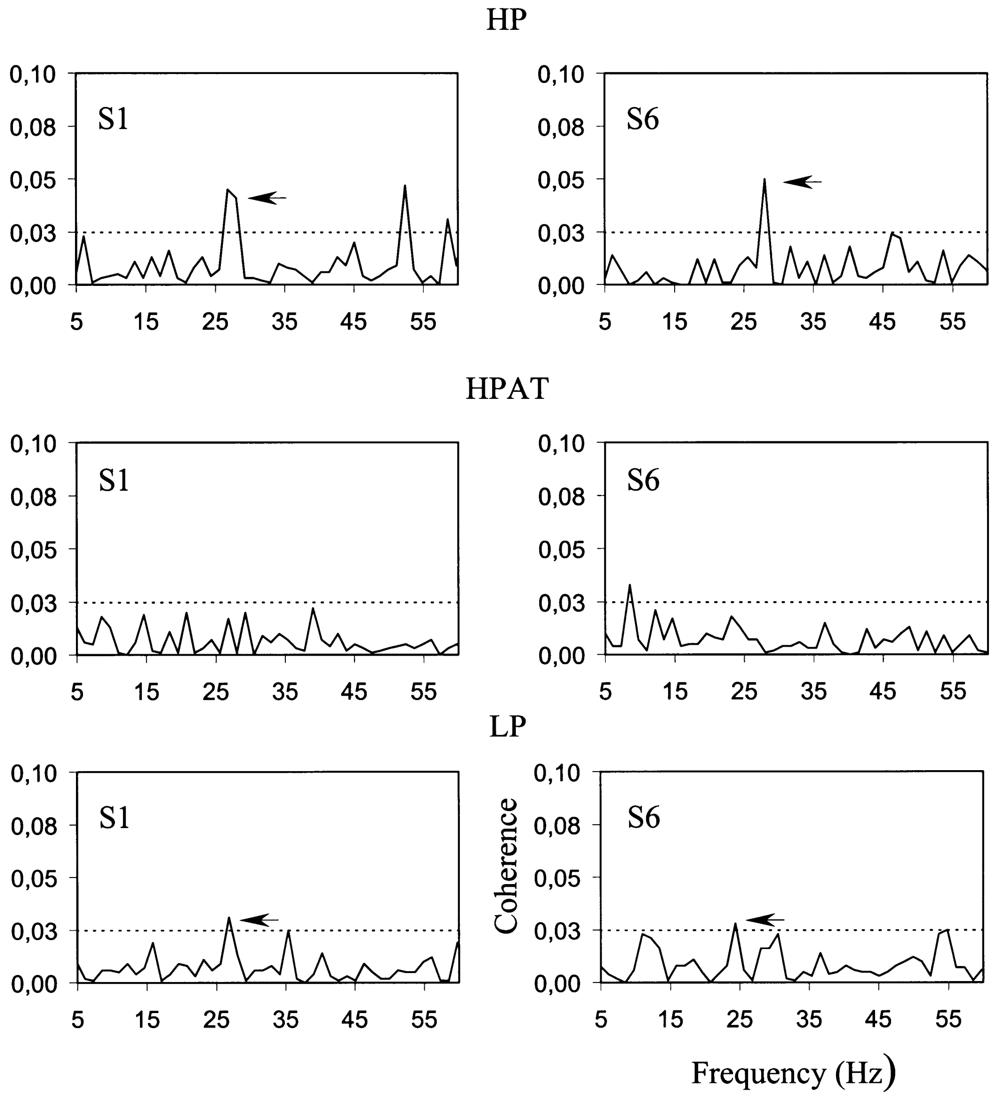

Fig. 2. Interindividual EEG-EMG coherence spectra. Estimated coherence spectra between EEG and EMG for two of the subjects investigated (S1 and S6) for the 3 different conditions (HP, HPAT, LP). The *X*-axis denotes the frequency in Hz and the *Y*-axis denotes the value of coherence. The horizontal dotted line indicates the 95% significance level for zero coherence. Each spectrum was estimated from 120 disjoint segments, each consisting of 2048 data points (0.8 s). Significant coherences are marked by arrows. Note that the beta range coherence in the HPAT condition is below the confidence level.

reported that the LP task required less attention than the HP task.

Fig. 2 shows the coherence results for two of the subjects investigated for the 3 different conditions: The coherency estimate for S1 for the HP condition shows a significant peak at 27–28 Hz and for S6 at 28 Hz. For the LP condition the coherence estimate shows a significant coherence peak at 27 Hz for S1 and at 24 Hz for S6. For HPAT condition no significant beta range EEG-EMG coherence peak was observed neither for S1 nor for S6.

From Fig. 2 it can also be seen that the coherence peaks are confined to narrow frequency bands of 1.2–3.6 Hz. Actually none of the subjects investigated showed broad coherence peaks.

From Fig. 2 it is difficult to decide whether the significant coherences found are statistical Type 1 errors or reflect underlying coupling. Therefore, we followed a procedure introduced by Farmer et al. (1993) and investigated the percentage of cases showing a significant coherence. Fig. 3 shows the percentage of the 30 cases (10 subjects times 3 pieces) studied, that showed significant values of coherence for each the 3 different conditions.

The most frequently occurring value of significant beta range EEG-EMG coherence in the HP condition was at a frequency of 28 Hz (50% of subjects; 23% of cases). In the HPAT condition the occurrence of significant beta range coherence does not exceed the 95% confidence level. In the LP condition the most frequently occurring value of significant beta range EEG-EMG coherence was at a frequency of 24 Hz (50% of subjects, 17% of cases), which is lower than that for the HP condition. Another frequently occurring value of significant coherence in the

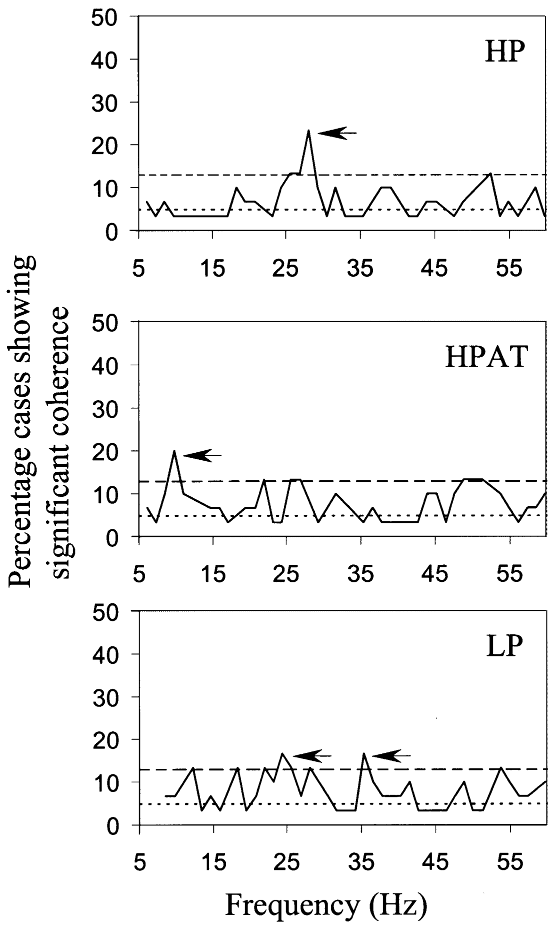

Fig. 3. Histogram of significant coherences. Histogram of the percentage of the 30 cases (10 subjects times 3 pieces) studied, that exhibited significant coherence peaks at each frequency in the range of 5–60 Hz. Data for the 3 different investigated conditions (HP, HPAT and LP) are given. The dotted line indicates the 5% level expected due to chance interactions alone. The dashed line indicates the upper 95% confidence level of statistical fluctuations of percentage cases of significant coherence around the 5% level based on the Poisson distribution. Arrows indicate the highest incidence of significant values of coherence. For HP condition the most frequently occurring value of significant coherence is 28 Hz. Note that the percentage cases of significant beta range coherence in HPAT does not exceed the 95% confidence level. Highest incidence of significant alpha range coherence at 10 Hz for HPAT condition. For LP condition high incidences of significant values of coherence occur within the beta range at 24 Hz and within the gamma range at 35 Hz.

LP condition was at a frequency 35 Hz, i.e. in the Piper range (40% of subjects, 17% of cases). Surprisingly, a high incidence of significant coherence at 10 Hz, i.e. rolandic mu-rhythm synchronization (60% of subjects, 20% of cases) for HPAT was found.

To exclude the possibility that the differences in the EEG-EMG coherence between HP, LP and HPAT conditions are related to a consistent difference in the muscle activation pattern, the mean rectified EMG of all pieces during the analyzed period for each condition and each subject was analyzed (Fig. 4). Two-tailed paired t tests for the group of 10 subjects revealed no difference in the flexor muscle activity between HP and HPAT ($P(9) = 0.186$) and between HP and LP ($P(9) = 0.184$). Furthermore, two-tailed paired t tests revealed no difference in the standard deviation of the flexor muscle activation between HP and HPAT ($P(9) = 0.187$). This means that the subjects performed the motor task in the HPAT condition equally well as in the HP condition, i.e. they performed the motor task according to the instruction. The difference for the standard deviation of the flexor muscle activity between HP and LP was not significant either ($P(9) = 0.133$). However, the higher fluctuation of the force pattern in the LP condition (seen for one of the subjects in Fig. 1) reveals a significant difference for the standard deviation of the force level between HP and LP ($P(9) < 0.001$) due to the higher amount of slow movements in the LP condition.

4. Discussion

The present study was designed to investigate the effects of attention and precision on the EEG-EMG synchronization during a maintained motor contraction task at low force level (at 8% MVC). The motivation to study the effects at this force level was the finding that the motor cortex is most concerned with coding of forces below 10% MVC as shown by animal studies (Maier et al., 1993).

4.1. *Effect of the divided attention on EEG-EMG synchronization*

We found that the amount of significant beta range synchronization decreases below the confidence level when the attention is divided between the motor task and another simultaneously performed task. This result is not due to a different muscle activation pattern because no consistent differences between HP and HPAT conditions were found either for the mean rectified flexor muscle

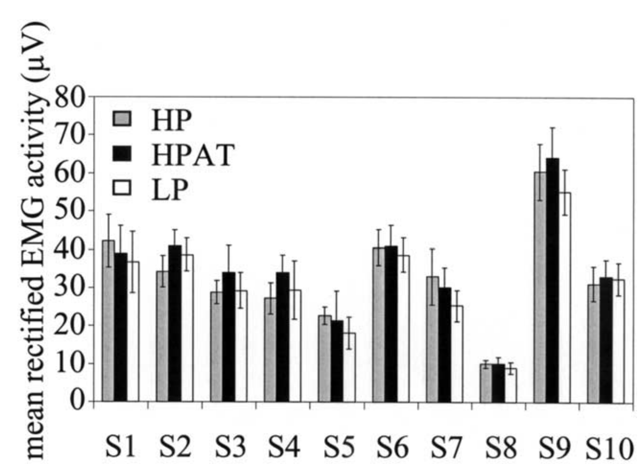

Fig. 4. Mean rectified EMG. Mean rectified EMG (μV) from flexor digitorum superficialis muscle from all analyzed pieces for HP (gray timbers), LP (blank timbers) and HPAT (black timbers) condition for each of the 10 subjects investigated. SDs are also given in the figure.

activity or for the standard deviation of the force level. Thus, our finding supports directly the view that beta range synchronization is associated with attention towards the motor task. Furthermore, the finding that beta range synchronization decreases below the confidence level when attention is divided supports the view that it plays an active role in motor control (Feige et al., 1996, 2000; Baker et al., 1999; Kilner et al., 1999) and does not reflect 'idling rhythm' as originally suggested (Pfurtscheller, 1992; Salenius et al., 1997).

The beta range synchronization was regarded as an 'indicator' of efficient motoneuron recruitment associated with a minimum of computational effort (Baker et al., 1999; Brown, 2000). It is possible that the cortico-muscular network works in this mode when the attentive resources are directed towards the motor task. This mode disappears when the attention is divided between the motor task and another simultaneously performed task.

4.2. Effect of the precision level of exerted force on beta range synchronization and possible mechanism of the precision-related coherence frequency

We found that the frequency of EEG-EMG synchronization is associated with the precision in force production: Lower-frequency ($\approx$24 Hz) synchronization occurs more frequently during a maintained motor contraction task with lower precision and higher-frequency ($\approx$28 Hz) synchronization during such a task with high precision. This result is not due to different muscle activation pattern because no consistent differences were found for the mean rectified EMG between the two conditions. Rather, this result is associated with the different precision in force production. However, one has to take into consideration that there was a larger amount of slow dynamic movement (the difference for the SD of the force level between HP and LP is significant; cf. also the force profile in Fig. 1) in the LP condition. This means that although both conditions, HP and LP imply continuous cortical visuomotor transformation processes based on visual feedback, in the LP condition the visual feedback varies much more in time. Therefore different networks with different spatiotemporal properties are activated.

Interestingly, although decreases in the level of precision shift the coherence from high frequencies to low frequencies, nevertheless, it still lies within the beta frequency range. This suggests that the frequency of synchronization is associated with, and possibly encodes, precision in force production. Why different frequencies may characterize different precision levels in force holding is hard to explain. Baker et al. (1999) suggest two different mechanisms for generation of the oscillations in the motor system: The first one may be the presence of 'chattering cells' similar to those described in the visual system (Jefferys et al. 1996) with intrinsic membrane properties leading to periodic bursting behavior with the inter-burst frequency ranging from 20 to 70 Hz. If such cells exist in the motor cortex they could be responsible for the beta range oscillations. The second mechanism proposed by Baker et al. (1999) is a dynamic network function for the generation of the oscillations which is shown to be dependent on the activity of the inhibitory interneurons. Changes in the inhibitory conduction delays and in the time course of inhibitory postsynaptic potentials both could effect a frequency shift of the network oscillations. Having in mind these two mechanisms suggested by Baker et al. (1999) the different frequency of synchronization between the high and low precision conditions may be due to precision-modulated intrinsic cell properties of the 'chattering cells' and/or to precision-modulated changes in the network dynamic function paced by the inhibitory interneurons.

Another possible explanation for the different beta frequency synchronization in the LP and HP condition comes from the investigation of the single units in the nucleus posterior pars medialis of the thalamus: Canu et al. (1994) have found that these cells display rhythmic activity in the beta frequency range. One can suggest that precision-modulated intrinsic cell properties of these 'beta-related cells' or precision-modulated changes in the thalamocortical network dynamic function can cause the different beta frequency synchronization in the HP and LP conditions.

One of the striking features of the results of our study is the difference between the shape of the EEG-EMG coherence from our data and others published in the literature. In most of the studies the significant coherence spans almost the entire beta frequency range. By contrast, the coherences in our study are confined to narrow frequency bands (1–3 data points = 1.2–3.6 Hz). None of the 10 subjects investigated shows broad coherence peaks. Therefore, this difference cannot be due to intersubject variability. Another striking feature of the results of this study is the relatively low values of the EEG-EMG coherence (of about 1% significance). The narrow frequency bands and the relatively low values in this study can be rather explained by tuning of the oscillatory neural network to a narrow frequency band when precision requirements for the motor task have to be met and/or when weak force (under 10% MVC) has to be maintained. Actually, both the LP and HPAT conditions affect attention, but perhaps in two different ways: in the HPAT condition attention is divided between both tasks. By contrast, the low precision condition differs from the high precision condition in that subjects must 'attend' less to the accuracy of the required force. The results show that both manipulations seem to modify beta coherence, but in two different ways.

4.3. Rolandic mu- and low-gamma (30–60 Hz, Piper rhythm) frequency range EEG-EMG synchronization

Although the subject of this study was to investigate whether beta range synchronization is associated with attention and precision in force production some additional findings regarding the alpha and low-gamma range coherence deserve attention: Mima et al. (2000) report that EEG-EMG coherence at 3–13 Hz always accompanies the beta-range synchronization during weak tonic contraction (10–20% MVC). In our study (cf. Fig. 3), the rolandic mu-rhythm EEG-EMG coherence occurs only in the HPAT condition when the attention is divided between the motor task and the arithmetic task. This finding indicates that the rolandic mu-rhythm synchronization does not necessarily accompany the beta range synchronization as is the case in the study of Mima et al. (2000). This finding of ours, together with the result that significant coherence between ECoG and EMG over 7–12 Hz is less frequent than the coherence over 15–30 Hz (Marsden et al., 2000) support the notion of different functional roles for 10 and 20 Hz components (Salmelin and Hari, 1994; Gross et al., 2000).

Interestingly, Sterman et al. (1994) suggest that the suppression of alpha band rhythmic activity in the central area observed during sustained psychomotor behavior may primarily reflect proprioceptive input to sensorimotor cortex. We find only in the HPAT condition, i.e. only in the divided attention paradigm rolandic mu-frequency range frequency EEG-EMG synchronization. Such mu-frequency synchronization was not found in HP and LP condition. This means, that the mu-frequency suppression over the rolandic areas can be related to the stationary attention to process the proprioceptive input to the sensorimotor cortex as suggested also by Mann et al. (1996).

Brown et al. (1998) described cortico-EMG coherence in the low gamma range with submaximal and maximal forces, i.e. in conditions when demands on the motor cortex are greater. The results from our study show that low gamma EEG-EMG synchronization occurs also with weak force production in the LP condition, i.e. in a condition when the motor areas are in a more 'mutable' state, because of the higher amount of slow movement in this condition and the more complicated visuomotor transformation.

Acknowledgements

We thank Mrs H. Hampel for technical help, Dr D. Halliday for statistical advice, Drs E. Fetz and H.-J. Huppertz for critical discussions and Dr G. Barnes for critical reading of the manuscript. Supported in part by DFG grant (Kr 1392/7-1).

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