



## **Corticomuscular Coherence with Low-Level Forces**

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**Summary:** The present study was aimed at investigating the corticomuscular synchronization in beta- (15-30 Hz) and gamma-range (30-45 Hz) during isometric compensation of low-level forces. It is still unknown to what extent the synchronization processes in these frequency ranges can coexist or influence each other when the static component only is modulated in a dynamic stimulation pattern. We investigated the corticomuscular coherence (CMC), as well as the cortical spectral power (SP) during a visuomotor task, where 8%, 16% and 24% of the maximal voluntary contraction (MVC) were used. Seven healthy right-handed female subjects compensated isometrically the different dynamic forces with their right index finger. EEG was recorded from 52 scalp positions and belly-tendon bipolar EMG from the first dorsal interosseus muscle (FDI). Under the three conditions investigated, the beta- and gamma-range CMC existed in parallel. They behaved in a different manner: while the beta-range coherence increased linearly during higher force application, the gamma-range CMC was not significantly modulated by the force levels.

Our results suggest that although gamma-range CMC is functionally associated to the isometric compensation of dynamic forces, broad beta-range CMC can fulfill functions of motor control simultaneously different when low-level forces are applied.

**Keywords:** Corticomuscular coherence, EEG, Beta-range, Gamma-range, EMG, Spectral power.

### **1. INTRODUCTION**

Much attention has been paid recently to the mechanism of synchronization in the central nervous system (CNS), which plays a relevant role in the effective coordination between the cortical motor areas and the muscles [10]. This universal mechanism can be described by the coherence function for different frequency ranges. During maintained motor contraction the cortical motor areas and the muscles are synchronized in the beta-range as shown in monkeys [5, 6, 22, 23] and humans [4, 8, 14, 29, 31]. Beta-range corticomuscular coherence (CMC) has been investigated in an extensive manner, showing that it is task-dependent [5, 15, 29]. CMC reflects attention [18], compliance [17], displacement [28], precision [19] and learning [27]. It was shown that increased beta-range CMC correlates with better performance, which suggested it as a mechanism for effective corticospinal interaction [19].

One of the main functions of the motor cortex is to control force output [2]. Brown et al. (1998) have shown that weak static forces were controlled by beta-range CMC and submaximal to maximal forces were controlled by gamma-range CMC [9]. During moderate contraction, Brown (2000) showed coexistence of beta- and gamma-range CMC [8]. Brown et al. (1998) also suggested that the gamma-range CMC correlated to higher involvement of the attention when the subject was producing submaximal and maximal forces [9]. Mima et al. (1999) have demonstrated that the shift of the CMC from beta- to gamma-range occurs when the change was made from weak to maximal force [21]. Beta-range CMC increases when the task requires the compensation of static forces at 16% of maximal voluntary contraction (MVC) instead of 4% MVC [31].

Gamma-range CMC has also been associated with isometric compensation of low dynamic force (4% MVC) and might function to provide rapid integration of visual, cognitive (preparatory attention) and somatosensory information [25]. In modeling studies gamma rhythms have been found to accompany states of vigilance or preparatory attention [7]. In studies in which the static or the dynamic component of the force profile were modulated, the gamma-range CMC was not modulated by the amplitude of the dynamic force [1, 31].

Therefore, it is still not sufficiently understood if the beta- and gamma-range synchronization processes coexist and behave differently or not, when only the static component of the compensated dynamic force is modulated. To approach this question, the present study applies a dynamic force paradigm with different force levels, where both static and dynamic components of the force are present, but the static component alone is manipulated, while the amplitude and frequency of the dynamic force remain constant. We therefore investigated CMC during isometric compensation of dynamic forces with three different force levels: 8%, 16% and 24%MVC.

According to previous extensive researches gamma-range CMC was observed during isometric compensation of dynamic forces and during static force the beta-range CMC increased distinctly from 4% to 16% MVC [1, 25, 31]. These results suggest different functional roles for CMC in the two frequency ranges: the increase of low-level

forces is associated with larger beta-range CMC while the gamma-range CMC allows for rapid sensorimotor and cognitive integration during fluctuating force output.

The findings of this study follow the idea and give extended and detailed analysis of the described in Chakarov et al. (2009) broad CMC in the 15-45 Hz frequency range [11]. They indicate that for low-level dynamic forces (8%, 16% and 24% MVC) beta- and gamma-range CMC coexist and behave in a different manner, where only the beta-range coherence alone increases significantly with the force level.

## 2. MATERIALS AND METHODS

### *Subjects*

The same group of subjects reported in Chakarov et al (2009) was used for the current extended analysis [11]. Seven healthy right-handed female subjects (mean age  $23.8 \pm 3.1$  years) with negative neurologic history participated in the study. Handedness was tested according to the Oldfield questionnaire. All subjects participated according to the declaration of Helsinki, with informed consent and the approval of the local ethics committee. None of the subjects had previously taken part in similar experiments.

### *Paradigm*

During the experimental session, the subject sat in an electrically shielded, dimly lit room. The right arm was supported by a splint, and the subject was instructed to place the hand over a sphere and the right index finger in the ring of a home-made manipulandum, which was designed for applying vertical forces on the finger, at the level of the metacarpophalangeal joint. A computer-controlled tooth belt drive produced a variable force on the ring, which the subject had to compensate isometrically. Visual feedback about the position of the ring was presented to the subject in the center of a 19" monitor, placed at 120 cm in front of her with two concentric circles: the green outer circle was fixed and represented the ring's reference position while the white inner circle moved corresponding to the ring's actual position. The subject had to maintain the small white circle inside the green circle at any time, so that when a given force was applied to the ring the subject had to apply the same force in the opposite direction (in this case flexion) to keep the ring in its initial

position. The sensitivity of the visual feedback with respect to the finger position corresponded to 2.85 mm on the screen for 1 mm ring displacement. During the experiment, finger and ring were hidden from the subject's visual field by a piece of cardboard.

Three different experimental conditions were investigated in each recording session. During these conditions the manipulandum generated a sinusoidally modulated force at 8%, 16% and 24% MVC respectively. The sine curve featured a frequency of 0.7 Hz and peak-to-peak amplitude of 4 % MVC. The MVC of the subject was measured prior to the beginning of the experiments. To ensure a smooth start and end of the generated force by the manipulandum, a rising cosine function was used. After the increase of the force to the given level, the subject had to compensate this force for about 12 sec. Each recording series consisted of 30 trials (10 for each condition) in which the sequence of the three conditions was randomized. To avoid muscle fatigue rest intervals of 5 to 10 sec were included between the trials. One experimental session included 5 to 8 series with breaks for about 5 minutes between them. The subjects were instructed to avoid any other movements and to fix their gaze on the visual feedback during the task. The subjects were given some practice at the beginning of the study to get familiar with the task.

### *Recordings*

Electrical potentials (bandpass 0-200 Hz, sampling rate 1000 Hz) were recorded from 52 scalp positions according to the international 10-10 system (Synamp 2, NeuroScan, El Paso, TX, USA) referenced to Cz with ground at FzA. Electrode impedances were kept under 5 kOhm. The electrooculogram (EOG, same bandpass and sampling rate as for EEG) was recorded to exclude trials contaminated with eye movements from further analysis. Electromyographic activity (EMG, bandpass 5-200 Hz; sampling rate 1000 Hz) was recorded with surface electrodes using a belly-tendon montage from the pars indicis of the right flexor digitorum superficialis muscle (FDI), the prime mover of the index finger flexion.

### *Data analysis*

Artifact rejection was visually performed off-line trial-by-trial to exclude segments contaminated with eye movements. To avoid transient effects, data related to the force ramp were not dealt with in this study. Continuous data of 10 sec, in-between level triggered markers was further divided into successive segments of 512 ms length, allowing for a frequency resolution of 1.96 Hz. The EEG signal was then transformed into the reference-free current source density distribution using the spherical spline interpolation method, which reflects the underlying cortical activity [24]. For the calculation of the spectral power (SP) and CMC a total of 300 artifact-free segments were analyzed for each subject using the commercial software 'BrainVision' 1.05 (München, Germany).

EMG signal was rectified, which is an appropriate procedure in power and coherence analysis [32] because it is known that full wave rectification provides the temporal pattern of grouped firing motor units. The discrete 512 points Fourier transform was calculated for each segment for the whole 1 to 500 Hz frequency range.

### *Statistical analysis of coherence and spectral power*

To test for any statistical difference on CMC and EEG and EMG SP between the three different levels of dynamic force, we measured the cumulative area ( $A$ ) under the coherence curve and above the 95% significance level,  $A_{coh}$ , and under the spectral power curve,  $A_{pow}$ , in-between two frequency windows: 15-30 Hz for the beta-range and 30-45 Hz for the gamma-range. For CMC peak we took the frequency of  $A_{coh}$  center of gravity. For the analysis of EMG SP we took the 5-200 Hz frequency range.

Afterwards, the non-parametric Friedman test was applied to compare values  $A_{coh}$  for CMC and  $A_{pow}$  for SP measured in all 3 force conditions for each single subject, with the null hypotheses that the distributions of the values tested are the same across all 3 conditions. The Friedman test with the global null hypothesis was calculated first to avoid an alpha-adjustment in the simultaneous paired hypotheses. When the Friedman test indicated that not all conditions were statistically equivalent, we performed a second non-parametric test (paired Wilcoxon test) on the resulting values  $A_{coh}$  and  $A_{pow}$ . The null hypothesis was that the difference between the matched samples of coherence and power spectra arises from a

distribution which is symmetric around zero. We applied this test on all possible condition pairs. To test a linear relationship between the CMC and the force level, we applied repeated ANOVA including an analysis of the polynomial contrast (linear and quadratic).

### 3. RESULTS

The maximum CMC were observed over the contralateral motor cortex (C3 or C1). Figure 1 shows the individual CMC curves for 8%, 16% and 24% MVC. As seen from the figure, there are significant broad-band coherences (over the 15–45 Hz range). For the 8% MVC condition two clearly separated cortico-muscular synchronization processes peaking in the beta at around 24 Hz (mean  $23.83 \pm 2.19$  Hz) and in gamma at around 35 Hz (mean  $34.44 \pm 1.0$  Hz) were observed. For the 16% and 24% MVC conditions, in most of the subjects the CMC pattern shows a rather broader synchronization process peaking in the beta at around 24 Hz (mean for 16%  $24.81 \pm 2.97$  Hz; 24%  $24.53 \pm 1.26$  Hz) and in gamma at around 34 Hz (mean for 16%  $35.14 \pm 2.11$  Hz; 24%  $33.84 \pm 1.39$  Hz).

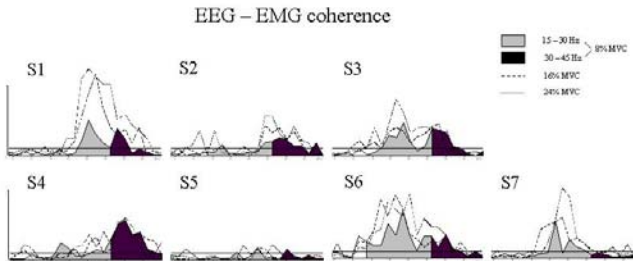


Fig. 1 Individual EEG-EMG coherences between the left sensorimotor area and the right FDI muscle for subjects S1 – S7 are shown for 8%, 16% and 24% MVC. The confidence level at 95% is marked with a horizontal line. Note that the beta-range coherence values increase from 8% to 16% to 24% MVC for all subjects.

The beta-range CMC increased significantly with the force level (Friedman test statistics 13.07; d.f. = 2;  $p < 0.002$ ). The *post hoc* Wilcoxon signed rank test further revealed significant differences between 8% and 16% MVC ( $Z = -2.01$ ,  $p < 0.027$ ), between 8% and 24% MVC ( $Z = -2.37$ ;  $p < 0.018$ ) and between 16% and 24% MVC ( $Z = -2.37$ ;  $p < 0.018$ ). The analysis of the polynomial contrast showed that the increment of the beta-range CMC was mostly due to a linear effect ( $p = 0.02$ ), the quadratic part was not significant.

Contrary to the beta-range CMC the gamma-range CMC did not show significant differences between the three force conditions.

We determined the cortical motor power over the contralateral left motor cortex. Neither the beta-range SP nor the gamma-range SP correlated with the dynamic force level.

No significant differences between the EMG spectral powers in the different force conditions were observed.

#### 4. DISCUSSION

##### *Coexistence of beta- and gamma-CMC*

The present study was designed to investigate how the beta- and gamma-range CMC behave when static and dynamic force components are superimposed and the force level is manipulated. The findings show that during isometric compensation of a periodically modulated (dynamic) force in the low force range (8% - 24% MVC) the beta- and gamma-range CMC can coexist but behave differently. The beta-range CMC increases significantly with the force level, while the gamma-range CMC remains unaltered.

Interestingly, gamma-range CMC was not significantly modulated by the force level but showed a tendency to increase from 8% to 16% to 24% MVC. Gamma-range CMC reflects rapid integration of the visual, somatosensory and cognitive (preparatory attention) information required to produce the appropriate motor command in order to isometrically compensate the periodically modulated forces [1, 25, 26, 31]. On the other hand, gamma-range CMC has been associated with the application of high-level forces and thereby with augmented attention [9]. Thus, the increasing force amplitude in our three conditions, together with their sinusoidal force modulation,

might have demanded higher attention resources and therefore caused the tendency for gamma-CMC, even if the force application remained in the low-level range.

The finding of this study, that beta-CMC increase with the force amplitude of static low-level forces is confirmed here in the presence of a dynamic force modulation. Our results favour the view that this function of beta-CMC is not confined to or specific for static forces. Rather, the sensorimotor system might resort to more beta-CMC to generate stable corticospinal interaction during increasing force level (the static component of the dynamic force). Riddle and Baker (2006) measured higher beta-CMC with more displacement prior to the static force [28]. The authors concluded that beta-CMC allows for the recalibration of proprioceptive parameters whose uncertainty is increased after larger movements. In this respect, the higher beta-CMC during higher force levels in our experiment may reflect a higher recalibration of tactile and proprioceptive information.

Coexistence of MEG-EMG coherence in the beta- and gamma-range was also reported during medium (50-60% MVC) static contraction [8]. Thus, we assume that the frequency of corticospinal beta- and gamma-rhythms is not specific to a certain motor act such as medium contraction [8] or superimposed static and dynamic low-level forces as in our case. However, different corticospinal circuits that are selected by different corticospinal synchronization patterns may designate the particular motor action [20]. We therefore suggest that the similar coherence pattern, which was observed by [8] and us during different motor acts, reflects the activation of different corticospinal circuits at the same frequencies. Those different corticospinal circuits however cannot be differentiated in non-invasive recordings such as EEG or MEG due to spatial smearing of neighbour neural fields [24]. Due to this smearing effect, we might have obtained a similar coherence pattern as [8], while performing a different task.

#### *Cortical motor spectral power*

Surprisingly, we neither found significant modulation of the beta- nor of the gamma-range SP in-between the different force levels of the dynamic force. With regard to the gamma-range, this result is in agreement with the former studies, which have reported relative independency of gamma-CMC and cortical motor SP in the gamma-



range [25, 30]. Concerning the beta-range, this result was unexpected since there is an evidence for a positive correlation between beta-range CMC and cortical motor SP in the beta-range [19]. On the other hand, elevated SP in the beta-band has been associated with decreased cortical excitability [12], whereas decreased cortical motor beta-power is known to correspond to motor acts demanding high-level attention [13, 16]. Even at the force level 24% MVC, a force condition consisting of superimposed static and dynamic force components still requires rapid recalibration of motor programs, high-level attention and thereby dynamic cortical processing – a state that may be incompatible with increased beta-synchronization of cortical motor cell assemblies despite the elevated beta-range CMC. Further evidence that beta-range CMC and cortical motor beta-power are not always positively correlated comes from a study, in which the authors amplified the beta-power through a diazepam-injection but did not observe a simultaneous increase of the beta-range CMC [3].

### *Conclusions*

The present study shows the simultaneous generation of beta- and gamma-range corticomuscular coherence during motor tasks containing a static and a periodical dynamic component. We suggest that the corticospinal beta- and gamma-rhythms correlate with the engagement of the motor system in the simultaneous control of both static and dynamic force components. Moreover, the beta-range CMC retains its behaviour to increase with the amplitude of the low-level force despite the concomitant activation of corticospinal gamma-range coherence. The results imply that our brain is able to construct composed force profiles through the simultaneous recruitment of mechanisms that usually characterize a single component of the composite force pattern.

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## REFERENCES

1. Andrykiewicz A., L. Patino, J. R. Naranjo, M. Witte, M.-C. Hepp-Reymond, R. Kristeva, Corticomuscular synchronization with small and large dynamic force output, *BMC Neurosci.*, 2007, 8, 101.
2. Ashe J., Force and the motor cortex. *Behav. Brain. Res.*, 1997, 86, 1–15.
3. Baker M.R., S. N. Baker, The effect of diazepam on motor cortical oscillations and corticomuscular coherence studied in man, *J. Physiol.*, 2003, 546, 931–942.
4. Baker S.N., Oscillatory interactions between sensorimotor cortex and the periphery, *Curr. Opin. Neurobiol.*, 2007, 17, 649–655.
5. Baker, S.N., J. Kilner, E. Pinches, R. N. Lemon, The role of synchrony and oscillations in the motor output. *Exp. Brain. Res.*, 1999, 128, 109–117.
6. Baker S.N., E. Olivier, R. N. Lemon, Coherent oscillations in monkey motor cortex and hand muscle EMG show task-dependent modulation, *J. Physiol.*, 1997, 501 ( Pt 1), 225–241.
7. Borgers C., S. Epstein, N. J. Kopell, Background gamma rhythmicity and attention in cortical local circuits: a computational study, *Proc. Natl. Acad. Sci. U S A*, 2005, 102, 7002–7007.
8. Brown P., Cortical drives to human muscle: the Piper and related rhythms, *Prog Neurobiol.*, 2000, 60, 97–108.
9. Brown P., S. Salenius, J. C. Rothwell, R. Hari, R., Cortical correlate of the Piper rhythm in humans, *J. Neurophysiol.* 1998, 80, 2911–2917.
10. Buzsáki G., A. Draguhn, Neuronal oscillations in cortical networks, *Science*, 2004, 304, 1926–1929.
11. Chakarov V., J.R. Naranjo, J. Schulte-Mönting, W. Omlor, F. Huethe, R. Kristeva, Beta-range EEG-EMG coherence with isometric compensation for increasing modulated low-level forces, *J Neurophysiol*, 2009, 102(2), 1115-1120.
12. Chen R., B. Corwell, M. Hallett, Modulation of motor cortex excitability by median nerve and digit stimulation, *Exp. Brain. Res.*, 1999, 129, 77–86.

13. Chen Y., M. Ding, J. A. Kelso, Task-related power and coherence changes in neuromagnetic activity during visuomotor coordination, *Exp. Brain. Res.*, 2003, 148, 105–116.
14. Conway B.A., D. M. Halliday, S. F. Farmer, U. Shahani, P. Maas, A. I. Weir, J. R. Rosenberg, Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man, *J. Physiol.*, 1995, 489 ( Pt 3), 917–924.
15. Feige B., A. Aertsen, R. Kristeva-Feige, Dynamic synchronization between multiple cortical motor areas and muscle activity in phasic voluntary movements, *J. Neurophysiol.*, 2000, 84, 2622–2629.
16. Jantzen K.J., A. Fuchs, J. M. Mayville, L. Deecke, J. A. Kelso, Neuromagnetic activity in alpha and beta bands reflect learning-induced increases in coordinative stability, *Clin. Neurophysiol.*, 2001. 112, 1685–1697.
17. Kilner J.M., S. N. Baker, S. Salenius, R. Hari, R. N. Lemon, Human cortical muscle coherence is directly related to specific motor parameters, *J. Neurosci.*, 2000. 20, 8838–8845.
18. Kristeva-Feige R., C. Fritsch, J. Timmer, C. H. Lucking, Effects of attention and precision of exerted force on beta range EEG-EMG synchronization during a maintained motor contraction task, *Clin. Neurophysiol.*, 2002, 113, 124–131.
19. Kristeva R., L. Patino, W. Omlor, Beta-range cortical motor spectral power and corticomuscular coherence as a mechanism for effective corticospinal interaction during steady-state motor output, *Neuroimage*, 2007, 36, 785–792.
20. Marsden J.F., K. J. Werhahn, P. Ashby, J. Rothwell, S. Noachtar, P. Brown, Organization of cortical activities related to movement in humans, *J. Neurosci.*, 2000, 20, 2307–2314.
21. Mima T., N. Simpkins, T. Oluwatimilehin, M. Hallett, Force level modulates human cortical oscillatory activities, *Neurosci. Lett.*, 1999. 275, 77–80.
22. Murthy V.N., E. E. Fetz, Coherent 25- to 35-Hz oscillations in the sensorimotor cortex of awake behaving monkeys, *Proc. Natl. Acad. Sci. U S A*, 1992, 89, 5670–5674.
23. Murthy V.N., E. E. Fetz, Oscillatory activity in sensorimotor cortex of awake monkeys: synchronization of local field potentials and relation to behaviour, *J. Neurophysiol.*, 1996. 76, 3949–3967.

24. Nunez P.L., R. Srinivasan, Electric fields of the brain: The neurophysics of EEG, Edn. 2, Oxford University Press, Oxford, 2006.
25. Omlor W., L. Patino, M.-C. Hepp-Reymond, R. Kristeva, Gamma-range corticomuscular coherence during dynamic force output, *Neuroimage*, 2007, 34, 1191–1198.
26. Patino L., W. Omlor, V. Chakarov, M.-C. Hepp-Reymond, R. Kristeva, Absence of gamma-range corticomuscular coherence during dynamic force in a deafferented patient, *J. Neurophysiol.*, 2008, 99, 1906–1916.
27. Perez M.A., J. Lundbye-Jensen, J. B. Nielsen, Changes in corticospinal drive to spinal motoneurons following visuo-motor skill learning in humans, *J. Physiol.*, 2006, 573, 843–855.
28. Riddle C.N., S. N. Baker, Digit displacement, not object compliance, underlies task dependent modulations in human corticomuscular coherence, *Neuroimage*, 2006. 33, 618–627.
29. Salenius S., K. Portin, M. Kajola, R. Salmelin, R. Hari, Cortical control of human motoneuron firing during isometric contraction, *J. Neurophysiol.*, 1997, 77, 3401–3405.
30. Schoffelen J.M., R. Oostenveld, P. Fries, Neuronal coherence as a mechanism of effective corticospinal interaction, *Science*, 2005. 308, 111–113.
31. Witte M., L. Patino, A. Andrykiewicz, M.-C. Hepp-Reymond, R. Kristeva, Modulation of human corticomuscular beta-range coherence with low-level static forces, *Eur. J. Neurosci.*, 2007, 26, 3564–3570.
32. Yao B., S. Salenius, G. H. Yue, R. W. Brown, J. Z. Liu, Effects of surface EMG rectification on power and coherence analyses: an EEG and MEG study, *J. Neurosci. Methods.*, 2007, 159, 215–223.