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8 authors, including:


Francesco Di Russo
Italian University of Sport and Movement "Fo...


Federica Menotti
Italian University of Sport and Movement "Fo...


Andrea Macaluso
Italian University of Sport and Movement "Fo...


Giuseppe De Vito
University College Dublin

Analysis of the Effects of Mechanically Induced tremor on EEG-EMG Coherence Using Wavelet and Partial Directed Coherence

Lara M. McManus*, *Student Member, IEEE,* , Francesco Budini, Francesco Di Russo, Marika Berchicci, Federica Menotti, Andrea Macaluso, Giuseppe De Vito and Madeleine M. Lowery, *Member, IEEE*

Abstract— **Corticomuscular coherence between human cortical rhythms and surface electromyography (sEMG) is commonly observed within the beta (13-35 Hz) and gamma (35-60 Hz) band frequency ranges, but is typically absent within the alpha band (8-12 Hz) in healthy subjects. A recent study has shown that significant alpha band corticomuscular coherence can be mechanically induced in healthy subjects using a spring of appropriate stiffness. Traditional coherence analysis is limited to examining whether a correlation exists between the electroencephalograph (EEG) and EMG recordings, by portraying instances of mutual synchrony. In this study the temporal evolution and directionality of the interaction between the EEG and EMG signals during mechanically induced alpha band coherence were investigated using two recent extensions of classical coherence, wavelet analysis and partial directed coherence. The results indicate a significant increase in directional information flow within the alpha and piper band frequency ranges in the EMG to EEG direction, and appear to provide evidence of the contribution of afferent feedback, and to a lesser extent descending cortical drives, to alpha band corticomuscular coherence.**

I. Introduction

Oscillations in the alpha (8-12 Hz) and beta (13-35 Hz) frequency band are commonly observed in recordings from the primary motor cortex [1]. Similar oscillations can also be detected in the electromyogram (EMG) of forearm and intrinsic hand muscles during sustained contraction. Although both cortical and muscle recordings show oscillations within the alpha and beta bands, significant corticomuscular coherence is usually only seen for the beta band, despite both frequency ranges being effectively carried down to the corticospinal tract from the motor cortex [2]. Based on these observations, Baker et al. (2003) speculated that the failure of motoneurons to phase-lock to cortical inputs around 10 Hz could be explained only if some neural system actively cancelled these inputs. This could be advantageous in the prevention of excess physiological tremor, which has a dominant frequency peak within the alpha band. Multiple interacting factors are involved in the generation of physiological tremor, with contributions not only from a 10 Hz centrally generated component, but also motor unit firing properties, mechanical resonances and reflex loop resonances. Several studies have provided evidence to suggest that both a descending cortical drive and afferent (feedback) pathways contribute to corticomuscular coupling [3].

The study of the interaction between multiple neurophysiological signals has for many years focused on the linear correlation between them, despite practical and theoretical limitations of traditional correlation and coherence measures. Basic Fourier coherence does not account for the temporal relationship between signals, nor does it offer any inference towards the direction of information flow between two structures. Wavelet coherence provides increased precision when analyzing temporal variations in the coupling between oscillatory neural signals [4], as enables time–dependent changes in the coherence to be examined.

The benefits offered by wavelet coherence are further complemented by the capabilities of partial directed coherence (PDC), a multivariate analysis technique evolved from the notion of Granger causality. For dynamic systems a signal $x_j(t)$ is said to "Granger-cause" another $x_i(t)$, if the past history of oscillations in x_j(t) can significantly improve the predictions of $x_i(t)$'s future. The relationship between these two signals is not reciprocal, and this property allows the direction of information flow (i.e. causal link) between the electroencephalograph (EEG) and EMG signals to be assessed. PDC analysis enables the detection of direct and indirect influences between the two signals, providing a unique insight into the origin of significant coherence.

In this study the effects of peripheral tremor on corticomuscular coherence were investigated during mechanically induced tremor in 13 healthy subjects. In a previous study, conventional Fourier coherence indicated a statistically significant increase in EEG-EMG coherence in the alpha band alone, following the introduction of a spring of appropriate stiffness, during elbow flexion at 20% maximum voluntary contraction [5]. In the present study two more stringent correlation measures, wavelet and partial directed coherence, were employed in order to gain further insight into the generator mechanism and functional relevance of the alpha coherence.

II. Methods

A. Experimental Procedure

Written informed consent and ethical approval was obtained for 13 healthy subjects, 8 male and 5 female volunteers before participation in the study. Maximum voluntary contraction (MVC) of the elbow flexor muscles was recorded and sub maximal contractions were then performed, both with and without a spring load at 20% of MVC. The amplitude of ~10 Hz oscillations was considerably enhanced by the introduction of a spring of appropriate stiffness (3.22 Nmm^{-1}) in series between the load cell and the handle [5]. This effect is attributed to the onset of stretch reflex instability around the short latency reflex loop [6]. Surface

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L. M. McManus and M. M. Lowery are with the School of Electrical, Electronic & Mechanical Engineering, University College Dublin, Dublin 4, Ireland. (e-mail: lara.mc-manus@ucdconnect.ie, madeleine.lowery@ucd.ie).

F. Budini and G. DeVito are UCD, Dublin 4, Ireland.

A. Macaluso, F. Di Russo, M. Berchicci, F. Menotti and G. De Vito are with the Department of Human Movement, Social and Health Sciences, University of Rome, "Foro Italico", Rome, Italy.

F. Di Russo is also with the Neuropsychological Unit, Santa Lucia Foundation IRCCS, Rome - Italy

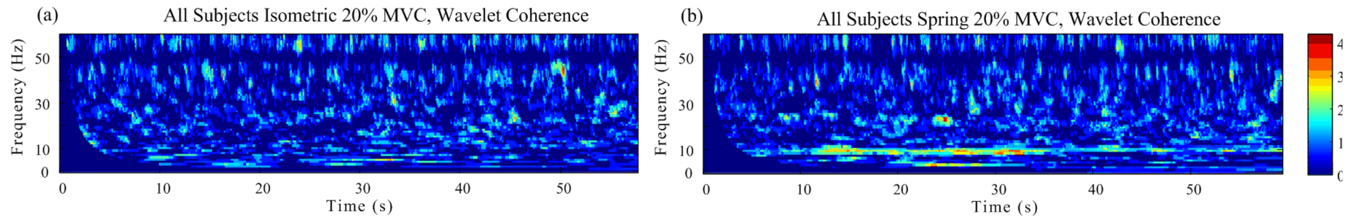


Figure 1. Wavelet coherence analysis plot summed across all subjects for isometric (a) and spring (b) condtitions show the temporal evolution of both the appearance of significant coherence and the strength of the EEG-EMG coupling for all frequencies.

EMG was recorded from the biceps brachii. The signal was amplified with a gain of 1000, band pass filtered with cut-off frequencies of 1 and 500 Hz and sampled at 1000Hz. EEG was recorded from the participants using a BrainVision™ 64-channel system, placed according to the 10-10 system montage. The EEG was digitized at 1000 Hz with an amplifier band-pass of 0.01-60 Hz together with a 50 Hz notch filter. The right mastoid (M1) was used as reference electrode and the M2 as ground.

B. Wavelet Coherence

The wavelet transform, $W_x(\tau, f)$, of a signal $x(u)$ is given by the convolution of the signal with a wavelet function and is a function of time (t) and frequency (f).. For this study the Morlet waveform $\Psi_{\tau,f}(u)$ was chosen, $\Psi_{\tau,f}(u)$ is the product of a sinusoidal wave of frequency (f), with a Gaussian function centered at time τ with standard deviation σ, inversely proportional to f.

$$W_x(\tau, f) = \int_{-\infty}^{+\infty} x(u).\Psi_{\tau,f}^{*}(u)du \tag{1}$$

In the wavelet coherence method, the length of the integration window decreases with increasing frequency, which improves the temporal resolution of the coherence estimate for higher frequencies. The parameters for selection are the number of cycles of the wavelet (n_{co} =10) and the number of cycles contained within the integration window (n_{cy} = 40). Confidence levels for the detection of significant coherence were calculated for these values of n_{co} and n_{cy} using surrogate white noise signals to compute the statistical thresholds [4]. Wavelet coherence was calculated between the right EMG muscle of the biceps brachii and 6 EEG electrodes on the contralateral side over the sensorimotor cortex (C3, C5, FC5, FC3, CP5 and CP3). Both isometric and spring conditions were investigated, at 20% MVC for each subject. For each frequency f, the width of the frequency interval measured is approximately equal to [f-4f/ n_{co} , f+4f/ n_{co}], with n_{co} determining the frequency resolution. The length of the integration window $\delta = n_{cy}/f$ also varies with frequency.

C. Partial Directed Coherence

Ordinary coherence analysis techniques focus on the mutual synchrony between the activity of two structures, and indicate very little about how these structures are functionally connected. The concept of Directed Coherence overcomes this limitation, allowing their interactions to be decomposed into “feedforward” and “feedback” aspects. The method of directed coherence can be expanded to multiple variables with the frequency domain method of Partial Directed Coherence [7]. (PDC) was therefore used here to examine the direction of information flow between the cortical signals and the contralateral muscle.

In order to assess Granger causality within a process of m different time series [$(x_1(t), x_2(t),\ldots x_m(t))^T$], the time series are first detrended to remove the mean value or linear trend so that they have approximately constant mean and variance. The time series are then modeled through a vector autoregressive (VAR) model of the form:

$$\begin{bmatrix} x_1(t)\\ \vdots \\ x_m(t)\end{bmatrix} = \sum_{r=1}^{p} A_r \begin{bmatrix} x_1(t-r)\\ \vdots\\ x_m(t-r)\end{bmatrix} + \begin{bmatrix}u_1(t)\\ \vdots \\ u_m(t)\end{bmatrix} \tag{2}$$

where [$(u_1(t), \ldots u_m(t))^T$] are uncorrelated Gaussian white noise processes representing the model residuals, with covariance matrix Σ. The VAR model’s order p represents the maximum temporal delay in the causal link between the modeled time series. The VAR coefficients A_r are $m\times m$ matrices, with each entry $A_r(ij)$ corresponding to the linear effect of x_j’s past value $x_j(t-r)$ on x_i’s present. The Fourier Transform is then performed on the matrix of VAR coefficients to produce a frequency-domain account of the VAR model. The PDC from time series x_j to x_i is defined as:

$$|\pi_{i\leftarrow j}(f)| = \frac{|\bar{A}_{ij}(f)|}{\sqrt{\sum_k |\bar{A}_{kj}(f)|^2}} \tag{3}$$

where $\bar{A}(f)$ is the difference between the identity matrix and $A(f)$ (i.e. $\bar{A}(f) = I - A(f)$). The PDC $\pi_{i\leftarrow j}(f)$ is zero for all frequencies only if $A_r(ij) = 0$ for all $r\in 1,2,\ldots,p$. An extended version of PDC is used in the analysis, information partial directed coherence (iPDC) [8], which uses information-theory formulations to explicitly define the relationship between information flow and PDC. This method provides an absolute signal scale invariant measure of direct connectivity strength between two structures as opposed to original and generalized PDC that provide only relative coupling assessments.

Initial investigations into the alpha band corticomuscular coherence analyzed 6 EEG data channels. In order to use smaller sample windows (8000 data points) and considerably reduce the computation time, the number of channels have to be reduced to 2 for the PDC calculations, The C5 and CP5 electrodes were selected because the most representative of somatosensory brain activity. The model order p must be set before VAR modeling of the time series takes place, p represents the delay of information transfer between the recorded brain or muscle regions. A model order of 200 was chosen for analysis, which equates to a time lag of 200ms. The null hypothesis of significant PDC was tested via its computed asymptotic statistical properties [8]. Directions of the interrelations between the left EEG and right EMG recorded were determined, with PDC values were calculated for windows of 8 seconds with a time step of 1 second. The sum of all partial directed coherences for both isometric and directions of information flow, in the low frequency (1-3Hz), alpha, beta, piper (40-50Hz) and gamma (30-60Hz) band. The sum of all significant coherence was calculated in the aforementioned frequency bands for each subject. The average value and standard deviation across all subject was determined. Statistical analysis between isometric and spring conditions for both the EEG→EMG and EMG→EEG directions was performed using a paired t-test (Fig. 3).

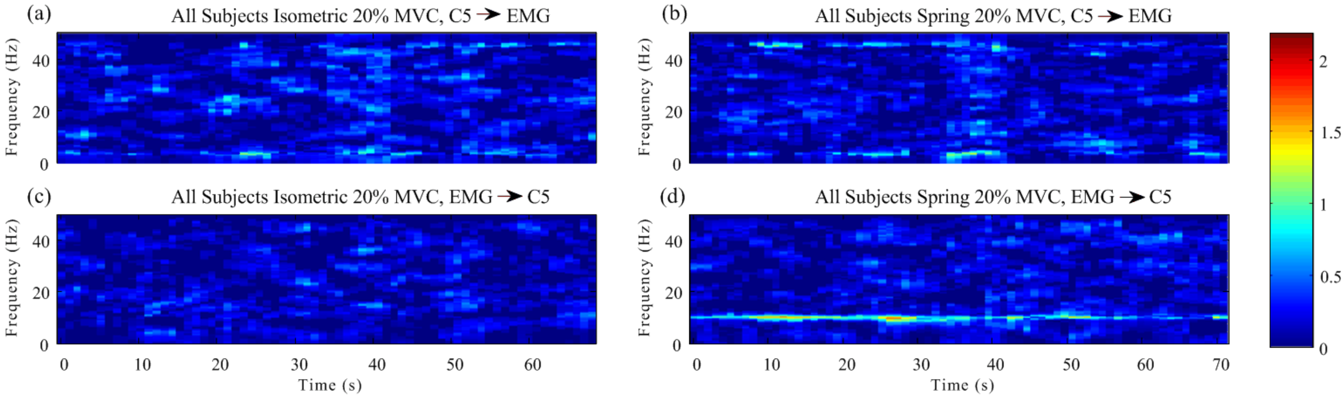


Figure 2. Partial directed coherence plots of summed coherence values across all 13 subjects shows the detection of significant information flow in the EEG→EMG direction (a & b) and the EMG→EEG direction (c & d) over time for isometric (a & c) and spring (b & d) conditions.

III. RESULTS

The results of the wavelet analysis summed across all subjects (Fig. 1) show a strong increase in alpha band corticomuscular coherence between the channel C5 and the EMG in the isometric and spring conditions. Results indicate that the mechanically induced corticomuscular coupling in the alpha band is not constant over the duration of the time series but appears and disappears intermittently, with no distinguishable pattern. From the wavelet analysis alone, it is not possible to differentiate whether the cortex imposes its oscillatory activity on the muscles via the corticospinal tract or whether the muscle activity is reflected in the cortex via sensory neurons, or a combination of both. In order to extend the analysis and determine the direction of information flow between EEG and EMG signals over time, the frequency domain approach of partial directed coherence was investigated.

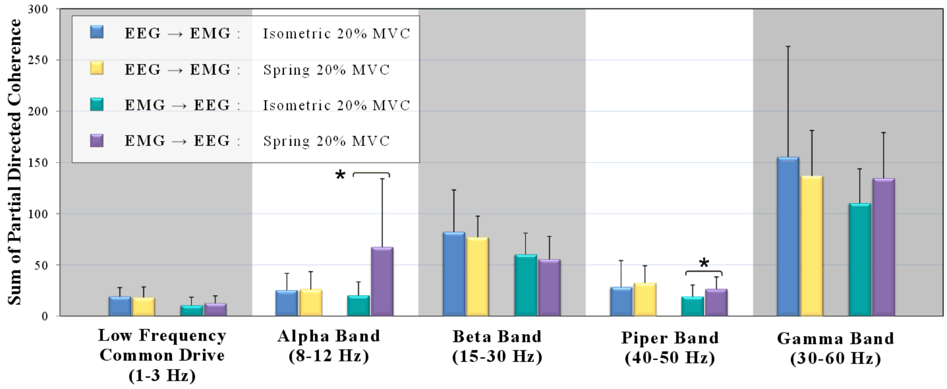
Significant PDC values were calculated for each subject in 1 second time steps and summed to show the collective PDC across all subjects (Fig. 2). Causal influences above threshold were detected in the EEG→EMG (a & b) and EMG→EEG direction (c & d) for two electrodes (only C3 electrode is pictured), for both isometric and spring conditions. A significant increase in alpha band coherence was observed from EMG→EEG with the addition of the spring (p = 0.0136). In the piper band, a significant increase in coherence is detected for EMG to EEG (p = 0.04695) direction. No significant increase was identified for the low frequency common drive, gamma band (30-60 Hz) or beta band (Fig. 3).

IV. DISCUSSION

Using wavelet analysis, the temporal evolution of corticomuscular alpha band coherence was investigated, and found to be present discontinuously over the duration of the recording (Fig. 1). In a study of patients with essential tremor, Raethjen et al. (2007) similarly found that corticomuscular coherence becomes insignificant intermittently, although reported the peripheral tremor retained approximately the same amplitude. They hypothesized that the recurrent loss in coherence may not necessarily reflect a complete lack of cortical contribution to the peripheral tremor, and may be explained by intermittent nonlinear corticomuscular interactions. Alternatively, this phenomenon could imply that phases with significant coherence mainly reflect cortical inputs from subcortical tremor generators. This may suggest that the alpha band corticomuscular coherence detected in this study is partially maintained through the reflection of spring induced synchronous activity in the contralateral somatosensory cortex via proprioceptive afferents. Further analysis with PDC appears to support the hypothesis that sensory feedback plays a more dominant role in maintaining alpha band corticomuscular coherence than centrally generated cortical drives.

Partial directed coherence offers additional insight into the functional significance of the alpha band corticomuscular coupling. The number of signals to be evaluated was reduced to two for the PDC calculations. The number of coefficients of the multivariate AR model is equal to k^2p (where k is the number of channels and p is the model order). This number must be several times smaller than the number of data points, which effectively limits the number of channels that may be simultaneously processed. In this study, a combination of linear and nonlinear processes was investigated, and a high model order was chosen in order to describe the nonlinear dynamics sufficiently well. The order of the fitted process should not be smaller than the true order, and the fluctuations in PDC introduced by a higher order are unproblematic in combination with a significance level. Partial directed coherence is a linear time series analysis technique, however, in most non-linear stochastic processes the dependence structure is reflected in the linear second order structure, so PDC has been observed empirically to be applicable in the case of weak nonlinearity [9]. This linear technique has shown superiority over non-linear techniques, such as phase dynamics modeling, when the nonlinear oscillatory structure of the dynamics is distorted significantly by the dynamical noise. The ability to detect nonlinear coupling is essential, as in many applications to brain neural networks the signals are at least weakly nonlinear. A significant directed influence from the muscle to cortex was more frequently detected than from cortex to muscle [10]. Statistical analysis on the PDC results revealed a significant increase in both alpha and piper band coherence in the EMG to EEG direction with the addition of the spring, with no significant increases in the EEG to EMG direction (Fig. 3).

Figure 2. Bar plot comparing average PDC values and standard deviation for each subject in the low frequency, alpha, beta, piper and gamma frequency bands. A significant increase in alpha band coherence was observed in the EMG to EEG direction with the addition of the spring (p = 0.0136). In the piper band, a significant increase in coherence is also detected for EMG to EEG (p = 0.04695) direction.



The increase in alpha band PDC from EMG to EEG could suggest that the spring-induced instability around the stretch reflex enhances afferent activity of the oscillating muscle spindle feedback loop to the extent that it overwhelms neural mechanisms that would minimize such oscillations under normal conditions. One of the potential neural circuits contributing to decorrelate alpha band activity in motoneuron firing is recurrent inhibition via Renshaw cells. Renshaw cells receive excitatory input from motoneurons and feedback inhibition to the same motoneuron pool. Williams et al. (2009) demonstrated that recurrent inhibition from spinal Renshaw cells could reduce 10 Hz components of motoneuron discharge, but suggested that they form only one component of the overall system [3]. The aforementioned study also revealed the generation of 30-40 Hz rhythms by Renshaw cell feedback loop resonance in a biophysically based computational model. It has also been shown that networks of inhibitory interneurons in the cortex can lead to synchronous oscillations in the gamma frequency band. It could be speculated therefore that the significant increase in the piper band corticomuscular coherence in the EMG to EEG could partially arise from the presence of Renshaw cell recurrent inhibition during mechanically induced tremor. The lack of a significant increase in alpha band PDC from EEG→EMG suggests that another neural circuit may be acting in this direction to filter ~10 Hz inputs to the motoneuron pool. Williams et al. (2010) hypothesized that excitatory spinal circuit interneurons also participate in reducing oscillations, by phase-inverting inputs to motoneurons. The convergence of antiphase activity from spinal motoneurons with descending oscillations from the cortex and subcortical centers will result in cancellation, diminishing the amplitude of oscillations transmitted to the periphery [11].

In conclusion, the results of this study support the hypothesis that the generation of alpha band corticomuscular coherence may arise partially through the reflection of muscle activity in the contralateral somatosensory cortex via proprioceptive afferents, and is not solely caused by the cortex imposing its oscillatory activity on muscle via the corticospinal tract [9]. Significant causal influences were transiently detected from the EEG to the contralateral EMG, indicating that the motor cortex does play a role in tremor generation. However, in this study, afferent feedback from the muscles to the cortex appears to play a more active part in the generation of tremor. The detection of increased alpha band corticomuscular coherence during mechanically induced tremor, in a previous study [5], may arise primarily due to the significant increase in information flow in the alpha band in the EMG to EEG direction. The lack of a similar significant increase in the EEG to EMG direction would support the suggestion that multiple neural systems exist that limit the motoneuron pool from synchronizing with the 10 Hz oscillations present in the cortical descending command.

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