Time–Frequency Modulation of ERD and EEG Coherence in Robot-Assisted Hand Performance

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Abstract A better understanding of cortical modifications related to movement preparation and execution after robot-assisted training could aid in refining rehabilitation therapy protocols for stroke patients. Electroencephalography (EEG) modifications of cortical activity in healthy subjects were evaluated using time–frequency event-related EEG and task-related coherence (TRCoh). Twenty-one channel EEG was recorded in eight subjects during protocols of active, passive, and imagined movements. The subjects performed robot-assisted tasks using the Bi-Manu-Track robot-assisted arm trainer. We applied time–frequency event-related synchronization/desynchronization (ERS/ERD) and TRCoh approaches to investigate where movement-related decreases in power were localized and to study the functional relationships between areas. Our results showed ERD of sensorimotor (SM) area over the contralateral side before the movement and bilateral ERD during execution of the movement. ERD during passive movements was similar in topography to that observed during voluntary movements, but without pre-movement components. No significant difference in time course ERD was observed among the three types of movement over the two SM areas. The TRCoh topography was similar for active and imagined movement; before passive movement, the frontal regions were uncoupled from the SM regions and did not contribute to task performance. This study suggests new perspectives for the evaluation of brain oscillatory activity and the neurological assessment of motor performance by means of quantitative EEG to better understand the planning and execution of movement.

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Introduction

With the knowledge gained from various different neurophysiological approaches to investigating motor and sensory cortical activity, we now have a better understanding of the neural underpinnings of movement execution and preparation in both healthy subjects and patients with neurological disorders. Among neurophysiological techniques, electroencephalography (EEG) allows for easy investigation of central nervous system activity during motor task performance.

Cortical activation related to movement preparation and execution has been the focus of interest in physiological studies. EEG oscillatory activity in alpha and beta bands

over the premotor and primary sensorimotor areas typically decreases in power during motor tasks (Chatrian et al. 1959; Pfurtscheller and Aranibar 1977). At the end of movement, a fast recovery of beta activity is found (Pfurtscheller et al. 1996, 1997, 1998) and can also be observed over the ipsilateral side (Stancák and Pfurtscheller 1996; Pfurtscheller et al. 1998). These phenomena were investigated extensively by Pfurtscheller, who introduced the terms "event-related desynchronization" (ERD) and "event-related synchronization" (ERS) to describe quantitatively the changes in EEG rhythms.

When a signal contains frequency components that emerge and vanish within certain time intervals, e.g., after a movement, time as well as frequency information is required. Accordingly, wavelet-based methods that can simultaneously describe EEG signal variation in time and frequency have been developed. There is increasing interest in the use of wavelet-based techniques for processing non-stationary EEG recordings not only with respect to oscillatory behavior (Samar et al. 1999) but also to evaluate the effects of a magnetic or electric stimulation (Manganotti et al. 2012, 2013; Formaggio et al. 2013a), and during EEG-functional magnetic resonance imaging co-registration (Storti et al. 2010; Formaggio et al. 2011). Because of the variety of reactive EEG frequencies, each exhibiting unique temporal and topographic patterns in association with functional brain activation, it is important to examine event-related changes in the time and frequency domains (Pfurtscheller and Lopes da Silva 1999). Voluntary movement produces alpha and beta ERD localized over the sensorimotor areas. This desynchronization starts about 2 s prior to movement onset over the contralateral primary sensorimotor area (SM1) and becomes bilaterally symmetrical immediately before the execution of movement.

Human EEG studies using coherence have attempted to clarify the functional connections between brain regions (Busk and Galbraith 1975; Sklar et al. 1972; Thatcher et al. 1986). Fourier analysis has been used extensively for studying the spectra of neurophysiological signals, particularly the correlated phenomena between two or more signals, such as synchronization between brain areas (Andrew and Pfurtscheller 1996; Shibata et al. 1998). Time–frequency coherence implementation provides a useful approach to investigating non-stationary signals, like EEG during movement, and allows for the analysis of dynamic coupling between different brain areas in relation to motor, sensory or cognitive events. Interpretation of functional coupling between brain regions can be inferred from the differences between different physiological conditions. In recent years, wavelet coherence analysis has been used to analyze EEG modifications after a cognitive task (Sun et al. 2003), in relation to electromyogram signal changes (Yang et al. 2010), elicited by visual stimulation

(Lachaux et al. 2002), in patients with schizophrenia (Sakkalis et al. 2006), and performing an isometric task (Saab et al. 2005).

The relationship between coherence and event-related changes in spectral power has been investigated in internally and externally paced (Gerloff et al. 1998; Rappelsberger et al. 1994), as well as in self-paced simple finger movements (Leocani et al. 1997). Gerloff et al. (1998) showed that simple internally and externally paced finger movements are associated with different patterns of functional coupling and regional activation of motor areas; in particular, coherence analysis suggested that the functional coupling of premotor and sensorimotor areas differs depending on the mode of pacing, with larger inter-regional coupling occurring during internally paced movements. Leocani et al. (1997) reported an increase in coherence over sensorimotor and frontal areas during the period of power decreases. Event-related coherence and phase coherence findings implicate the frontal lobes in the control of movement planning and execution. Using a task-related coherence, Manganotti et al. (1998) showed an active intercommunication between bilateral, mesial central, and prefrontal regions which became more intense as movement complexity increased.

In a previous study, we evaluated the changes in cortical activity during voluntary active movement, passive robot-assisted movement, and motor imagery performed under unimanual and bimanual protocols using Bi-Manu-Track (BMT) in eight healthy subjects (Formaggio et al. 2013b). In this study, voluntary active unilateral hand movement was observed to significantly activate the contralateral side; however, bilateral activation was noted in all subjects for both the unilateral and bilateral active tasks, as well as desynchronization of alpha and beta brain oscillations during the passive robot-assisted motor tasks. Finally, significant contralateral EEG desynchronization was observed during the unilateral motor imagery task which became bilateral during the bimanual task. The approach we adopted in this study, based on Fourier transform, is the most widely used to provide power spectral changes information (Formaggio et al. 2008; Manganotti et al. 1998), however, the time information is completely missing. Fourier transform, performed for the frequency analysis, provides quantitative information about the overall modifications of the power spectral bands in an averaged 2-s period during movement and suggests possible processes related to cortical oscillation activity. But because of its stationary assumption, it does not yield information about the time at which these modifications occur. Time–frequency analysis, instead, addresses this issue: monitoring the time course of spectral parameters adds to the information on the time interval at which a modification occurs. In studying functional relationships, coherence

analysis can reveal new aspects about brain activities which complement the data obtained by power spectral analysis. Accordingly, rather than using ERD and coherence measurements based on averaged spectra of a number of epochs of some seconds, here we applied a time–frequency method to estimate event-related EEG modifications and coherence between signals recorded from different locations within short time intervals.

The purpose of this study was to investigate the spatial–temporal patterns of task-related oscillatory brain activity during highly standardized motor performance provided by a robotic device, focusing on the evaluation of the time course of spectral parameters during the preparation and repetitive execution of the task. This represents a preliminary approach to the quantitative analysis of EEG signal during robot-assisted motor performance. Since it allows for evaluating the spatial–temporal modulation and the functional connectivity of brain oscillatory activity, this new approach could find use in stroke rehabilitation. In particular, this study highlights the possibility to analyze functional brain network reorganization after robot-assisted training in stroke patients with clinical impairments, i.e., hemiparesis, deafferentation and ideomotor apraxia, given that the cerebral network is particularly dynamic and can be modified by stroke lesions and by rehabilitation. The high temporal resolution of EEG, few milliseconds, allows to separate the assessment of brain activity related to movement preparation from movement execution; hence, evaluating the planning and the execution of movement in stroke patients could enhance our understanding of these phenomena and the role of the affected and unaffected hemisphere. Moreover, the assessment of changes in the functional activity of the brain could also aid in understanding the behavioral consequences of stroke. Coherence analysis of brain oscillations between different areas after robot-assisted training may provide new insights into the pathophysiology underlying neurological deficit and inform the planning of appropriate therapies.

Materials and Methods

We analyzed the same EEG dataset as discussed in Formaggio et al. (2013b), focusing the EEG analysis here on the time–frequency domain and on the functional coupling between cortical regions by means of EEG coherence analysis.

Subjects

The study sample was 8 right-handed (Oldfield 1971) healthy subjects [3 men and 5 women; mean age 26.38 years, standard deviation (SD) 2.62 years]. All subjects gave written informed consent to participate in the study in accordance with the Declaration of Helsinki. The study design and protocol were approved by the Local Ethics Committee of the Verona University Department and Hospital.

Experimental Setup and Motor Paradigm

Robot-assisted tasks were performed using the BMT robotic arm trainer (Reha-stim Co, Berlin, Germany) as in Formaggio et al. 2013b. We analyzed a subset of the motor conditions reported in our previous study, selecting sessions composed of protocols involving unimanual (right hand) active and passive movements and imagination of movement. During the session the subject sat a height-adjustable table with elbows bent at 90° and forearms in a mid position between pronation and supination in an arm trough. The BMT handle set has a vertical axis that enables wrist movement. The wrist continuously moved at the constant speed of 1 Hz (metronome paced) during activation condition (20 s). The range of motion was set to 20° dorsiflexion and 20° volarflexion of the wrist. Movement task started always in the same position performing a wrist flexion (first second of analysis) followed by an extension; at second 5 the subject was with the wrist flexed as at the beginning of the task. The protocols were delivered in random order across the subjects as described in Formaggio et al. 2013b. Six runs of rest alternating with six runs of execution were performed in each session (each run lasted 20 s).

EEG Data Analysis

The EEG data were acquired as described in Formaggio et al. (2013b) and processed in Matlab 7 (MathWorks, Natick, MA) using scripts based on EEGLAB (http://www.sccn.ucsd.edu/eeglab), as well as a dedicated home-made code created for this study. Visible artifacts in the EEG recordings (i.e., eye movements, cardiac activity, and scalp muscle contraction) were removed using an independent component analysis procedure.

The data were processed using an average reference. The EEG recordings were band-pass filtered from 1 to 30 Hz using a finite impulse response filter. Time–frequency power based on continuous wavelet transform (CWT) was computed for the six epochs of 15 s (10 s before and 5 s after the beginning of the movement, '0' indicates movement onset) and averaged among epochs. After discarding epochs with artifacts, an average of 5.6 epochs across all subjects for active and passive movement, and 5.7 for imagination of movement were considered in the analysis. The time course of ERD for the electrode x was computed according to:
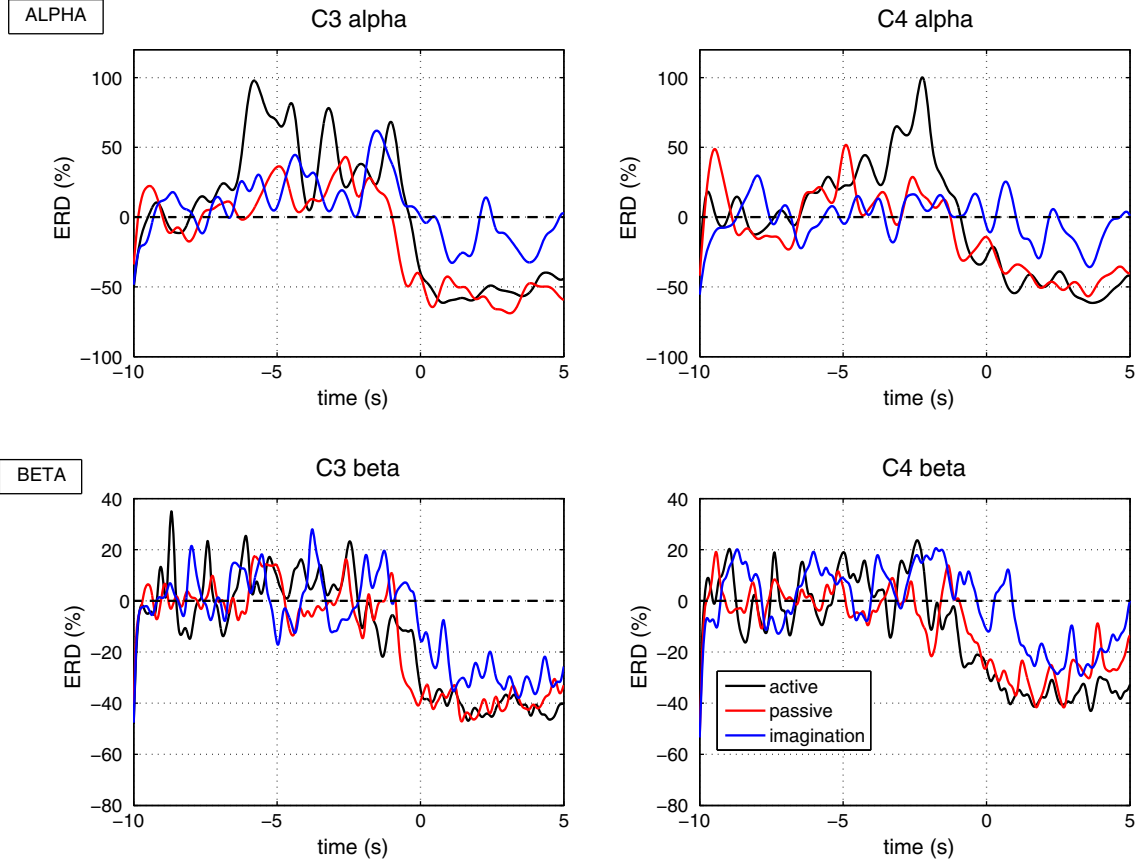
Fig. 1 Grand average of the ERD/ERS time course in the alpha and beta bands during active (*black*), passive (*red*) and imaged (*blue*) movements. '0' indicates movement onset (Color figure online)

$$ERD_x(\tau,f) = \frac{P_x activation(\tau,f) - P_x rest(\tau_0,f)}{P_x rest(\tau_0,f)} \times 100 \tag{1}$$

where $P_x rest(\tau_0, f)$ is an average power in reference time (epoch from -10 to -7 s before movement) (Fig. 1). In the physiological study of human motor control, alpha and central beta bands are mainly involved in the preparation and execution of movement (Leocani et al. 1997). Due to the large inter-individual differences of the alpha frequency, some portions of the alpha band power may fall outside a fixed frequency window. However, because movement preparation and execution produce ERD over the sensorimotor area at 10 and 20 Hz (Leocani et al. 1997) only the upper alpha (10–12 Hz) and beta (13–30 Hz) frequency ranges were analyzed.

Alpha and beta grand mean topographic maps showing the changes in ERD/ERS over time for all 8 subjects were computed. A paired sample two-tailed t test was computed to identify significant differences between ERD/ERS values and a reference condition, when the power computed at rest is equal to the power computed during the active condition. Then, two-dimensional grand mean t-maps were computed from the t-values to check the topographical distribution of the significance (t-maps were thresholded at $p < 0.05$, $|t| > 2.364$) (Formaggio et al. 2008). ANOVA for repeated measures was applied to alpha and beta ERD/ERS time course for all the channels with the factors "condition" (active, passive, and imagination of movement) and "time point" (number of time points in 15 s: 3,750). Post-hoc paired t test adjusted for multiple comparisons with Bonferroni method was used. Statistical significance was set at $p < 0.05$.

In order to study the relationship between two non-stationary processes, the time frequency coherence was computed using CWT, according to the equation:

$$Coh_{xy}^2(\tau,f) = \frac{\left|S_{xy}(\tau,f)\right|^2}{S_x(\tau,f)S_y(\tau,f)} \tag{2}$$

where

$$S_x(\tau,f) = \frac{1}{K}\sum_{k=1}^{K} |X_k(\tau,f)|^2 \tag{3}$$

4

$$S_y(\tau,f) = \frac{1}{K}\sum_{k=1}^{K}|Y_k(\tau,f)|^2 \tag{4}$$

$$S_{xy}(\tau,f) = \frac{1}{K}\sum_{k=1}^{K}\left|X_k(\tau,f)Y_k^*(\tau,f)\right|^2 \tag{5}$$

and K is the number of trials.

The two EEG channels contain a series of repeated trials $\{x_1(t)\ldots x_k(t)\}$ and $\{y_1(t)\ldots y_k(t)\}$ that are recorded simultaneously. In each trial, the time–frequency representations $X_k(\tau, f)$ and $Y_k(\tau, f)$ are calculated using CWT; their square magnitude $|X_k(\tau, f)|^2$ and $|Y_k(\tau, f)|^2$ as well as the cross spectrum $X_k(\tau, f)Y_k^*(\tau, f)$ are also calculated. After averaging across multiple trials, the estimates of auto spectra and cross spectrum are obtained and then an estimate of the time–frequency coherence is computed as in Eq. 2. Finally, task-related coherence (TRCoh) is obtained by subtracting the coherence values during rest ($Coh_{xy}rest$), an average coherence in reference time (epoch from -10 s to -7 s before movement), from the coherence values during the activation task ($Coh_{xy}activation$) according to the equation:

$$TRCoh(\tau,f) = Coh_{xy}activation(\tau,f) - Coh_{xy}rest(\tau_0,f). \tag{6}$$

Coherence decrements are expressed as negative values, while coherence increments are expressed as positive values. Increments or decrements in spatiotemporal EEG coherence between baseline and task conditions for electrode x vs. electrode y are displayed on the scalp maps as color-coded 'links' plots. Since all movements were performed with the right hand, EEG coherence is here documented for electrode C3 vs. the other eight electrodes (F3, Fz, F4, Cz, C4, P3, Pz, and P4). A paired sample two-tailed t-test was computed to identify significant differences between TRCoh values (C3 vs. all the electrodes) and a reference condition. Two-dimensional grand mean t-maps were computed from the t-values and thresholded at $p < 0.05$ ($|t| > 2.364$). ANOVA for repeated measures was conducted on the TRCoh time course values of the alpha and beta band (C3 vs. all the electrodes) with respect to the three different types of movement (factor "condition": active, passive, imagination). A post hoc paired t-test adjusted for multiple comparisons with Bonferroni method was used. Statistical significance was set at $p < 0.05$.

Results

Group Spatiotemporal EEG and TRCoh Patterns

ANOVA of the ERD time course showed a significant main effect for the factor "condition" only in F7 ($F(2,14) = 5.167$, $p < 0.05$), in alpha range. A post hoc t-test for paired samples showed significant differences between active and imagination (6 and 1 s before movement onset, at the beginning of the movement, and from 2 to 3 s after movement onset) and between passive and imagination (at the beginning of the movement and 3 s after it). No significant differences were found in C3 and C4 (Fig. 1), indicating comparable event-related power values for the three different movements.

The ANOVA results of the TRCoh time course (C3 vs. all the channels) showed significant differences for the three types of movements in F4 ($F(2,14) = 4.09$, $p < 0.05$) and Cz ($F(2,14) = 6.58$, $p < 0.01$) in alpha range; and in Fp2 ($F(2,14) = 7.066$, $p < 0.01$), F4 ($F(2,14) = 8.548$, $p < 0.01$) and C4 ($F(2,14) = 4.995$, $p < 0.05$) in beta range. Significant differences in time for the three types of movements were detected by the t-test (for time interval details, see Supplementary Material, Fig. 1).

Active Movement (Fig. 2)

During right hand movement, a marked alpha synchronization was observed from 5 to 3 s before movement, which was localized over Cz and became bilaterally distributed at 2 s and contralaterally at 1 s before movement. From 1 to 5 s after movement onset, ERD significantly decreased in a balanced way over the bilateral SM1 areas (C3 and C4). The synchronization pattern was less evident in beta range and localized more over the ipsilateral (C4) than over the contralateral side at -5 s. The ERD were significantly distributed bilaterally, over C3 and C4, from the beginning of movement, with predominance on C3 especially at 4 s after movement onset.

TRCoh increase in alpha range occurred in the frontal regions before the execution of movement; during movement, a TRCoh increase was also observed in the parietal regions (Pz and P4). The increment in the parietal regions was significant before movement (at 5 s) in P3 and Pz, at the beginning of movement (at 1 s) in P4, and during movement (at 4 and 5 s) in Pz and P4. A significant increase was also observed in Cz and C4 at 4 and 5 s after movement onset, respectively. The pattern of coherence between the two electrodes over motor areas (C3 and C4) was not well defined. There was an increase of coherence up to 3 s before movement; a non-significant decrease was observed 2 s before movement onset. During active movement, the increase was consistent throughout the time window analyzed, except for second 2 during movement. Focusing on beta band, a diffused slight TRCoh decrease was observed before movement; during movement, an increment of connection with the frontal and parietal electrodes was still present, especially with Fz and Pz. The increase was significant in P4 at 5 s before movement, in C4 at movement onset, and in Cz at 3 s during movement.
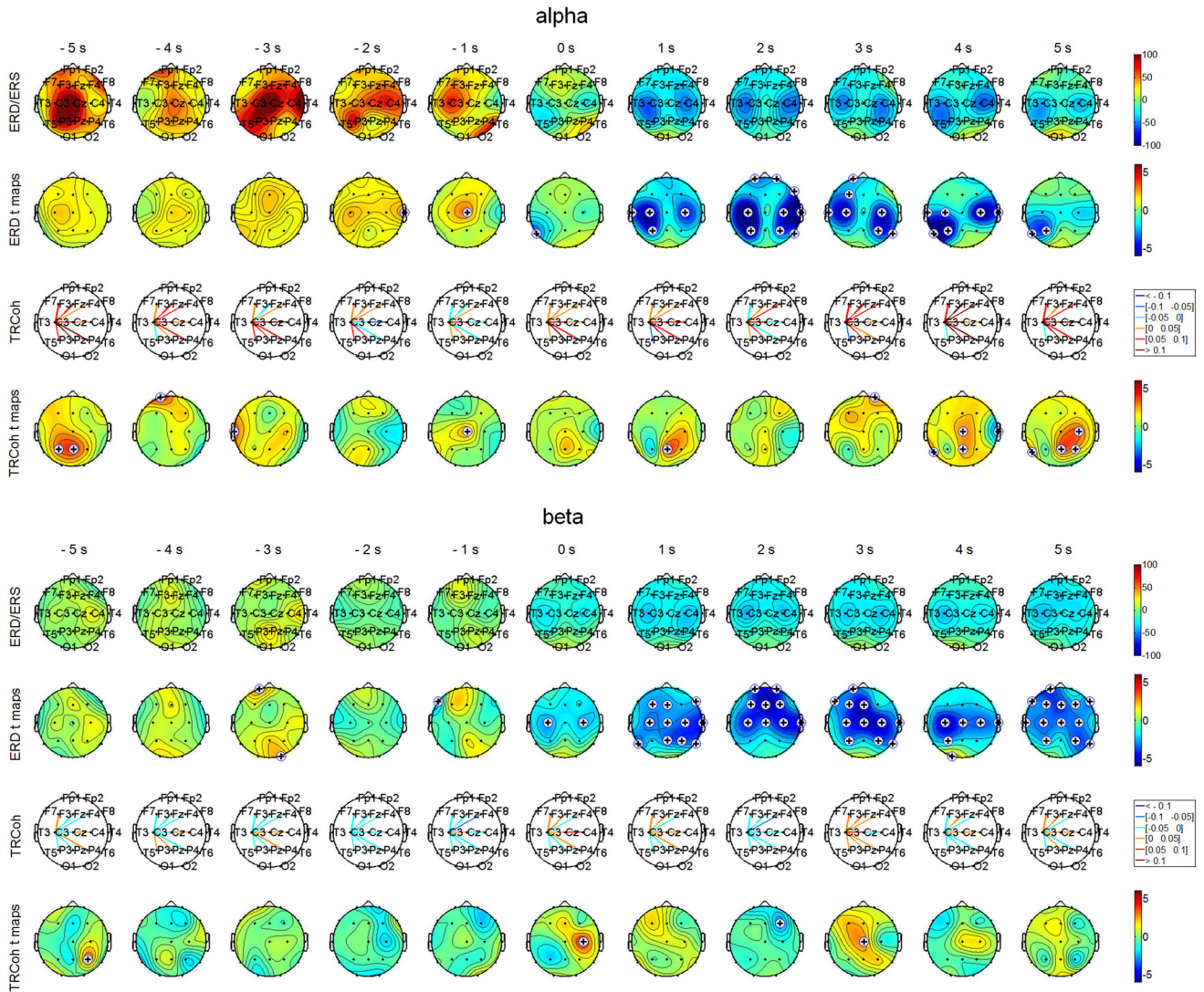
Fig. 2 Active movement. Grand average maps of ERD/ERS in alpha and beta bands. *Blue* color-coding indicates maximal ERD (power decrease). The *number* above each map indicates the time instant in seconds, '0' indicates movement onset. Grand average t-maps of ERD/ERS in alpha and beta bands thresholded at $p < 0.05$ ($|t| > 2.364$). Grand average TRCoh maps between C3 and F3, Fz, F4, Cz, C4, P3, Pz, P4 in alpha and beta bands. *Red lines* indicate coherence increase, *blue lines* coherence decrease. Grand average t-maps of TRCoh between C3 vs. all the electrodes in alpha and beta bands thresholded at $p < 0.05$ ($|t| > 2.364$). (+) indicates significance for $p < 0.05$ (Color figure online)

Robot-Assisted Passive Movement (Fig. 3)

During right-hand passive movement, significant alpha ERS was observed over C3 at -5 s, marked ERS over F3 and P4 at -5 s, and over the frontal area (F3 and Fz) from -3 to 0 s. Significant ERD was observed over C4 1 s before movement onset; it became contralateral at 0 s and bilateral during movement, with predominance on the contralateral side from 3 to 5 s. Differently from alpha range, the beta ERS pattern was less evident, with a predominance over contralateral SM1 and the ipsilateral frontal area at -5 s; desynchronization began at -2 s in the ipsilateral SM1 area and became bilateral at movement onset, with predominance over C3 from 2 to 5 s.

TRCoh increase with the frontal region was observed before movement and the increase persisted with the parietal electrodes (Pz and P4) particularly during movement; a coherence decrease with P4 and Pz was observed at 2 s after movement onset. A significant increase was observed at 5 s before movement onset in the contralateral regions (F4, C4 and P4) and during movement in the frontal regions (Fz, F3, F7). In beta range, increments were generally much less prominent than coherence decrements both before and during movement. A slight coherence increase with the frontal electrodes was observed from -2 to 0 s; the increment was significant at -4 s and at 3 s during movement. A decrease with ipsilateral frontal electrodes was predominant during movement. A slight
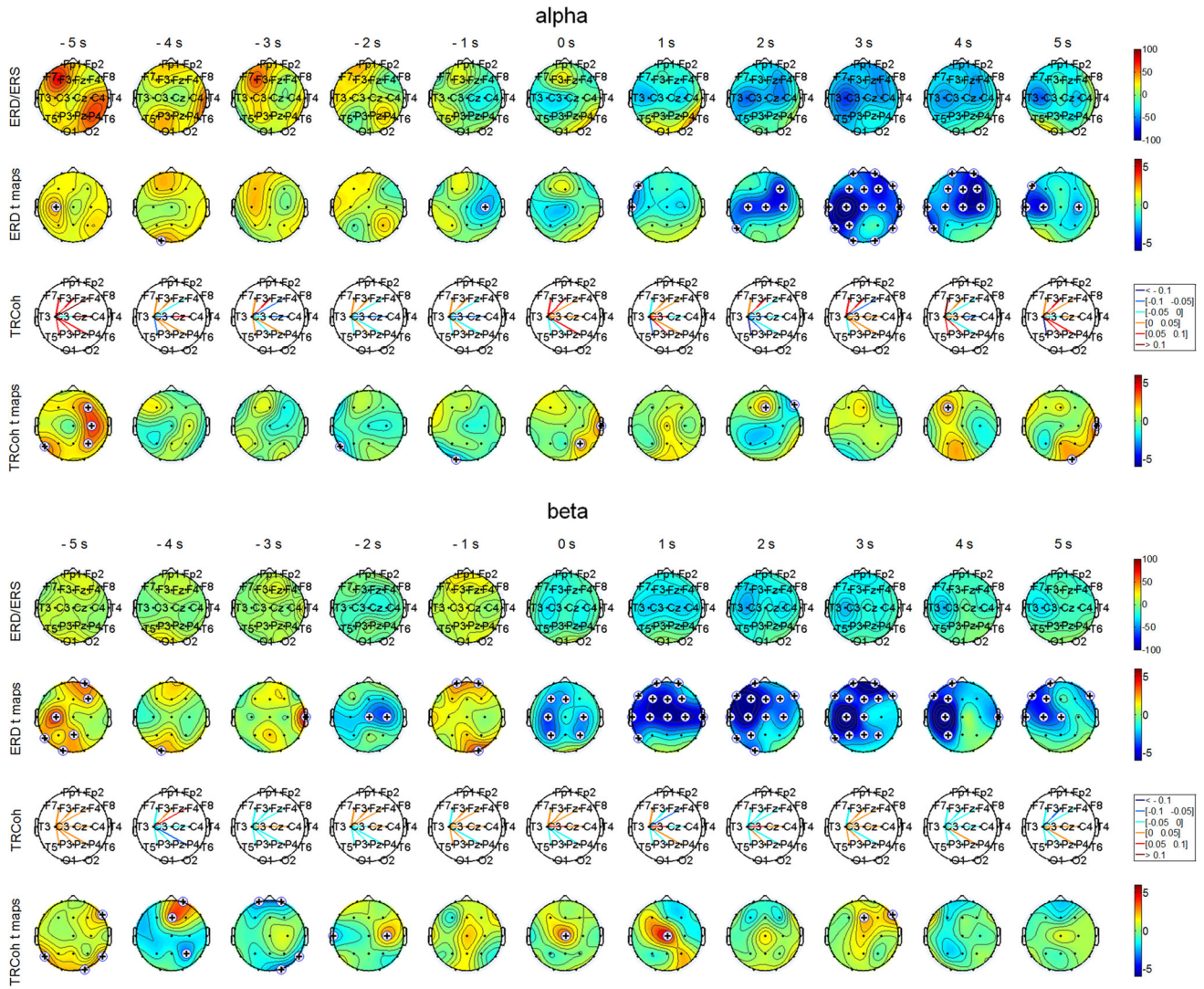
Fig. 3 Passive movement. Grand average maps of ERD/ERS in alpha and beta bands. *Blue* color-coding indicates maximal ERD (power decrease). The number above each map indicates the time instant in seconds, '0' indicates movement onset. Grand average t-maps of ERD/ERS in alpha and beta bands thresholded at $p < 0.05$ (|t| > 2.364). Grand average TRCoh maps between C3 and F3, Fz, F4, Cz, C4, P3, Pz, P4 in alpha and beta bands. *Red lines* indicate coherence increase, *blue lines* coherence decrease. Grand average t-maps of TRCoh between C3 vs. all the electrodes in alpha and beta bands thresholded at $p < 0.05$ (|t| > 2.364). (+) indicates significance for $p < 0.05$ (Color figure online)

TRCoh decrease between C3 and C4 was observed only during movement (at 1 s and at 4 s); a significant increase was observed in C4 at −2 s and in Cz at 0 and 1 s after the beginning of movement.

Imagination of Movement (Fig. 4)

During imagination of right-hand movement, significant alpha ERS over the contralateral SM1 was observed only at −1 s though a marked synchronization was present during the entire period of movement planning. The imagination of movement produced ERD over C3, which became significant after 4 s from the beginning of movement. Beta ERD was significantly localized over the contralateral central (C3) and parietal electrodes (P3 and T5) at 3 s before movement onset; beta ERS was observed over the central (Cz) and frontal (F4) electrodes 2 s prior to the imagination task. The imagination of movement produced contralateral ERD significantly localized over the central, parietal, and frontal electrodes from 1 to 4 s after movement onset.

The TRCoh topography was similar for active and imagined movement, however, coherence changes during the imagination task, as compared to the baseline, were higher especially during the imagination task. The increase in the parietal and occipital regions was significant after
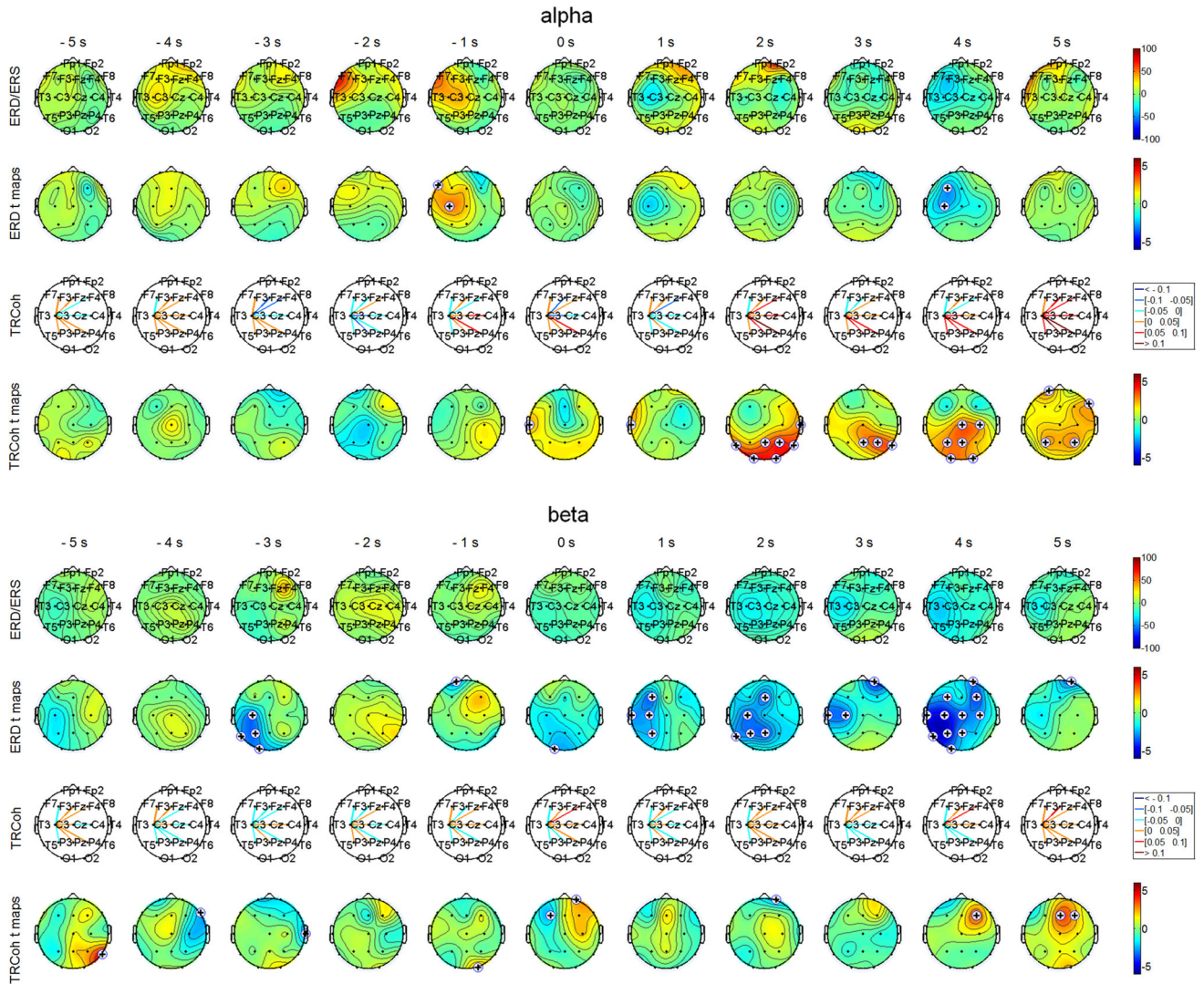
Fig. 4 Imagination of movement. Grand average maps of ERD/ERS in alpha and beta bands. *Blue* color-coding indicates maximal ERD (power decrease). The number above each map indicates the time instant in seconds, '0' indicates movement onset. Grand average t-maps of ERD/ERS in alpha and beta bands thresholded at $p < 0.05$ ($|t| > 2.364$). Grand average TRCoh maps between C3 and F3, Fz, F4, Cz, C4, P3, Pz, P4 in alpha and beta bands. *Red lines* indicate coherence increase, *blue lines* coherence decrease. Grand average t-maps of TRCoh between C3 vs. all the electrodes in alpha and beta bands thresholded at $p < 0.05$ ($|t| > 2.364$). (+) indicates significance for $p < 0.05$ (Color figure online)

movement onset; the link with the frontal regions decreased from 3 s before movement onset to 1 s after the beginning of the task. The coherence between the two motor areas decreased before and increased during the imagination task. Beta TRCoh decreased in the frontal and parietal regions from 3 to 1 s before the beginning of the task, but it significantly increased in the frontal regions from 4 to 5 s during the imagination of movement.

Discussion

This study evaluates the patterns of task-related oscillatory brain activity during a robot-assisted hand performance.

Starting from the same dataset as reported in Formaggio et al. 2013b, we focused the EEG analysis on the time–frequency domain and the functional coupling between cortical regions by means of EEG coherence analysis. In our previous study, the temporal modification in the EEG power was missing because we based the frequency analysis on Fourier transform. The present study reports for the first time temporal ERD and EEG coherence changes during different highly standardized robot-assisted tasks. This study suggests new perspectives for neurological assessment of motor performance. In particular, the evaluation of brain oscillatory activity by quantitative EEG could be useful to better understand the mechanisms concerning the planning and execution of movement, as

compared to controls (e.g., if the desynchronization is delayed or less strong) and the role of the affected hemisphere.

Our results showed bilateral ERD of SM1 area during unilateral active movement and predominant ERD over the contralateral side during passive movement and imagination of movement, confirming our previous results. A marked synchronization was observed before active movement, principally localized over Cz and C3, and before the imagination of movement over C3, whereas ERS during passive movement was localized over the contralateral frontal and ipsilateral parietal electrodes. A strong synchronization in the alpha range was also observed over the supplementary motor area (SMA) up to 3 s before the execution of active movement; a slighter ERS over SMA was also detected some seconds before the imagination of movement in the beta range. The involvement of the SMA in motor imagery, as previously reported in our EEG-fMRI study (Formaggio et al. 2010), was probably due to the complexity of the movement imagination task. These findings support the idea that active and kinesthetic experiences of movement share the same functional networks activated during movement planning, preparation, and execution. In this way, imagery could be an effective way to control alpha and beta rhythm amplitude, playing an important role in EEG-based communication (Brain Computer Interface).

During simple motor tasks, alpha desynchronization is found over the contralateral hand area during the preparation of movement and bilateral ERD over both hand areas during the execution of movement (Chatrian et al. 1959). Our results showed synchronization over the contralateral side before the movement and bilateral ERD during the execution of movement. A possible explanation for the bilateral activation during unilateral execution of movement observed in our study could be sought in the type of movement performed, as discussed in our previous study (Formaggio et al. 2013b). The flexor-extension of the wrist can be viewed as a more proximal task than movement of the fingers and proximal movements tend to bilaterally activate SM1 (Nirkko et al. 2001). The role of the wrist in upper limb movement can be considered postural to the extent that it stabilizes the wrist joint and allows the fingers to move. Bilateral activation could be due to the complexity of movement in relation to wrist flexion and the grasping of fingers over the device (joystick); indeed, bilateral activation can increase from simple to more complex performance also for distal finger movement, which is associated with an increase in event-related coherence between the two homologous areas (Manganotti et al. 1998).

Unilateral passive movement induced localized ERD over the contralateral SM1 area, with a scalp topography similar and even more localized, especially in the beta band, than the topography ERD produced during performance on the active motor task (Formaggio et al. 2013b). As reported in Alegre et al. (2002), beta ERD/ERS during passive movements was similar in topography to that observed during voluntary movements, but without pre-movement components. Comparing passive with active movement could be useful to understand the different effects they have on the central nervous system and, possibly, to plan specific treatments. A better understanding of cortical modifications after robot-assisted training could also aid in refining rehabilitation therapy protocols for stroke patients (Turner et al. 2013). The role of afferent input during passive movements and the induced synchronization of brain network is a matter of investigation not only as a model of cerebral functioning but as an intriguing area for clinical rehabilitative applications. Since the results of this study are preliminary, no solid conclusions can be drawn from comparison of the three types of movement. Nevertheless, no significant difference in time course ERD was observed among the three types of movement, especially over the two sensorimotor areas, underscoring the importance of passive and imagination of movement in the motor recovery process. However, this methodological approach can be easily performed in clinical practice and it could be advantageous to highlight the neural underpinnings of specific functional deficits not detectable in healthy subjects.

Connectivity has been investigated using coherence analysis in different tasks in healthy subjects and in numerous studies (see the review of van Wijk et al. 2012). Interhemispheric beta band coherence between motor areas arises during both unimanual and bimanual rhythmic movements (Gross et al. 2005; Mima et al. 2000) and increases with task complexity (Gerloff et al. 1998; Manganotti et al. 1998; Gross et al. 2005). Distinguishing between spontaneous movements and externally triggered movements represents a fundamental theoretical approach in neurological rehabilitation. This has been documented by several studies (Gerloff et al. 1998; Serrien 2008), which showed that coherence between sensorimotor cortex and mesial premotor areas is larger for internally compared to externally paced movements. In our study, we did not perform an internally paced movement; indeed, all types of movement are externally paced by rhythmic sound. What we did find was a clear difference in task-related coherence between active/imagination of movement and passive movement. The major difference between active and passive movement was an increase in the alpha functional links between C3 and both frontal/precentral and parietal regions before active movement compared to passive movement, and this link was not only limited to the preparatory phase but also persisted after movement onset.

This difference indicates that before passive movement, the frontal regions were uncoupled from the sensorimotor region and did not contribute to task performance. In the passive condition there was a less clear TRCoh increase with the frontal region before movement onset, while an increase persisted with the parietal electrodes, particularly during movement. The decrease in connectivity between SMA and the motor areas, as documented by the minor increase in coherence between the central and frontal regions, is not surprising, due to the no planning of the passive movement, in which SMA and frontal regions plays a principal role. Nonetheless, the role of posterior SMA in sensory feedback, as described in mirror movements (Mukamel et al. 2010), cannot be excluded. Planning of movement is instead present during the active and imagination task. Indeed, in these two conditions the pattern of coherence was similar and a TRCoh increase between the sensorimotor area and frontal region could be observed. A significant TRCoh increase was also noted between C3 and the central-parietal electrodes during the imagination of movement and during active movement.

If coherence increase could be interpreted as an inter-regional communication, then the coherence decrease should indicate a state of functional disconnection (Bullock 1992; Singer 1995). The previous finding of a coherence increase between contralateral SM1 and the frontal areas before a stimulus-triggered movement (Rappelsberger et al. 1994) is consistent with our findings, notwithstanding the different methods used for the calculation of coherence (Fourier transform). The preparation of movement is not primarily reflected by the ERD itself but more likely by the coherence increase between the frontal and central areas. The pattern of coherence between the two motor areas was not well defined in our results. In the active movement condition, a significant task-related coherence increase was observed only during movement (at 5 s), while the decrease was mainly found before movement onset. Because central mu-rhythms are generated by relatively independent generator systems in both hemispheres, resulting in a low interhemispheric coherence between C3 and C4 (Storm van Leeuwen et al. 1978), it is not surprising that interhemispheric coherence is low during rest and increased during movement. During passive movement, a significant alpha coherence increase was noted only several seconds before movement and a beta coherence increase 2 s before the task. Only alpha TRCoh significantly increased during imagination of movement (at 4 s). Significant TRCoh differences for the three types of movements were principally observed before the movement onset in F4 and Cz (alpha range); and in Fp2, F4 and C4 (beta range).

Regional activation, as reflected by the patterns of event-related power, and functional coupling, as reflected by event-related coherence, could work independently of each other. ERD/ERS and TRCoh topography were not identical, with a more anterior and posterior distribution of the coherence changes. This different behavior indicates that the activity of a cortical network can be modulated in two at least ways that could be partially independent: by increasing or decreasing activity at any region or by enhancing or suppressing functional coupling between any of the regions. The presence of coherence data suggests that the cortical areas work function in a network-like fashion and may use synchronization and desynchronization of cortical activity between regions. Task-related coherence and task-related power can diverge, i.e., during a motor task, the cortical network may modulate inter-regional coupling even without obvious changes in regional activation (Gerloff et al. 1998). The EEG desynchronization found over both sensorimotor areas is not accompanied by bilateral coherence, even if it would be reasonable to expect some functional interactions between sensorimotor areas. However, this different behavior demonstrates the independence of the neural circuits responsible for generating these sensorimotor rhythms in the left and right hemispheres (Andrew and Pfurtscheller 1996).

The coupling between regions could represent an expression of functional connectivity during a motor or cognitive task. Investigation of brain oscillations during highly standardized robotic passive movement represents the main finding of the study. Specifically, the coherence between the two time series is modulated by passive rhythmic and regular execution. This reveals the importance of the afferent proprioceptive system in eliciting a synchronous network and not only a simple and focal activation, as documented by neuroimaging (Boscolo Galazzo et al. 2013) and electrophysiological (Formaggio et al. 2013b) studies.

The results of this study are preliminary. Further investigations on larger populations are needed to generalize the results so as to have clinical implications. Nonetheless, our data do add important insights into the patterns of oscillatory activity during robot-assisted motor performance and indicate the potential this new approach to analysis holds in the evaluation of cortical oscillatory activity time changes in neurological patients presenting with either motor or sensitive deficit due to lesions in motor control systems. The neurophysiological evaluation, performed using power spectra and functional connectivity analysis, may be relevant for studying the mechanisms of brain plasticity and recovery after brain injury or induced by rehabilitation treatments and for investigating specific disorders of motor planning. Moreover, time frequency ERD and task-related coherence offer a new opportunity to study the relationship and interaction between different

cortical areas in time and yield additional information about brain dynamics.

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