Quantitative EEG Evaluation During Robot-Assisted Foot Movement

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***Abstract*— Passive and imagined limb movements induce changes in cerebral oscillatory activity. Central modulatory effects play a role in plastic changes, and are of uttermost importance in rehabilitation. This has extensively been studied for upper limb, but less is known for lower limb. The aim of this study is to investigate the topographical distribution of event-related desynchronization/synchronization (ERD/ERS) and task-related coherence during a robot-assisted and a motor imagery task of lower limb in healthy subjects to inform rehabilitation paradigms. 32-channels electroencephalogram (EEG) was recorded in twenty-one healthy right footed and handed subjects during a robot-assisted single-joint cyclic right ankle movement performed by the BTS ANYMOV robotic hospital bed. Data were acquired with a block protocol for passive and imagined movement at a frequency of 0.2 Hz. ERD/ERS and task related coherence were calculated in alpha1 (8–10 Hz), alpha2 (10.5–12.5 Hz) and beta (13–30 Hz) frequency ranges. During passive movement, alpha2 rhythm desynchronized over C3 and ipsilateral frontal areas (F4, FC2, FC6); beta ERD was detected over the bilateral motor areas (Cz, C3, C4). During motor imagery, a significant desynchronization was evident for alpha1 over contralateral sensorimotor cortex (C3), for alpha2 over bilateral motor areas (C3 and C4), and for beta over central scalp areas. Task-related coherence decreased during passive movement in alpha2 band between contralateral central area (C3, CP5, CP1, P3) and ipsilateral frontal area (F8, FC6, T8); beta band coherence decreased between C3-C4 electrodes, and increased between C3-Cz. These data contribute to the understanding of oscillatory activity and functional neuronal interactions during lower limb robot-assisted motor performance. The final output of this line of research is to inform the design and development of neurorehabilitation protocols.**

***Index Terms*— Electroencephalogram (EEG) event-related synchronization/desynchronization, EEG task-related coherence, motor imagery, rehabilitation robotics.**

I. INTRODUCTION

ROBOTIC rehabilitation aims at improving impaired motor function due to central nervous system (CNS) lesion. It is based on the theoretical framework of neural plasticity, according to which stereotypy and high frequency of movements of the affected limb promote synaptic plasticity both in humans [1] and in animal models [2]. Robotic rehabilitation is highly repeatable and intense, and offers a quantitative evaluation of the subjects outcomes, since the mechatronic devices have built-in sensors that measure kinematic and pressure parameters. Robot assisted training generates more complex, controlled and multi-sensory stimulations than standard physiotherapy, that mimic the complexity of the input sensorimotor of natural movements. Nonetheless, robotics can only provide task-specific training: translation into functional activity can only take place with the intervention of therapists, for whom robotics is a tool to achieve a higher level of functioning of the client.

Robots for lower limb (LL) mobilization are electromechanical devices that facilitate recovery of standing and walking. They can be divided into two broad categories: gait trainers, which aim at recovering walking patterns, being either exoskeletons (e.g., EKSO, developed by Ekso Bionics, Richmond, CA, USA) or suspension devices (e.g., LOKOMAT, developed by Hocoma, Zurich, Switzerland), and robotic devices that mobilize specific lower limb joints (e.g., the Rutgers ankle robot, developed by State University, New Jersey, USA). Recent attempts have been made to merge the two components, coupling the concept of walk training with that of passive joint mobilization (ANYMOV robotic bed, BTS Bioengineering, Milan, Italy). The compresence of the two training modalities should ideally cover the rehabilitation needs from the very acute phase to successive steps of recovery.

Changes of brain activity during passive, active and imagined movements have been extensively studied with techniques ranging from functional magnetic resonance imaging (fMRI) [3]–[5], positron emission tomography (PET) [6], [7], near-infrared spectroscopy (NIRS) [8], to magnetoencephalography (MEG) [9], [10], electroencephalogram (EEG) [11] and EEG-fMRI co-registration [12]–[14]. EEG alpha and beta band powers decrease during motor execution over the premotor and primary sensorimotor cortex [11], [15]. At conclusion of the motor task, beta displays a rebound of activity over the same contralateral [16] and ipsilateral areas [7]. These frequency changes were named respectively event-related desynchronization (ERD)—i.e., power band decrease—and event-related synchronization (ERS)—i.e., power band increase [16]. Similar activation patterns were described for passive and imagined movement [18], [19].

Functional connectivity between brain regions describes the interactions between differently organized cortical regions,

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reflecting dynamics of information flow. Functional connections remodel after a brain lesion and subsequent recovery. The coherence function can be used to estimate the synchronization between two signals at a particular frequency, interpreted as characteristic of brain network organization. The significance of functional coupling between brain regions can be inferred from differences between physiological conditions. Task-related coherence [20] allows to investigate the functional modifications produced by a motor task, by comparing resting coherence with coherence during the task. In the upper limb (UL), internally and externally paced finger movements are associated with different patterns of functional coupling and regional activation of motor areas [21], with mode of pacing shaping functional coupling of premotor and sensorimotor areas—e.g., larger inter-regional coupling occurring during internally paced movements [22]. No data have been reported up to now on task-related coherence of LL movements.

EEG cortical activity associated with robot-assisted therapy is a growing research field. Cortical activity during robot-assisted UL tasks has been described [23]–[28]. In recent studies, EEG changes and brain connectivity modifications during motor robot-assisted UL tasks were quantified in healthy subjects [25], [26], stressing high similarity of neural activations during active, passive, and imagined movement. EEG can be also used to quantify the effectiveness of a rehabilitative treatment and the reorganization following cerebral stroke [27].

Mainly due to anatomical reasons, the majority of neurophysiological and neuroimaging research on robotic rehabilitation and its neural correlates focused on UL. There is little knowledge of the neural mechanisms underlying lower limb functional recovery and the impact of LL robot-assisted therapy on neuroplasticity [29]–[31]. A recent study [29] compared the ERD patterns during active movement, passive movement and functional electric stimulation (FES)-induced movement of the lower limb in twenty healthy subjects and in one hemiplegic stroke patient, describing a substantial similarity between the FES-induced activation and that of active movement. In a MEG study [31], patterns of beta activity during active and passive ankle dorsiflexion appeared similar, leading the authors to hypothesize that passive motion provides somatosensory afferences that are processed as for voluntary control.

The focus of our research is the implementation of better neurorehabilitation paradigms, endowing robotic training. Our focus thus shifts from that of main research on ERD/ERS, mainly interested in detecting brain signals to transduce them into Brain Computer Interface devices. The study of brain oscillatory activity, both in terms of areas generating the signal and of the interactions of them into a functional network—as defined by functional coherence—is a new field in neurorehabilitation, despite the substantial role this information could play. Seminal studies in the area of neuronal reorganization after stroke by neuroimaging [3], [32] have only later on been paralleled by studies trying to explain how the neurophysiological activity of the brain changes after an insult [33]. This literature, while arising the attention to the potential plastic changes of the brain, did not generate a direct input to research which rehabilitation methods could better boost recovery.

The aim of this research is to investigate the topographical distribution of ERD/ERS and task-related coherence during a robot-assisted and a motor imagery task of lower limb in a sample of healthy subjects. The results may be relevant for defining a baseline in future studies on the neural correlates changes after robot-assisted training in people with CNS lesions, and to identify which type of assistance is optimal for inducing neuroplasticity. The final output of this line of research is to inform the design and development of more efficient rehabilitation protocols.

II. METHODS

A. Subjects

The study sample was 21 right-handed [34] and right-footed (Waterloo Handedness Questionnaire [35]) healthy subjects (9 men and 12 women; mean age 45.14 years, standard deviation [SD] 14 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 Padova University and Hospital (protocol n.AOP0422, 13/07/2015)

B. Experimental Protocol

Robot-assisted single-joint cyclic ankle movements were performed by the BTS ANYMOV robotic hospital bed (BTS Bioengineering, Milan, Italy) (Fig. 1 A). BTS ANYMOV is the first robotic platform for intensive and targeted rehabilitation therapy during acute and sub-acute phases of illness. It allows early passive, continuous and segmental mobilization of patient directly from the hospital bed.

BTS ANYMOV is divided into four moving sections controlled by 13 high precision engines: the bed base is adjustable and moves upwards and sideways thanks to its telescopic columns; the back support can recline up to 90° allowing complete subject verticalization. Its two distal sections for lower extremities allow hip abduction/adduction. Dorsi-plantar flexion of tibio-tarsal joints and knee flexion-extension movements are assisted by two dedicated engines placed in the lower limbs support section (Fig. 1 B). Frequency of each movement of hip, knee, and ankle can be adjusted setting the proper number of repetitions and speed through the built-in touchpad.

During the session the right foot passive dorsi-plantar flexion was performed using the robot-assisted single-joint cyclic ankle movement of the BTS ANYMOV. The ankle movement was set to the maximum range of motion, that is 15° of dorsiflexion and 30° of plantar-flexion (Fig. 1 C). The frequency of the cyclic ankle movement (starting from plantar flexion toward dorsiflexion and return to plantar flexion) was 0.2 Hz (12 repetitions of cycle/min). During the run of execution, four repetitions of the cyclic task were performed.

The motor paradigm was recorded during a single experimental session including right foot passive dorsi-plantar flexion (BTS ANYMOV) and movement imagination (motor imagery) of the same movement. Six runs of rest alternating

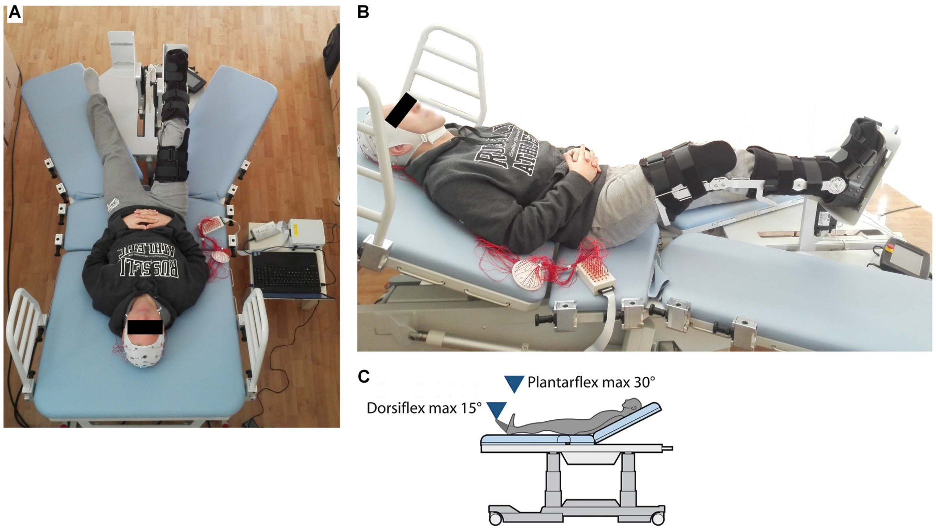

Fig. 1. BTS ANYMOV robotic bed and EEG system.

with six runs of execution were performed in each session 20 sNrun). Task execution was acoustically paced with a metronome at a frequency of 0.2 Hz. The metronome ticking continued during activation and rest blocks to keep the sensory input constant. To perform the task correctly, each subject was trained for several minutes before the experiment. During the passive movement task, the subjects were instructed to keep their eyes open, to avoid blinking, and to look at a stationary point positioned 2 m away from them. During the motor imagery task, the subjects were instructed to keep their eyes closed to avoid external distractors, and to start and stop the imagination task at the experimenters acoustic signal. They were asked to imagine the kinesthetic experience of passively performed movement, avoiding any visualization or muscle contraction [36]. Before each recording, the subjects were asked to relax for 1 min.

C. EEG Data Acquisition and Analysis

EEG signal (32-channels EEG system; BrainAmp 32MRplus, BrainProducts GmbH, Munich, Germany) was continuously acquired during passive and imagined lower limb movements (Fig. 1). The EEG data were acquired at a sampling rate of 500 Hz, with the reference between Fz and Cz and the ground anterior to Fz positioned according to a 10/20 system, band pass-filtered at 0.1–1000 Hz and digitized. Electromyographic (EMG) signal from the ipsilateral tibialis anterior muscle was acquired through a polygraphic recording, positioning two pre-gelled electrodes over the muscle belly (recording electrode) and on the head of the fibula (band-pass filter 50 Hz−1 kHz).

The data were processed in Matlab 7 (MathWorks, Natick, MA, USA) using scripts based on EEGLAB toolbox [37], as well as a dedicated home-made code created for this study. The EEG recordings were band-pass filtered from 1 to 30 Hz using a finite impulse response (FIR) filter. Visible artifacts (i.e., eyes movements, cardiac activity, and scalp muscle contraction) were removed using an independent component analysis procedure, and data were processed using a common average reference. The EEG data of each rest and active run (20 s each) were divided into 10 epochs of 2 s. A fast Fourier transform (FFT) was applied to non-overlapping epochs and then averaged across epochs under the same conditions. The recordings were Hamming-windowed to control for spectral leakage. Power spectral density was estimated in alpha1 (8–10 Hz), alpha2 (10.5–12.5 Hz) and beta (13–30 Hz) frequency ranges. An accepted ERD/ERS procedure was used to quantify the event-related relative changes in EEG power [11]. The ERD/ERS transformation was defined as the percentage decrease/increase of power density during the task with respect to the baseline value (rest condition). Alpha and beta topographic maps showing the ERD/ERS changes for each subject and grand average topographic maps were computed.

A paired sample two-tailed t-test was performed for identifying significant differences between the alpha and beta ERD/ERS values and a reference condition, when the power computed at rest is equal to the power computed during the active condition. T-maps were represented to detect the topographical distribution of the significance (the t-maps were thresholded at $p < 0.00001$ for both tasks).

To study the relationship between active and resting state, the coherence was computed using FFT. After averaging across epochs, the estimates of auto spectra and cross spectrum were obtained and an estimate of the coherence was computed in alpha1 (8–10 Hz), alpha2 (10.5–12.5 Hz) and beta (13–30 Hz) frequency ranges. Lastly, task-related coherence (TRCoh) [20], [38] was obtained by subtracting the coherence values during rest from the coherence values during the task. A paired-sample two-tailed t-test was computed to identify significant differences between TRCoh values and a reference condition. T-maps were then computed from the t-values and thresholded at $p < 0.01$.

III. RESULTS

A. ERD/ERS (Fig. 2)

During right foot passive robotic-driven movement, alpha1 and alpha2 ERD localized over the contralateral motor cortical region (C3) and beta ERD over C3 and C4.

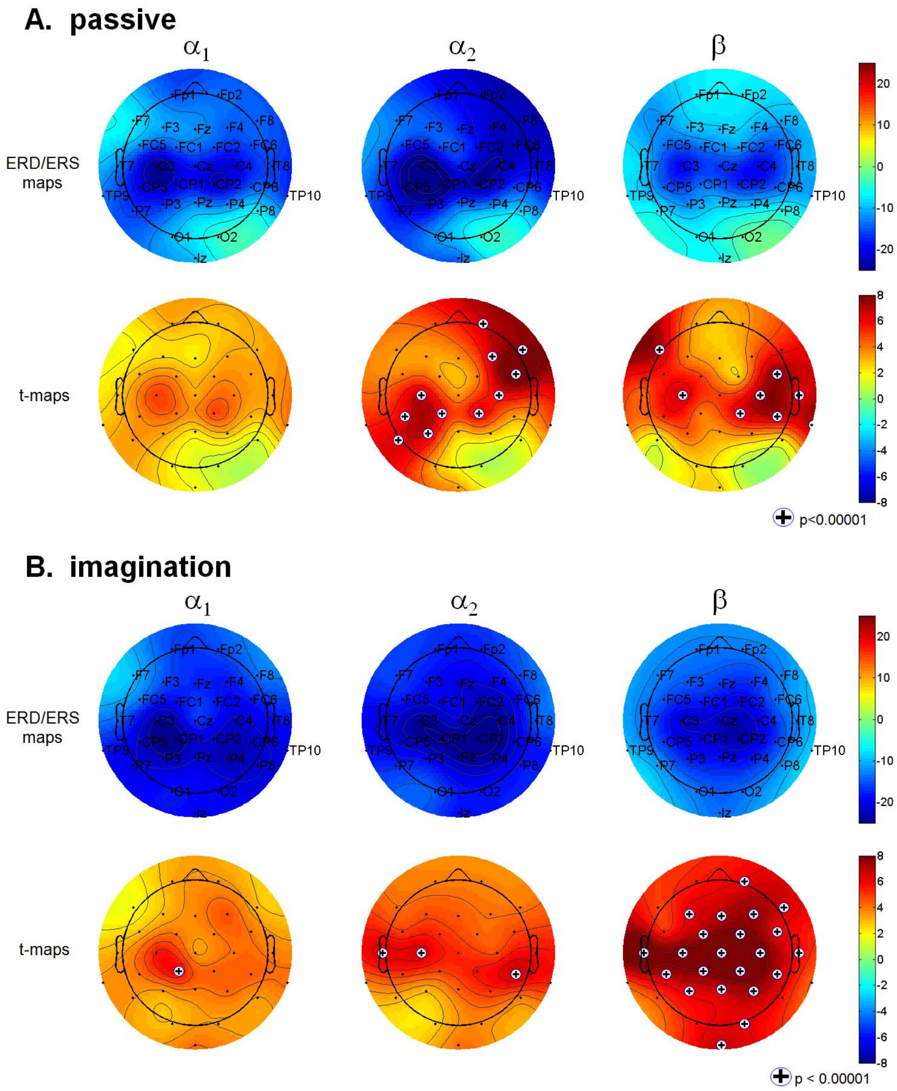

Fig. 2. Grand-average event-related desynchronization/synchronization (ERD/ERS) topographies for the 21 subjects during passive (A) and imagination of movement (B) in alpha1, alpha2 and beta bands. Event-related power decreases, that represent a decrease in synchrony of the underlying neuronal populations and indicate cortical activation state, are expressed as negative values. Event-related power increases indicating a cortical idling state were expressed as positive values. Blue color coding indicates maximal ERD (%). T-maps derived from the paired sample t-test applied on ERD/ERS data [thresholded at $p < 0.00001$ for passive and motor imagery task (+)].

During motor imagery, alpha1 and alpha2 desynchronized ove C3 and C4 with predominance on the contralateral motor area, and beta over central scalp areas.

T-maps of the passive condition showed a significant desynchronization of alpha2 over the contralateral motor area and the ipsilateral frontal area (Fp2, F8, F4, FC6, FC2, T8); beta desynchronized over the bilateral side ($p < 0.00001$).

During motor imagery, a significant desynchronization was evident over CP1 for alpha1, bilaterally over C3, T7 and CP6 for alpha2, and over central scalp areas for beta ($p < 0.00001$).

B. Task-Related Coherence (Fig. 3)

Right foot passive movement produced a significant coherence decrease during movement in alpha2 band between left central area (C3, CP5, and CP1) and right frontal (F4, F8, Fp2, FC2) and left parietal areas (P3) ($p < 0.01$). A significant beta coherence increase occurred between C3-Cz electrodes, while a decrease occurred between C3-C4 and C3-P3 electrodes.

During the imagination task, no relevant and significant task-related coherence was detected.

IV. DISCUSSION

This study reports the results of a quantitative evaluation of brain activity during robot-assisted cyclic ankle movements. Data on event related synchronization and desynchronization were obtained, and task related coherence analysis revealed the pattern of interaction of brain areas during a lower limb task.

During right foot robotically-driven passive dorsi-flexion we observed ERD in the upper alpha (mu) band over C3 and ipsilateral frontal area (F4, FC2, FC6); beta ERD was detected over the bilateral motor areas (Cz, C3, C4). During motor imagery of the same movement, beta ERD was prominent over central scalp areas. Task-related coherence showed significant difference only during the passive task.

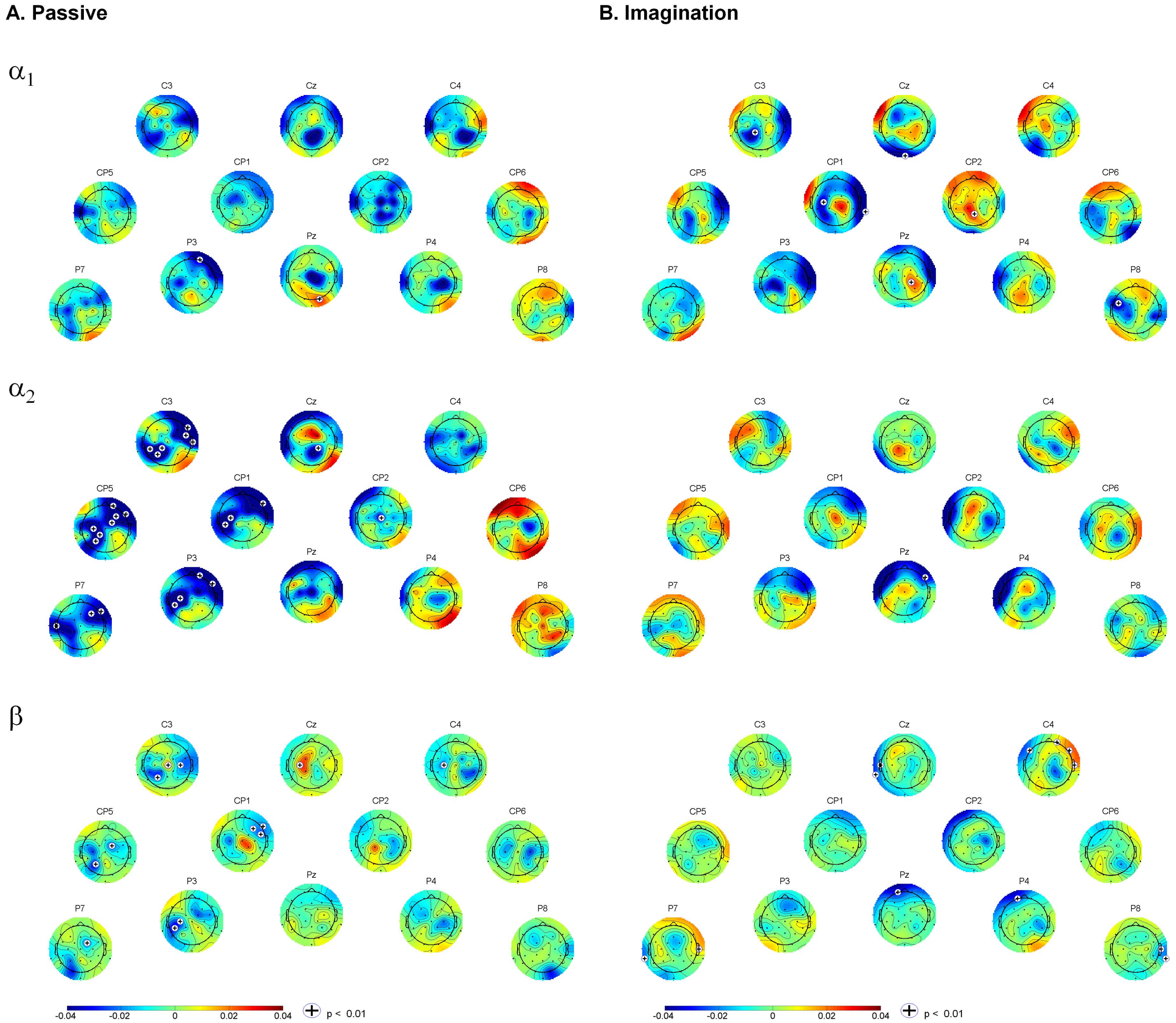

Fig. 3. Task-related coherence maps during passive movement with BTS ANYMOV (A) and during imagination of movement (B)(+) indicates significance for $p < 0.01$. At each electrode position we place a small circle also representing the scalp and containing the task-related coherence maps of the respective electrode (C3, Cz, C4, CP5, CP1, CP3, CP4, P7, P3, Pz, P4, P8) with all other electrodes. The value at each electrode pair represents the average coherence in alpha1 (8–10 Hz), alpha2 (10.5–12.5 Hz) and beta (13–30 Hz) frequency ranges.

Alpha2 coupling between contralateral central areas (C3, CP5, CP1, P3) and ipsilateral frontal areas (F8, FC6, T8) decreased during movement; beta coherence decreased between C3-C4 electrodes, and increased between Cz-C3.

Cortical activation of the motor cortex is signaled by alpha ERD [39], but the processing of somatosensory afferent input [40], prevalent in the beta band, also plays an important role.

Passive movement produces clear-cut modifications in oscillatory activity both in upper and lower limb [41], [42]. Beta (15–30 Hz) and mu rhythm (alpha2, 10–12 Hz) are the primary involved frequencies. They are physiological oscillations over the motor (mu band) and sensory-motor (beta band) cortices. Mu and lower beta band ERD have been observed over the primary lower limb representation cortex during foot movements [39]. Mu oscillation has also a characteristic reactivity to motor imagery [39], [43], [44], localized mainly in the post-Rolandic somatosensory area.

The function specificity of those rhythms explains ERD distribution during passive movement: mu ERD localizes over the contralateral central-posterior areas, corresponding to the motor cortex, and the ipsilateral prefrontal cortex. Beta ERD has a more widespread, lateralized distribution, encompassing the somatosensory cortices.

Our data match results derived from fMRI [45] and MEG [31] studies on cortical activations during passive ankle dorsi-flexion: a contralateral activation of the primary motor area (M1) couples with a bilateral activation of the primary and secondary sensory cortices (S1 and S2) detected as blood oxygenation level dependent (BOLD) activation or source localization.

A novel finding is the activation of ipsilateral frontal cortex: this could be related to the rhythmicity of the robot-assisted movement and its relation with the gait cycle. Ankle dorsiflexion is endowed in the gait cycle, and used as proxy for gait in experimental settings. Preparation of gait-related movements shows BOLD activation over the anterior prefrontal cortex, as during the preparation of cued ankle flexion-extension [46]. EEG modifications occur over the ipsilateral supplementary motor area and M1 at gait initiation [47], and NIRS shows activation of the prefrontal, premotor and primary sensorimotor cortex (SM1) in human locomotion [48], [49]. The concomitant desynchronization, prevalent in the mu band, that we observe over the ipsilateral frontal cortex is likely to represent the preparatory activity of the contralateral leg in the physiological rhythmic gait cycle.

During the passive task, beta ERD distributed bilaterally over C3 and C4, reflecting the reverberation of sensory inputs from the thalamic rel to cortical sensory areas, with a consistent drive to the ipsilateral parietal cortex.

Motor imagery induced a widespread beta band desynchronization over the central areas. The predominance of beta oscillations rests on the fact that this frequency band constitutes the neural substrate of sustained attention, as well as the tendency to maintain the status quo [50]. Motor imagery itself is a demanding attentional task, possibly explaining this neural tag. In addition, isolated foot flexion-extension is unusual: it recurs embedded in the joint movements sequence of gait, but is rarely generated in isolation. Its execution requires thus a greater effort than other motor tasks normally used in motor imagery studies.

ERD beta band distribution, compared to the UL equivalent [25], [26], appears more centrally localized over the scalp, reflecting the representation of the LL motor area in the interhemispheric sulcus. The deep location of these generators implies that the signal we recorded on the scalp represents a far-filed potential, that can be recorded over larger areas than that of a cortical generator itself.

The application of task-related coherence to our data provides novel information. Connectivity has been investigated using task-related coherence analysis focused on UL [20], [25], [26], [51], whereas studies on LL are lacking. Our data show that during passive movement alpha2 coupling reduces between contralateral motor area and ipsilateral frontal cortex. This implies a different timing of activation of these areas—i.e., when the one is active, the other is silent and vice-versa. The physiological meaning of this alternation is the intermittent activations during gait cycle. Specifically, when the trailing leg reaches maximum dorsi-flexion, the supporting limb initiates plantar-flexion: tibio-tarsal joints work in an alternate manner during walking.

Beta coherence decrease between C3-C4 electrodes represents the existence of two independent lateralized generators underlying motor areas, stressing the mutual exclusion of one area on the basis of the non-bilateral nature of the task. Conversely, a coherence increase between C3-Cz mirrors the functional coupling of areas that represent the physiological projection of the LL cortical area in the midline sulcus. This beta coupling is lacking in motor imagery: given the prevalent sensory-motor somatotype of beta, it is no surprise that in the imagined condition, during which sensory afferent inputs are missing, no functional connectivity between LL areas can be recognized in this band.

The focus of our research is the implementation of better neurorehabilitation paradigms, endowing robotic training. Studies in the area of neuronal reorganization after stroke [3], [32] have tried to explain how the neurophysiological activity of the brain changes after an insult. This literature, while arising the attention to the potential plastic changes of the brain, did not generate a direct input to research which rehabilitation methods could boost recovery. This limitation could have been partially dictated by the lack of standardization of rehabilitation methods (i.e., different techniques such as Bobath, Vojta, etc adapted by each therapist to each client). The introduction of robotic rehabilitation has provided a means to standardize the type and amount of rehabilitation provided. Indeed, it has to be stressed that robotics can by no means substitute the therapist in the process of restoring the lost function: robots are only a tool to reinforce specific tasks to be translated into functional patterns. On this ground, our focus could not have been comparing differences between robotic or therapist assisted passive movement, but ascertaining the effects on neuronal reorganization of a highly repetitive, stereotyped movement on neuronal reorganization. Similarly, we were not interested in comparing active, passive or imagined movement: the substantial overlap of these patterns has already been described in detail in the literature (e.g., [25], [26]). Lastly, the innovative contribution of our study is the computational analysis provided by task-related coherence during ankle-dorsiflexion: to our best knowledge, this analysis has been applied only to UL movements [20]–[22], [26], [38]. Its importance rests on the chance of observing, based on EEG data, the brain network activated during specific movements, and in future studies provide a potential explanation of how changes of these networks can contribute to motor recovery after a brain insult. The final output of this line of research is to inform the design and development of stroke rehabilitation protocols.

A limitation of our study was the lack of a standardized device to induce and control the torque mechanism of passive movement, that can affect sensory afferents. We studied only cortical effects of passive and imagined movements of the dominant limb, but no active movement: this decision rest on the fact that in clinical practice no standardization of active movements can be obtained in subject who suffered a CNS lesion, and thus these data would not eventually be comparable in pathological conditions.

A direct comparison between the two tasks was not carried out given the different experimental setting (passive movement performed with eyes open, motor imagery with eyes closed). We preferred subjects to keep their eyes closed during the imagination task to avoid any environmental distraction: an ankle dorsiflexion is a movement not usually performed in isolation. It has also to be reminded that real motor imagery consists in the kinesthetic experience of the movement, avoiding any visual component. Taken together, these two factors make true mental imagery a quite demanding task, that in our opinion would benefit of a more focused mental setting. Conversly, during passive movement participants were asked to keep eyes open, as reported in previous protocols [25]. A limitation of the study ensues: the different settings (eyes open/eyes closed) prevent a comparison of the passive and imagined movement. In fact, the almost overlapping brain activation of the two condition has already been demonstrated [18], [36] and was beyond the scope of our study.

A computational feature that could potentially have affected results is the beta frequency range used for analysis. It is possible that different neuronal networks discharging during passive and imagined movement, distinguished on the basis of frequency in the beta range, exist [29]. We cannot exclude that the two tasks are generated by not completely overlapping neuronal networks, each of which with a peculiar oscillation that could have been identified splitting beta band into subranges. Indeed, the frequency range used for analysis is that usually reported for beta, and widely accepted in the literature [25], [26], [52].

The results of this study are preliminary. Additional experiments on larger populations are needed to generalize and translate them into clinical practice. These data contribute to the understanding of the patterns of oscillatory activity during lower limb robot-assisted motor performance and point to the advantages of this analysis to evaluate cortical oscillations changes. The design and development of stroke rehabilitation protocols is the ultimate goal of this area of research.

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