Comparison of sensorimotor rhythms in EEG signals during simple and combined motor imageries over the contra and ipsilateral hemispheres

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Abstract— **Imaginary motor tasks cause brain oscillations that can be detected through the analysis of electroencephalographic (EEG) recordings. This article aims at studying whether or not the characteristics of the brain activity induced by the combined motor imagery (MI) of both hands can be assumed as the superposition of the activity generated during simple hand MIs. After analyzing the sensorimotor rhythms in EEG signals of five healthy subjects, results show that the imagination of both hands movement generates in each brain hemisphere similar activity as the one produced by each simple hand MI in the contralateral side. Furthermore, during simple hand MIs, brain activity over the ipsilateral hemisphere presents similar characteristics as those observed during the rest condition. Thus, it is shown that the proposed scheme is valid and promising for brain-computer interfaces (BCI) control, allowing to easily detect patterns induced by combined MIs.**

I. INTRODUCTION

Brain activity, during and following an imagined body part movement, exhibits within the primary sensorimotor cortex an oscillatory behavior of neurons that is observable in electroencephalographic (EEG) recording as a modulation of both the alpha (8-13 Hz) and beta (13-25 Hz) bands. In the course of a motor imagery (MI), this modulation presents a reduction in oscillatory power known as event-related desynchronization (ERD) over the contralateral hemisphere of the body part used in the process [1], [2]. Simultaneously, in the ipsilateral hemisphere, an increase of the oscillatory power known as event-related synchronization (ERS) is observed. Moreover, after the termination of a MI, an ERS can be detected during a few hundred milliseconds over the contralateral motor areas, which is known as post-movement rebound [3].

Regarding to the design of MI-based brain-computer interfaces (BCI) systems, simple MIs have been widely studied; nevertheless, the combination of two or more body parts to produce suitable patterns for combined movements detection, remains as an emerging line of research; even though it has been reported that they exhibit separable difference between simple MIs, and that can be used to build multimodal classification paradigms [4]. However, the design of these systems implies a high complexity that lies especially on the multi-classification problem that needs to be solved in order to detect the corresponding brain states [5], [6]. In the present study a new approach for characterizing the combined movements as the superposition of simple MIs is reported; which allows to determine in terms of the ERD associated with the corresponding MI if they are active or inactive, and thus to reduce the multi-classification problem into binary decisions restricted to the corresponding regions within the primary sensorimotor area.

II. MATERIAL

EEG signals were recorded through the openVibe platform from five right-handed healthy subjects at 256 Hz using a commercial REFA amplifier developed by TMS International™. The EEG cap was fitted with 26 electrodes re-referenced with respect to the common average reference across all channels and located over the extended international 10-20 system positions to cover the primary sensorimotor cortex (Fig. 1). Subjects were asked to perform three different MIs (left hand; right hand; both hands) together with rest condition, while seated in a confortable chair with the arms at their sides in front of a computer screen showing the task to be performed. The whole session consisted of 4 runs containing 20 trials per task for a total of 80 trials per class. Each trial was randomly displayed during 12 seconds, starting at second 0 with a cross at the center of the screen and an overlaid arrow indicating for the next 6 seconds the task cue to be performed (arrow pointing to the left: left hand; arrow pointing to the right: right hand; two arrows pointing to the left and right sides: both hands; and no arrow: rest). After second 6, the arrow disappeared and the cross was remaining for the next 6 seconds indicating the pause period before the next trial started (Fig. 1). All experiments were carried out with the consent agreement of each participant and following the statements of the WMA declaration of Helsinki on ethical principles for medical research involving human subjects.

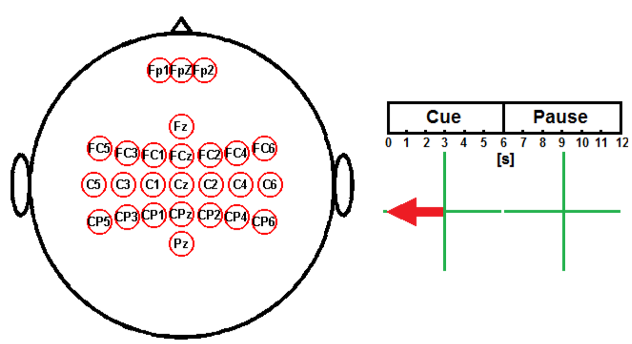

Fig. 1. Positions of the 26 electrodes used during the experiments (left side). Timing scheme for one trial: MIs are performed from second 0 (cue) to second 6 and followed by a 6-second pause period (right side).

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III. METHODS

This section describes the process to quantify and analyze the evolution during time of the ERD/ERS% along the different MI tasks.

A. Estimation of the oscillatory power

Each trial was considered 2 seconds before the task cue appeared on the screen and 6 seconds after it disappeared, so that each segment corresponds to a 14s-length signal over 26 electrodes. All segments were filtered using a 5th-order Butterworth filter within the frequency ranges 8-25 Hz and 14-25 Hz, in relation to the analyses described in the present study.

The power of each segment was computed by squaring its samples and smoothing the resulting signal by using a 2-second-sliding window with a 125 ms shifting step. The process was carried out as it is stated in the classic formula by [1] in terms of the following equation:

$$ERD/ERS\% = \frac{\overline{x^2} - \overline{BL^2}}{\overline{BL^2}} \times 100 \qquad (1)$$

where $\overline{x^2}$ is the mean of the 2s-length squared signal; $\overline{BL^2}$ is the mean of a 2s-length baseline taken at the beginning of the corresponding trial, and ERD/ERS% is the percentage of the oscillatory power estimated for each step of the sliding window. Oscillations greater than the baseline during the MI task produce positive percentage values that are assumed as a modulation of ERS, whereas the negative values generated by smaller oscillations are considered as a modulation of ERD.

Fig. 2 shows the resulting oscillatory power for each class within the frequency range (8-25 Hz) in electrodes C3 and C4 for all subjects. In the case of simple MIs, it can be observed that there are strong ERD% values in the contralateral hemisphere showing similar magnitude as those found on both sides for the combined MI. Furthermore, in the ipsilateral hemisphere, simple MIs produce similar ERS% values to the ones estimated for the rest condition on both sides.

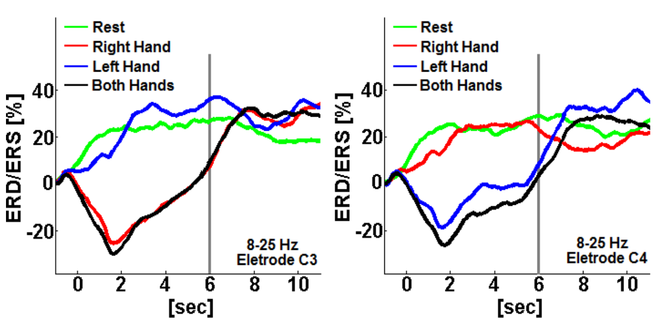

Fig. 2. Grand average (n=5) of ERD/ERS% values estimated according to Eq. (1) for all classes within the frequency range (8-25 Hz) for electrodes C_3 (left side) and C_4 (right side).

Fig. 3 presents the oscillatory power computed in the same way over electrodes C3 and C4 within the frequency range (14-25 Hz), which corresponds to the beta band characterized by its modulation of ERS after the termination of MIs, i.e., post-movement beta rebound. In the case of simple MIs, an increase of the oscillatory power at the end of the task (second 6) is induced over the contralateral hemisphere; and on both sides for the combined MI, where the magnitude is in comparison considerably lower.

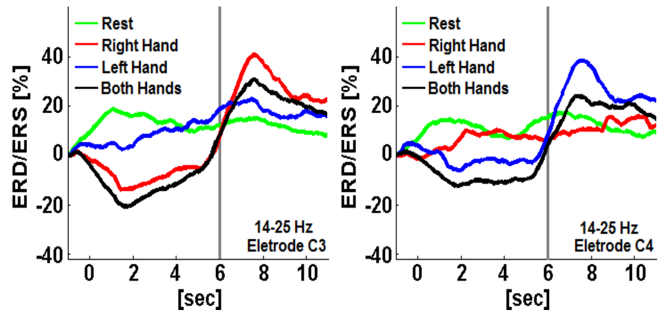

Fig. 3. Grand average (n=5) of ERD/ERS% values estimated according to Eq. (1) for all classes within the frequency range (14-25 Hz) for electrodes C_3 (left side) and C_4 (right side).

Fig. 4 presents a topographic representation showing the ERD/ERS% values within the frequency range (8-25 Hz) across all electrodes during the 6-second-period of the MIs. Over the contralateral hemisphere throughout simple MIs, similar ERD values than those generated in the corresponding side during the combined MI can be observed. In the same way, over the ipsilateral hemisphere during simple MIs, the ERS activity is comparable to the registered one throughout the rest condition.

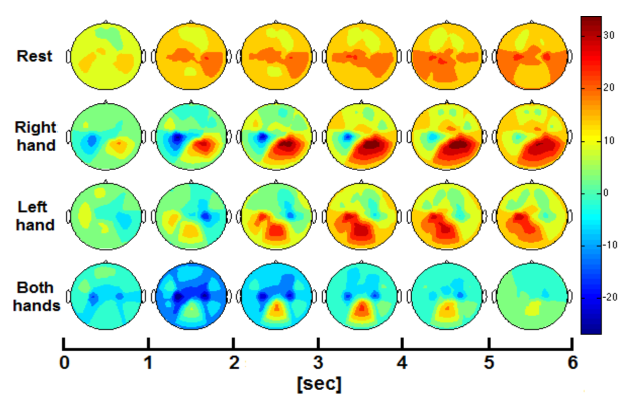

Fig. 4. Grand average (n=5) of ERD/ERS topographies for all classes within the frequency band (8-25 Hz) during the 6-second-period of the MI tasks. The relative oscilatory power was estimated according to Eq. (1) using a cubic interpolation method [7].

The ERD/ERS% values within the beta band during the 6 seconds after the MIs were completed are shown in the topographies of Fig. 5. It can be noticed that the activity is distributed in a similar way as during the motor tasks, but with higher activity levels, indicating a modulation of neuronal synchronization.

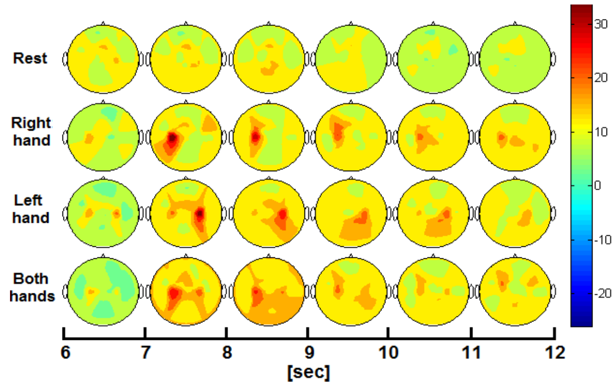

Fig. 5. Grand average (n=5) of ERD/ERS topographies for all classes within the frequency band (14-25 Hz) during the following six seconds after the MIs were completed. The relative oscilatory power was estimated according to Eq. (1) using a cubic interpolation method [7].

B. Evaluation of the significance levels between MI tasks

From Fig. 2 it can be seen that the lowest ERD% values are reached within the interval (1-2 s). For this reason, in order to better evaluate the differences between conditions, all filtered trials were taken only during such a period, within which the frequency spectrum was computed for all channels. Subsequently, the range from 8 to 25 Hz was scanned by taking subintervals of 2 Hz to compute the correlation between different conditions in terms of R^2 [8]. High R^2 values indicate that there is a significant difference between the corresponding MIs at the given frequency over the corresponding electrodes position. On the contrary, small R^2 values show that the evaluated conditions do not present a significant difference and, therefore, are similar between each other. Fig. 6 shows the resulting R^2 values generated for each comparison among all classes. Fig. 6-A presents the comparison between the left hand MI and the rest condition; it can be observed that the highest R^2 values are found at 12 Hz around C_4 on the right hemisphere. This is due to the fact that for the rest condition there are ERS% values in both hemispheres, whereas for the left hand MI there is ERS only in the ipsilateral side, since the contralateral presents ERD. Fig. 6-B shows the comparison between left hand MI and both hands MI. In this case the highest R^2 values are found in the left side around C_3, since for the both hands MI there are ERD% values in both hemispheres, whereas for the left hand MI there is ERD only in the contralateral side, given that the ipsilateral hemisphere presents ERS. Fig. 6-C and fig. 6-D present, respectively, the comparisons between right hand MI and rest condition, and between right hand MI and both hands MI. The situation is similar as the one described for the left hand MI but with the highest R^2 values found in the other way around, since the ERD/ERS% values occur in the same manner but with respect to the right hemisphere. In fig. 6-E the comparison between left hand MI and right hand MI is shown. In this case, the highest R^2 values are also at 12 Hz and distributed around elctrodes C_3 and C_4 simultaneosly. This is because the brain activity within both hemispheres presents an opposite behavior during the course of the MIs and, therefore, there is always a significant difference between each other. In the same way, the comparison between both hands MI and the rest condition presented in figure 6-F shows high R^2 values in both hemispheres, since the both hands MI generates ERD% values in both sides, whereas the rest condition produces ERS.

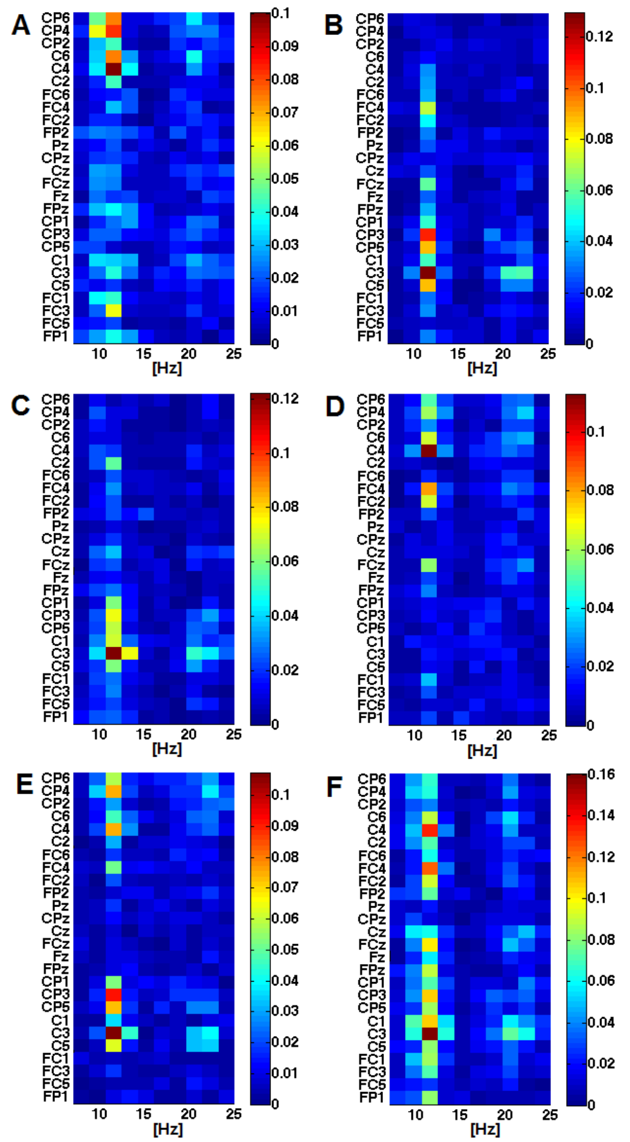

Fig. 6. Grand average (n=5) of correlation values in terms of R^2 for the comparisons between: A) left hand MI and rest condition; B) left hand MI and both hands MI; C) right hand MI and rest condition; D) right hand MI and both hands MI; E) left hand MI and right hand MI and F) both hands MI and rest condition. High R^2 values indicate that there is a significant difference between the corresponding MIs at the given frequency over the corresponding electrodes position.

IV. RESULTS

It has been seen that during the course of MIs, brain activity has important components around 12 Hz and that it is distributed over the primary sensorimotor cortex according to the motor task being performed, especially around electrodes C_3 and C_4. With this in mind, it is possible to estimate for each subject the level of significance between different classes. To this end, the power spectrum of the one-second segment (i.e., from 1 to 2 s) for each filtered trial within the frequency range (8-25 Hz) over electrodes C_3 and C_4 was computed. Subsequently, all values at 12 Hz belonging to the same class at each electrode were gathered together, and an unpaired t-test was applied to determine with a 5% level of significance whether or not two different conditions present comparable activity in the left and right hemispheres. Table I shows the p-values obtained from the unpaired t-test for each comparison between two classes in electrode C_3. They are marked as < 0.01 (very significant); < 0.05 (significant) or the true value for > 0.05. In table II the corresponding p-values for the same comparisons over electrode C_4 are presented. It can be observed for almost all tests and subjects, except for subject 2, which exhibits no significance difference in most of the cases, that simple MIs in the contralateral hemisphere are comparable with the combined MI in the corresponding side; and that simple MIs in the ipsilateral hemisphere are comparable with the rest condition in the corresponding side.

TABLE I

UNPAIRED T-TEST FOR COMPARING DIFFERENT CLASSES IN ELECTRODE C_3 WITH SIGNIFICANCE LEVEL AT 5%

Electrode C3						
Sub	Rest-Right	Rest-Left	Rest-Both	Right-Left	Right-Both	Left-Both
1	$p < 0.05$	$p < 0.05$	$p < 0.01$	p = 0.75	p = 0.27	p = 0.13
2	p = 0.20	p = 0.25	p = 0.81	$p < 0.01$	p = 0.15	p = 0.40
3	$p < 0.01$	p = 0.80	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
4	$p < 0.01$	p = 0.80	$p < 0.01$	$p < 0.01$	p = 0.80	$p < 0.01$
5	$p < 0.01$	$p < 0.01$	$p < 0.01$	p = 0.26	p = 0.56	$p < 0.05$

TABLE II

UNPAIRED T-TEST FOR COMPARING DIFFERENT CLASSES IN ELECTRODE C_4 WITH SIGNIFICANCE LEVEL AT 5%

Electrode C4						
Sub	Rest-Right	Rest-Left	Rest-Both	Right-Left	Right-Both	Left-Both
1	p = 0.17	$p < 0.01$	$p < 0.01$	$p < 0.05$	$p < 0.01$	p = 0.37
2	p = 0.48	p = 0.33	p = 0.55	p = 0.07	p = 0.15	p = 0.65
3	p = 0.20	p = 0.12	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
4	p = 0.39	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	p = 0.26
5	p = 0.10	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.05$	p = 0.71

Fig. 7 shows a boxplot comparing the power spectrum for subject 4 at 12 Hz of each MI in electrodes C_3 (left side) and C_4 (right side). It can be noticed that there is no significant difference between the rest condition and the simple MIs in the ipsilateral hemisphere, nor is there for the combined MI and simple MIs in the contralateral hemisphere.

The same analysis within the beta band at the end of MIs revealed similar results for the ERS elicited during the post-movement rebound; nevertheless, the contrast between the two groups showing similar behavior, i.e., the combined MI together with the simple MI in the contralateral hemisphere; and the rest condition together with the simple MI in the ipsilateral hemisphere, is not as defined as for the ERD% values during the course of MIs.

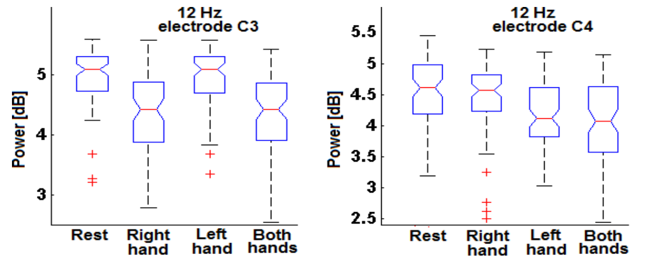

Fig. 7. Boxplots for subject 4 of all classes power spectrum at 12 Hz within the frequency range (8-25) during the time interval (1-2 s) showing the first three quartiles together with the data range in C_3 (left side) and C_4 (right side). The distribution of the data shows that there is no significant difference between simple hand MIs in the contralateral hemisphere with the combined MI in the corresponding side, nor is there between simple hand MIs in the ipsilateral hemisphere with the rest condition.

V. CONCLUSIONS

After analyzing the EEG signals of five healthy subjects during simple and combined MIs using right and left hands, t-tests with a significance level at 5% show that there is no difference between simple hand MIs in the contralateral hemisphere with the combined movement in the corresponding side, nor is there in the ipsilateral hemisphere with the rest condition. Thus, the brain activity generated during the MI task involving both hands can be considered as the superposition of simple MIs in their contralateral hemispheres. Furthermore, the fact that simple MIs in the ipsilateral hemisphere show no difference with the rest condition implies that it is feasible to consider the involved regions within the sensorimotor area as active or inactive in terms of ERD during the corresponding MI. In this way, the multi-classification task can be reduced into two binary-classification problems restricted to the sensorimotor areas within each brain hemisphere; leading to a much simpler recognition approach.

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