

Inter- and Intra-Hemispheric EEG Connectivity in Healthy Subjects and Chronic Stroke Survivors

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Abstract—Brain connectivity has been assessed by phase indexes and other measures that rely or are based on Cross Power Spectral Density, normalizing it or taking only its imaginary part, leaving aside some interesting features that magnitude can describe differences for two kinds of populations. This paper shows the first results during resting state for a study that aims at describing the Interconnectivity between brain areas in stroke survivors through EEG while they played a game involving bimanual coordination. Resting state EEG recordings were collected from a control population of 13 people (8 Males, 5 Females; Age 29.15 ± 5.57 y) and 10 stroke survivors (6 Males, 4 Females; Age 61.8 ± 7.45 y), and analyzed with Power Spectral Density (PSD) and Cross Power Spectral Density (CPSD) from the EEGs. Results show that PSD and CPSD in Beta Band are promissory features able to differentiate between Controls and Stroke Survivors, being possible to describe these aspects for a brain with| motor challenges, even in the analysis of Inter- and Intra-hemispheric connectivity.

Keywords— Stroke, EEG, PSD, CPSD

I. INTRODUCTION

The interruption in the supply of blood to the brain caused by clots in arteries or break out in an artery could produce an ischemic or hemorrhagic stroke episode. These episodes can fall into partial paralysis or permanent damage, between others possible impairments, doing Stroke episodes one of the biggest causes of impairment around the world, with the probability that 1 of 6 people worldwide will experiment a stroke in their lifetime [1], being in conjunction with heart diseases the cause of one third of the deaths of women and a quarter for men in Portugal [2].

The recovery for stroke survivors requires the engagement of full team of health professionals with the objective of recovering to the largest extent the abilities previous to the stroke event. Therapies have been mostly focused in unilateral limb recovery, leaving coordination activities as bimanual tasks underexplored in the rehabilitation area [3]. Because most of daily living activities involve the coordination of two arms, it becomes a necessity to further explore the topic with advanced methodologies, such as EEG.

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The majority of EEG studies in stroke populations have focused on acute stages, and correlation of features as Power Spectral Density (PSD) and Band Power Ratios as Delta Alpha Ratio (DAR) as predictive outcome parameter and correlation with clinical assessments [4], such as Montreal Cognitive Assessment (MoCA) with as low resolution as a single electrode [5]. One important topic that is still being researched even in healthy subjects, is that of synchronization and connectivity. From it, a variety of connectivity measures and indexes have emerged. Connectivity between two EEG signals has been measured through its Coherence (C) [6], based on the correlation for spectral amplitude and normalization with their auto-spectrum magnitudes; also through the Imaginary Coherence, which takes only the complex part [7]; and phase measures such as the Phase Lag Index, proposed in [8] and the Weighted Phase Lag Index [9]. All of them are based on the Cross Spectrum or Cross Spectral Density (CPSD) between two signals.

In this paper we present a bimanual game that can be used as bimanual rehabilitation strategy. We combined both simultaneous upper limb training and recording of the brain activity with EEG. The aim was to study the connectivity between electrode activity. To that end we conducted a study healthy and a stroke sample to identify EEG features related to brain connectivity during bimanual task execution and resting state for both healthy and stroke survivors. For that we selected PSD and the magnitude of the CPSD to study connectivity between electrode activity and avoiding the focus on its phase shift. The results presented here analyze these connectivity EEG features of stroke survivors and healthy controls in resting state, testing its candidacy as possible biomarkers of connectivity during task performance and motor function.

II. METHODOLOGY

The aim of this study was to find the connectivity differences that should overlie on EEG patterns from a stroke and healthy control population using spectral descriptors during resting state and bimanual coordination.

A. Bimanual Coordination Task

We designed an infinite runner type of game called Butterfly Catcher (Fig. 1), in which the main character, a

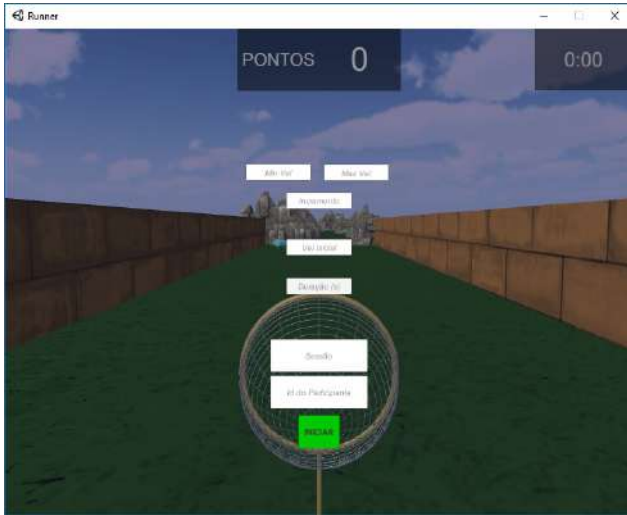


Fig. 1. Configuration of Butterfly Catcher Game

butterfly net, moves forward trying to catch butterflies while moving to the right or the left and avoiding obstacles represented by rocks. The game is configured to present the same quantity of obstacles and butterflies, appearing at random positions. The velocity of the player is modulated by its task performance, increasing the velocity if the player scores and decreasing it if the player hits an obstacle. The game menu, showed in Fig. 1, allows to configure the minimum and maximum velocities, the step size for the variation of the velocity, the ID for the player and the time desired to play. The link between the game and the bimanual coordination task was achieved implementing a wood control structure based on separate sliders and controls for each hand. The two handles that act as controllers are tagged on the top part with a unique tracker pattern. A webcam based tag tracker software, AnTS [10], was used to translate the movements of the hands to the lateral displacements of the butterfly catcher. The physical setup can be seen it on Fig. 2.

B. Inclusion Criteria

The inclusion criteria for our control sample focused on avoiding a history of neurological diseases, while the stroke sample required:

- No hemi-spatial neglect;
- Token test score greater than 7;
- Chronic stroke (more than 6 months after stroke);



Fig. 2. Physical setup including A. EEG system; B. Computer; C. Tags for being tracked; D. Wood surface structure; E. Tracking Camera (Above structure, not visible in the image)

- Stroke in the supra-tentorial region, including infarctions in the Medial Cerebral Artery (MCA), other lesions on the cerebral lobes, and internal Lacunar strokes.

C. Population description

Two population samples participated in this study. A stroke survivor sample of 13 participants and a healthy control group of 16 participants. Data from some participants had to be removed due to high noise presence on EEG. Hence, the here presented analysis is based on a sample of 10 stroke survivors (6 Males, 4 Females; Age $61,8 \pm 7,45$ y) and 13 controls (8 Males, 5 Females; Age 29.15 ± 5.57 y). Among stroke survivor's, there are 8 ischemic cases and 2 hemorrhagic, with 6 people with right hemisphere stroke and 4 left hemisphere ones. A better description about stroke survivor sample population can be seen in Table 1.

D. Acquisition of data

We collected both clinical and electrophysiological data. Clinical assessment was done only with stroke survivors. We used cognitive and motor assessments such as the simplified Token Test [11], which is used to evaluate language comprehension; Montreal Cognitive Assessment (MoCA) [12], to detect cognitive deterioration and dementia; and Fugl-Meyer Assessment (FMA) [13], dedicated to evaluate function deficit after Stroke events. Spasticity was assessed using the modified Ashworth scale [14] and functionality of the affected arm with the Chedoke Arm and Hand Activity Inventory, version 9 (CAHAI-9) [15]. The Bells test [16] was also applied to discriminate patients with hemi-spatial and visual neglect. Electrophysiological data was recorded in an isolated room with an EEG Enobio 8 wireless system during 3 minutes of resting state with closed eyes, placing the electrodes around primary motor and somatosensory cortices following the 10-20 system. We used electrodes FC5, CP5, C3, C1, C2, C4, FC6, and CP6, as shown on Fig. 3.

E. Data Pre-processing

EEG pre-processing was done using Matlab [17] with an custom developed tool based on EEGLab [18]. Filtering was done in the frequency band of 1 – 40 Hz, employing low pass and high pass Chebyshev filters, applying a forward-backward strategic filtering [19] to avoid the non-desired effects of applying filters in the phase of a signal. Rejection of blinking artifacts was done visually and also with the recommendation of an automatic statistical analysis. Spectral densities were estimated using Hanning windowing method with 50% overlap and frequency resolution of 0.5 Hz.

F. Extraction of features

The goal was to research Theta, Alpha and Beta frequency bands, analyzing the power spectral density and the spectral connectivity of channels in pairs using the Cross Power Spectral Density. CPSD describes the correlated spectrum between two signals of interest. That is, if two signals are correlated only in a specific frequency, the Cross Spectrum would be sharp in that frequency and flat in the rest of the frequency domain. If there exists a phase shift between them,

Table 1. Stroke Survivor Sample Population

ID	Gender	Age	Months after stroke	Stroke Type	Stroke Location	Affected Limb	Handedness	
							Edinburgh Test (Present)	Self report (Past)
3	M	64	7,81	Ischemic	Lacunar, left Pons	Right	Right (73,3)	Right
1	M	60	72,23	Ischemic	Right hemisphere (non-clinical image)	Left	Right (100)	Right
7	M	64	17,77	Ischemic	Lacunar, right striatum region	Left	Right (68,4)	Right
2	M	70	143,13	Ischemic	Right hemisphere (non-clinical image)	Left	Right (100)	Right
6	M	53	22,71	Hemorrhagic	Left frontal-temporal lobes	Right	mixed right user (38,5)	Right
5	F	71	43,94	Ischemic	Left hemisphere; ischemic leukoencephalopathy	Right	mixed left user (26,3)	Left
9	M	63	49,71	Hemorrhagic	Right hemisphere (non-clinical image)	Left	Right (100)	Right
8	F	64	32,26	Ischemic	Lacunar, left ramifications of the basilar artery	Left	Right (100)	Right
11	F	46	73,16	Ischemic	Left fronto-parietal lobes	Right	Left(100)	Right
12	F	63	8,32	Ischemic	Right occipital lobe	Left	Right (100)	Right

an imaginary component would appear in the CPSD, but magnitude would remain constant. Therefore, the magnitude of the Cross Spectrum is a useful tool to describe frequency correlations for electrodes' activity, with the possibility to relate this to a synchronization of activity between different sources, p.e. left-right hemisphere relations. Thus, having this in mind, the evaluation of the spectral flatness in a particular frequency band of interest can provide valuable information about activities related to that specific band, being flat for a total correlation of signals in the whole spectrum and maximum sharp for a unique relation in a particular frequency. In this case, the interest lays on analyzing these relations in the frequency bands Delta (1-4 Hz), Theta (4-8 Hz), Alpha (8-12 Hz) and Beta (12 -30 Hz) through their spectral flatness, also known as Wiener Entropy [20] per each band which measures the flatness of a spectrum with values between 0 for a pure tone (a peak in only one particular frequency) and 1 for a complete flatness spectrum.

$$SF = \frac{\sqrt[n]{\prod_{i=1}^n x(i)}}{1/n \sum_{i=1}^n x(i)} \quad (1)$$

Therefore, measuring the spectral flatness between two electrodes would give information of the sharing components in the spectrum, a CPSD completely flat can be understood as equal activity in all the frequencies in a particular band for both electrodes with a flatness value of 1, while a sharp CPSD stays for a relation in a unique particular frequency with a spectral flatness value of 0.

Relations of interest between electrodes are linked to the positioning of them. Therefore, EEG signals were flipped from patients with lesions on the left hemisphere, p.e FC5 activity to FC6 and vice versa. To describe their connectivity two groups of interest were selected, intra-hemispheric short distances and inter-hemispheric distances between electrodes, as is possible to see in Fig. 3. Therefore, three sets of relationships were chosen: intra-hemispheric from left hemisphere, intra-hemispheric from right hemisphere and Inter-hemispheric relations.

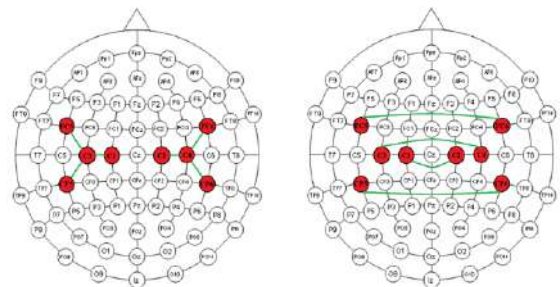


Fig. 3. Electrode coupling groups. Left. Intra-hemispheric short. Right. Inter-hemispheric

The selected couples per group were based on couple connectivity proposed on [8] covering primary and somatosensory areas as: FC5-C3, CP5-C3, and C1-C3 for Intra-hemispheric left; FC6-C4, CP6-C4, and C2-C4 for Intra-hemispheric right; FC5-FC6, CP5-CP6, C3-C4 and C1-C2 for Inter-hemispheric (Fig. 3).

G. Data Analysis

A two tailed t-Test was selected as the method to indicate significance for comparisons with the p-value as indicator. As the aim of this study was to look out for features that can describe differences in motor areas during resting state to apply during motor activation in the execution of a task it wasn't use a multiple comparison correction for p-values.

III. RESULTS

As a first approach to address inter and intra-hemispheric connectivity in the proposed bimanual activity, we focused on evaluating candidate features that can describe the differences in brain connectivity during a resting state condition between healthy controls and stroke survivors. Hence, we evaluated PSD, CPSD and their flatness in Delta, Theta, Alpha, and Beta frequency bands. Table 2 shows the p-values obtained for the evaluated features.

From Table 2 it is possible to see that power (PSD) and Interhemispheric connectivity (CPSD) in Beta band revealed significant differences between both healthy and stroke groups with p-values < 0.05.

Table 2. p-values of the comparisons for the extracted features

Feature	Frequency Band	Left H /Intrah	Right H /Intrah	Inter-hemispheric
PSD	Delta	0,6309	0,8261	-
	Theta	0,4198	0,7219	-
	Alpha	0,4622	0,8208	-
	Beta	0,1361	0,0288	-
CPSD	Delta	0,858	0,6312	0,3044
	Theta	0,5491	0,3639	0,446
	Alpha	0,5758	0,3846	0,4378
	Beta	0,0813	0,2282	0,04845
Flatness PSD	Delta	0,231	0,448	-
	Theta	0,933	0,3781	-
	Alpha	0,8069	0,3941	-
	Beta	0,595	0,3939	-
Flatness CPSD	Delta	0,4995	0,8735	0,2441
	Theta	0,1804	0,137	0,4343
	Alpha	0,8069	0,8601	0,9012
	Beta	0,5392	0,0995	0,744

PSD values in Beta band were significant, being possible alternative biomarkers to differentiate brain activity patterns between the two groups. We found that values for Stroke Survivors were higher than the Control group for the Right hemisphere ($PSD_{Control} = 0.00109 \pm 9.3 \times 10^{-5} \mu V^2/Hz$, $PSD_{Stroke} = 0.00118 \pm 9.42 \times 10^{-5} \mu V^2/Hz$, $p=0.0288$).

Also, these different patterns can be confirmed by looking at the averaged PSD values from both hemispheres in Fig. 4, which shows a normalized PSD brain map in the Beta band for the two groups, where a distinct pattern for right hemisphere can be observed. Higher PSD values can be seen for Stroke Survivors than for Controls.

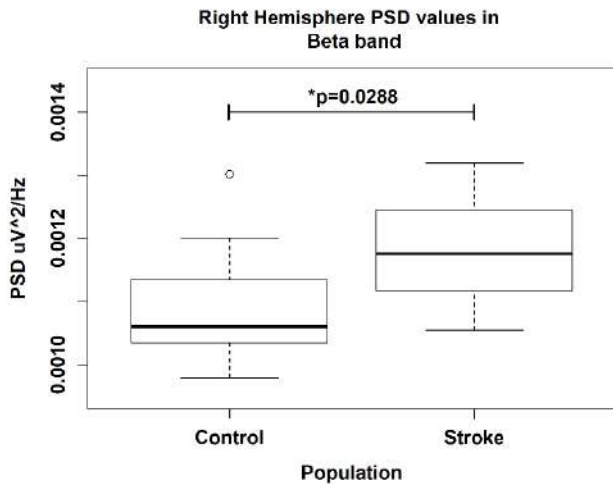


Fig. 4. PSD in Left and Right Hemispheres for the two groups.

PSD values for Controls and Stroke Survivors in Beta Band

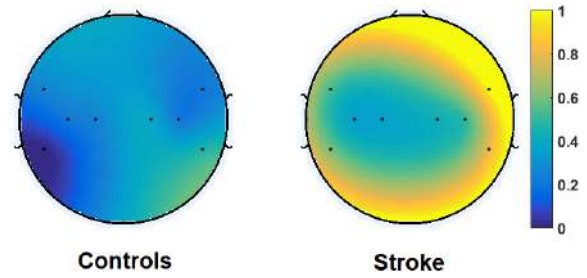


Fig. 5. PSD map in Beta Band for Healthy Controls and Stroke Survivors.

Besides the average PSD results in Beta band, we observed differences between the two groups for Inter-hemispheric and Intra-hemispheric Connectivity in Beta band assessed by CPSD normalized values, being the clearer differences in both higher values for Inter-hemispheric and left Intra-hemispheric Fig. 6 for Stroke participants.

Values for Inter and Intra hemispheric connectivity in Beta band as measured by the CPSD are shown as in Fig. 7. Again, and consistent with the previous data, here is possible to observe higher values for Stroke Survivors with a smaller standard deviation, while values for Control population are more spread with a lower mean (Inter-hemispheric $CPSD_{Control} = 0.367 \pm 0.057$, $CPSD_{Stroke} = 0.416 \pm 0.05$, $p=0.04845$; Intra-hemispheric Left $CPSD_{Control} = 0.368 \pm 0.059$, $CPSD_{Stroke} = 0.414 \pm 0.055$, $p=0.0813$).

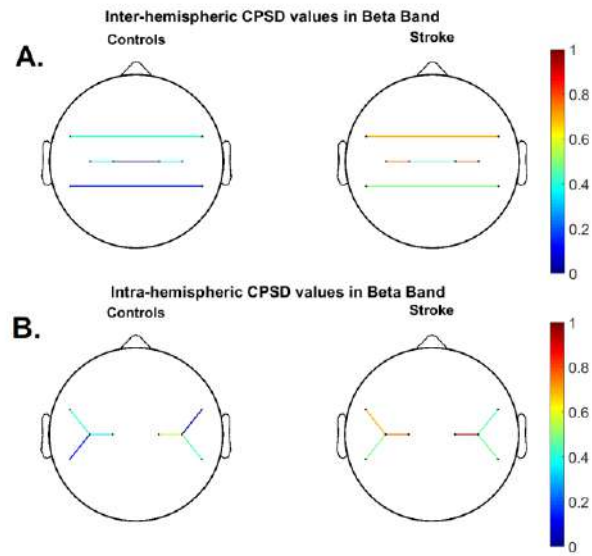


Fig. 6. CPSD values in Beta band for Control and Stroke Survivor populations. A. Inter-hemispheric; B. Intra-hemispheric

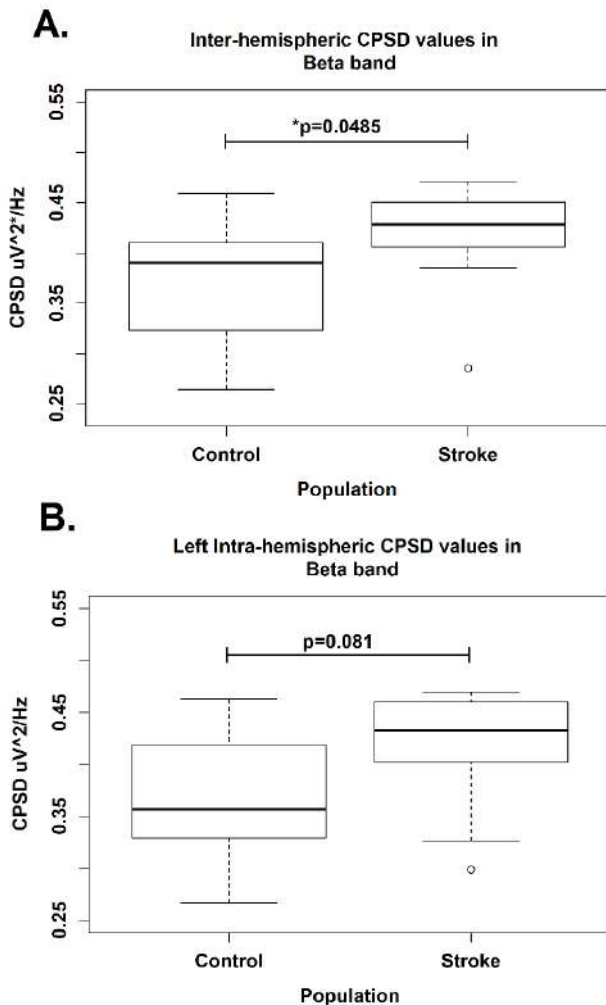


Fig. 7. CPSD values in Beta band for Controls and Stroke Survivor populations A. Inter-hemispherical; B. Left Intra-hemispherical.

IV. CONCLUSION AND DISCUSSION

The main goal of this preliminary study was to evaluate PSD and CPSD features in resting state to know if they could be exploited as signatures for the differences in brain connectivity patterns between a healthy state and a state where changes in connectivity are expected as part of the recovery of a stroke event. Although results are preliminary on a reduced sample size, this is a step towards exploring the use of resting state biomarkers on stroke survivor's EEG. Such analysis can give us information for an idle or kick off processing state as has been found previously in fMRI studies with the Default Mode Network and also studied in EEG [21].

Results show an increased level of Beta power in Stroke patients accompanied by higher inter-hemispheric and intra-hemispheric connectivity compared to the control population. As in this study we used electrodes directly near to the surface of motor cortices, this can be interpreted as a predetermined status for stroke brains, suggesting that motor areas try to compensate the lack of communication synchronizing in similar frequencies at Beta band level.

Further, PSD and CPSD in Beta band have been found as candidate features. A follow up of this study will incorporate the analysis of all the here identified features during motor coordination. Also, we will also consider to evaluate particularly the connectivity description for electrodes C2-C4 in lower frequency bands, it may improve the discrimination between Stroke and Control populations as it can be seen in Fig. 6B. Besides, evaluation of correlations between cognitive and motor scores with extracted features can be explored to know if they can be proposed as useful diagnostic features in resting.

To sum up, our analysis corroborate Beta band as an important source of information in the processing for a brain with motor challenges, even in the analysis of Inter- and Intra-hemispheric connectivity. These findings are consistent with a study that clear disturbances of connectivity in Beta band using Magnitude Squared Coherence in Acute Stroke cases [22].

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