Mu-Beta Rhythm ERD/ERS Quantification for Foot Motor Execution and Imagery Tasks in BCI Applications

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***Abstract*—Viable usage of Brain-Computer Interface (BCI) in real-time applications significantly relies on the pre-processing techniques applied on the detected electroencephalography (EEG) signals. In EEG, sensorimotor (SMR)/oscillatory signals, such as *mu* and *beta* rhythm based BCIs, can be used to restore motor function by neuro-plasticity applied to re-establish normal brain function. This study is based on the evaluation of the foot motor execution (ME) and motor imagery (MI), in order to design a BCI neurorehabilitation system. Because foot ME and MI reflect the user's physical and imagination state of foot movement respectively, in order to be used as control signals, their appropriate translation is the basic challenge. This paper mainly focuses on the quantification and investigation of *mu-beta* event-related desynchronization (ERD) and event-related synchronization (ERS), for inter and intra-subject variability, making use of the available design tools in open-source platforms such as the OpenViBE software. Results show that the frequency of the most reactive components for *mu* was 8.8±0.5 Hz and 21.3±0.4 Hz for *beta*. Interestingly a contralateral dominance was visible at electrode position C3 during right foot ME/MI tasks. The results have enabled the implementation of a good platform for left-right foot ME/MI discrimination based BCI applications.**

Keywords*—Brain-Computer Interface (BCI); electroencephalography (EEG); neuro-plasticity; event-related desynchronization (ERD); event-related synchronization (ERS); Graz-BCI protocol

I. INTRODUCTION

Neurodegeneration, spinal cord injury (SCI) or stroke causing paralysis can affect the lower limbs (LL) of a human body in addition to amputation, ending up in gait impairment. The primary therapeutic goal of such people is the rehabilitation of gait, or development of assistive technologies [1] for people with non-standard cognitive characteristics [2] to re-gain the dorsiflexion of foot drop. The rehabilitation of gait intents to ameliorate the motor control functions by inducing neuro-plasticity. This could be achieved by detecting and translating particular brain features, which correspond to the ME or MI of the affected limb, such as foot, into an output control command. A feedback on this output command can be sent to the user that in turn can affect the brain activity of the user, and re-establish the motor control. One apt tool that could be employed to turn this problem into real-time application is the BCI technology.

BCIs based on particular EEG features used to decipher user intent are of different types; one being the SMR/oscillatory rhythms. SMR generate in the somatic sensorimotor areas and are concentrated in the alpha, or mu (8-12 Hz) and beta (12-32 Hz) frequency bands, but also include gamma (35-200 Hz) frequency bands [3]. SMR have been deployed by researchers in order to identify any changes in them relating to any ME or MI task. Such changes in rhythms are detected based on feature extraction and classification. The execution, or imagination of body part movements, e.g. foot, creates a unique pattern in the SMR.

These patterns in the SMR are reflected in form of, a power decrease called ERD, or a power increase called ERS, in the EEG signal. Each of the ERD/ERS is associated to an internal or external event. An ERD pattern exhibits an actual or imagined movement of a limb, characterized by localized cortical topography and frequency specificity. On the contrary the ERS relates to the rest, or relaxation period [4, 5].

ERD patterns are useful in determining the correlation of brain activity during the task with actual performance, or as an estimator of brain activity related to an event. This can be achieved by quantifying the ERD/ERS patterns using tools such as topographic, or time-frequency maps. Topographic maps represent the spatial distribution of ERD/ERS for a specific frequency, where they can be studied as a function of space. The time-frequency maps are used to detect the transient event-related spectral perturbation (ERSP) or event-related shifts in the power spectrum and inter-trial coherence (ITC) events in the signal. Amongst the available tools for data evaluation, EEGLAB, a MATLAB toolbox for processing EEG signals was used in this study.

The cortical localization of ERD patterns is due to the somatotopic arrangement of the sensory and motor cortices. This arrangement has the hand area representation on the mantle of the cortex, followed by lateralizion the reason why ERD patterns of the left and right hand can be easily discriminated spatially in EEG. Whereas the foot's motor area

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is deep within the interhemispheric fissure of the cortex which makes it difficult to detect ERD patterns through EEG [6].

Although there is literature about the detection of lower limbs (LL) tasks [7], the detection of distinct left and right foot tasks for applications as brain controlled robotic foot is limited. This study therefore focuses on the quantification of ERD/ERS patterns for foot ME-MI tasks in order to expand the limited knowledge about the discrimination of left-right foot tasks to be used as a CogInfo Communication [8] tool for neurorehabilitation in controlling BCI based robot applications [9] for LL.

II. Materials and Methods

A. *Subjects and Experimental Paradigm*

Three female subjects with no BCI experience and no history of any neurological disorder (age range 22-32 years) voluntary participated in this study. Ethics approval was granted by the CHEAN (College Human Ethics Advisory Network) of RMIT University, Melbourne, Australia.

Each subject was instructed to sit comfortably in front of a monitor screen (17’’) at a distance of about 1.5 m from the screen. At the beginning of each run a blank screen was presented for 30 seconds. This period was used as baseline and the participant was asked to relax and become ready for experiment. After the baseline measurement, each trial started with the presentation of a fixation cross for 3 seconds followed by 2 seconds of visual cue display and 5 seconds of performing the task (execution/ imagery), making a total of 10 seconds for one trial. The visual cues reflected right and left foot dorsiflexion-plantarflexion. Subjects were asked to dorsiflex and planterflex their foot only once during each task performance period in each trial. Visual cues were displayed in random order to ensure no adaptation took place. Each trial was followed by a random pause interval between 1.5 seconds to 3.5 seconds where the subject was asked to relax/rest. Each session/run consisted of 40 trials, ensuring a total of 20 trials for each task. Furthermore, the experiment was divided into 4 sessions/runs, 2 for motor execution (ME) and 2 for motor imagery (MI) tasks. A schematic overview of protocol timing can be seen in *Fig. 1*, left. For the first trial only an audio stimulus (beep) of 1 second before the visual cue display was incorporated to alert the subject that the experiment was about to begin.

B. *Data Acquisition*

For data acquisition the 24 channel EEG neurofeedback BrainMaster Discovery 24E amplifier (BrainMaster Technologies Inc., Bedford, USA) was interfaced with the acquisition server of the open source software OpenViBE (http://openvibe.inria.fr/downloads/). An electrode cap (10-20 Electro-cap) with incorporated 20 electrodes was placed over the scalp of different brain areas following the international 10–20 [10]. Channels were referenced to linked earlobes (LE) derived from the electrodes A1 and A2 (see *Fig. 1*, right). Data was sampled with 256 Hz on all channels, with a resolution of 24-bit and amplifier bandwidth from 0 Hz to 100 Hz and EEG channel bandwidth of 0.43 to 80 Hz.

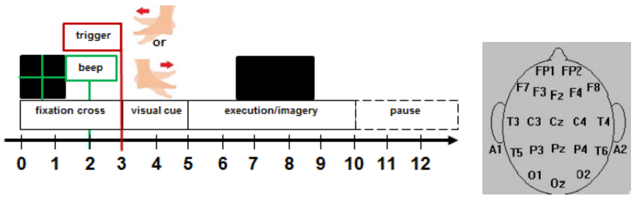

Fig. 1. Experimental protocol reflecting timing of cue including ‘beep’, for the first trial only, at the beginning of each session (left) and electrode channel locations (right)

Experimental protocol was set using the OpenViBE designer tool with its integrated feature boxes presented in *Fig. 2*. To allow for different onset visual cue timing, the default settings and the .lua script inside the Graz-Stimulator box were modified. Synchronization of the BrainMaster Discovery software with OpenViBE was achieved by setting the acquisition server properties and connecting the modules appropriately ensuring establishment of data connection via TCP/IP connection as shown in *Fig. 3*. To gather and visualize all the cues in recorded EEG data different trigger points were sent as stimulations, in real time, to the visual cue display box inside the OpenViBE designer via TCP/IP protocol. All data was saved using the edf and gdf writer boxes to store signals and stimulations together in .edf and .gdf file format, respectively.

C. *Data Processing*

As OpenViBE is a streaming tool for online/real-time BCI experiments and not for data analysis and data exploration, the classical statistical free package EEGLAB (http://www.sccn.ucsd.edu/eeglab/) was used for offline processing of the acquired data.

To get topographic maps of the scalp, EEG segments (trials) of 10 seconds’ length with 3 seconds prior to cue onset were extracted and analysed. Data was band pass filtered between 5 Hz and 40 Hz. Artefact removal was carried out using independent component analysis (ICA) [11] alongside visual inspection (and other artefact rejection) tools integrated in EEGLAB toolbox.

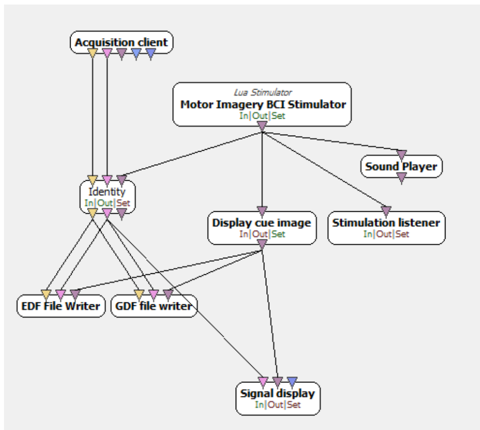

Fig. 2. OpenViBE Designer graphical user interface. Schematic overview of boxes used for experimental protocol

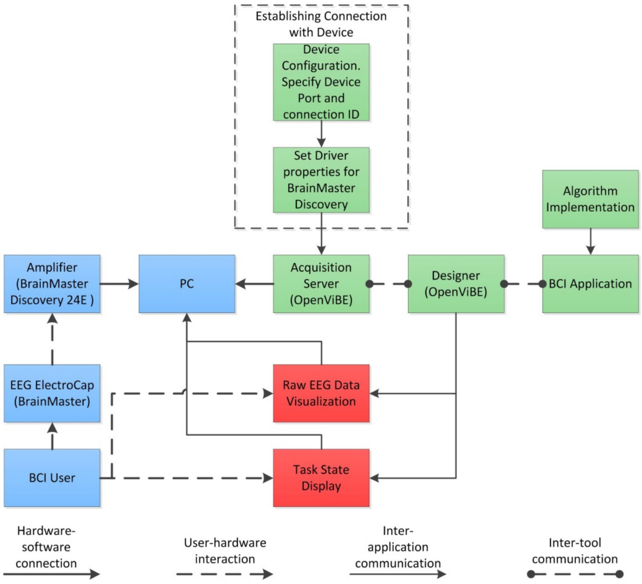

Fig. 3. Flow diagram of the established hardware-software connection between BrainMaster and OpenViBE with the user

Time-frequency maps were obtained with frequency range of 5 to 40 Hz with a step of 1 Hz. They were then used for selecting mu and beta bands with the most significant band power decrease or increase during the ME and MI tasks at the central electrode positions C3, Cz, and C4.

ERD/ERS quantification was conducted following the methods proposed by [12]. The ERD/ERS is defined as the proportional power decrease (ERD) or power increase (ERS) relative to the reference interval, that is usually several seconds before the event onset [4]. For this study the interval containing 3 seconds prior to visual cue onset was selected. Samples were squared and labelled as y_{ij} after subtracting the mean of the band pass filtered data for each sample to overcome masking of induced activities by the evoked potentials (Equation 1). Furthermore, samples were averaged over trials and over sample points (Equation 2-4) [4, 13].

$$y_{ij} = (x_{ij} - \bar{x}_j)^2 \quad (1)$$

$$P_j = \frac{1}{N-1}\sum_{i=1}^{N} y_{ij} \quad (2)$$

$$R = \frac{1}{k+1}\sum_{r_0}^{r_0+k} P_j \quad (3)$$

$$ERDS_j = \frac{P_j - R}{R} * 100\% \quad (4)$$

where N is the total number of trials, x_{ij} is the j^{th} sample of the i^{th} trial of the bandpass filtered data, and $\bar{x}_j$ is the mean of the j^{th} sample averaged over all bandpass filtered trials. P_j is the power or inter-trial variance of the j^{th} sample and R is the average power in the reference interval (r_0, r_0+k) [5].

III. Results

As subject 3 (S3) could not participate in all training sessions, she did not show any significant output results, therefore only the results of subject 1 (S1) and subject 2 (S2) have been reported. *Fig. 4* and *Fig. 5* show the topographical scalp maps of S1 and S2, left and right foot ME and MI tasks. The color bar indicates the spectral power concentration over the scalp for all channels

A. Topographical Scalp Maps

Motor execution task:

S1: At the mu frequency range, corresponding to frequencies between 8-11 Hz, during right foot ME a high power concentration was reflected near the center lobe or mid central mu ERD which is the activation of the foot representation area. At frequencies between 16-30Hz, corresponding to beta rhythm, a shift towards the central region occurred. Especially the right side was more active at electrode position C4 than the left side at electrode position C3. This contralateral power distribution was however only dominant for left foot movement, shown in *Fig. 4*. At the central electrode position Cz the power concentration was decreased during higher frequencies. S2: At the mu frequency range the power is concentrated over the frontal and central region probably because of the proprioceptive induced due to movement of the foot (ME task). For the beta frequency range this trend was again visible in the frontal area followed by an interesting enhancement in the hand area beta rhythm representation power decrease (beta ERS). Furthermore, the central region showed a decrease in spectral power with increasing frequency. Left foot ME resulted in lower a power concentration than right foot motor execution.

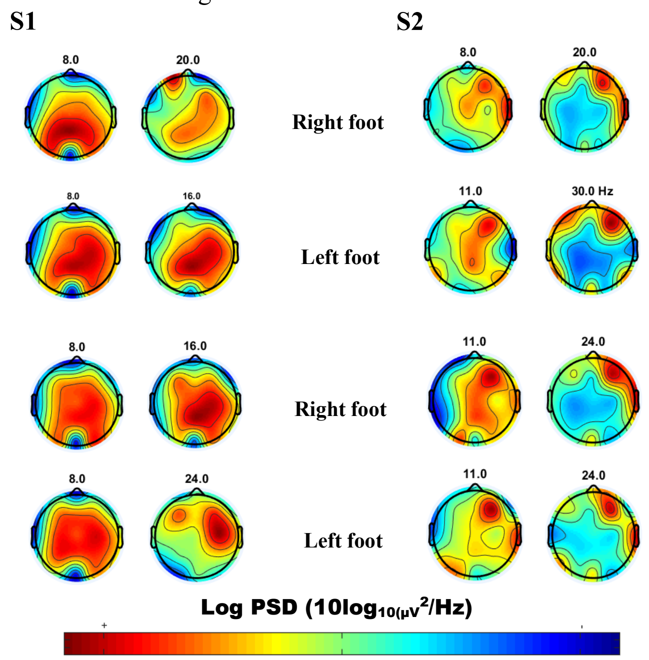

Fig. 4. *Topographical scalp maps showing mean power spectral distribution for right-left foot ME (top rows) and MI (bottom rows) for all channels*

Motor imagery task:

S1: At the mu frequency range, spectral power was concentrated in the central region. The left foot MI interestingly enhanced the hand area mu rhythm (mu ERD). At the beta frequency range a shift from the central region occurred. C4 and F4 showed higher power concentration during left foot imagery and at frequencies higher than 24 Hz. S2: At the mu frequency range the power is concentrated over the frontal and central region with increased power values for the right side of the cortex for both right and left foot MI. For the beta frequency range there was a decrease in power concentration in the central region, followed by an enhancement in the hand area beta rhythm (beta ERS) representation visible for lateralization of ERS i.e. right foot MI enhanced left side beta ERS. But this trend was not followed in the case of left foot MI, *Fig. 4*.

In general ME and MI scalp maps showed relatively same power distribution pattern for intra subject. In contrast, prominent inter subject differences were obtained regarding decreased spectral power at higher frequencies at the central region.

B. *Time Frequency Maps*

Fig. 5 show the time-frequency maps of the most reactive ERD/ERS at electrode positions C3 and Cz for S2 during left and right foot motor tasks obtained from EEGLAB. Because only most reactive ERD/ERS have been reported, we did not include C4 as it did not reflect prominent ERD/ERS patterns. Only significant values (α=0.05) are displayed in color: red indicates ERD and blue indicates ERS. Non- significant values are displayed in green. The colour bar indicates the ERSP in decibel.

The right foot ME (*Fig. 5 (a)*) resulted in a significant ERD at electrode position C3 during the end of visual cue display at second 2 between 8-35 Hz for a period till execution of task ends. Similarly for Cz ERD was visible from the beginning of visual cue between low mu 8 Hz and beta 22 Hz frequency till the subject finished performing the task at second 4-5. An ERS at the end of the execution period over approximately whole frequency range (8-30 Hz) was evident at Cz but little ERS was seen at position C3 after task completion. The ERS was visible from aprroximately 4 seconds because the subject only performed the task once (dorsiflexion-planterflexion of foot) which is no longer than 1.5 to 2 seconds. It is therefore justified that ERD gets visible right from the beginning when the subject prepares for the presentation of visual cue till performance of task is done, followed by an ERS (blue) reflecting a relaxation period. In *Fig. 5 (b)* the left foot ME resulted in a significant ERD at electode position C3 right from start of visual cue display at approxmiately all frequencies between 8-40 Hz. ERS was not very significant and occurred near the completion of the task at 3.5 seconds. At position Cz ERD was prominent starting from visual cue onset at frequencies between 5-25 Hz and a dominant ERS was visible at near 5 seconds upon finishing of task and relaxing from 24 to 37 Hz. *Fig. 5 (c)* reflected the time frequency maps during the right foot MI task at position C3 and Cz. At C3 a very dominant ERD pattern was visible from 8 to 32 Hz during the cue onset till execution of task. Prominent ERS occurred at 4 till 5.5 seconds indicating the ending of task and initialization of rest. The map at electrode position Cz for the right foot MI didn't show a clear ERD pattern. It rather reflected scattered ERD powers in low mu and high beta ranges followed by a dominant ERS occuring during the imagery task between 9 to 20 Hz.

In general, not all electrode positions depicted explicitly clear ERD/ERS patterns; however in few conditions the electrodes reflected good results.

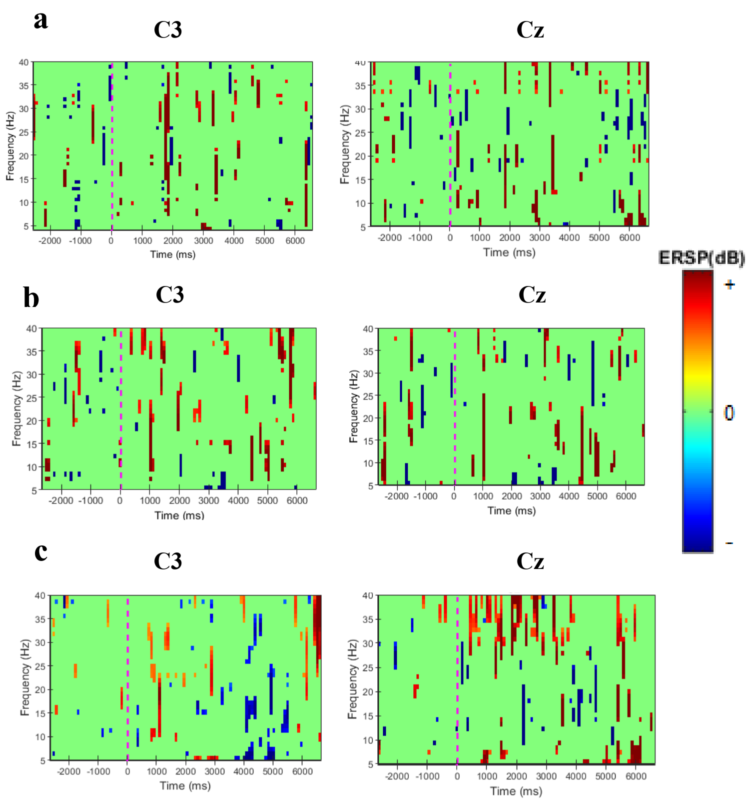

Fig. 5. Time-frequency maps displaying significant ERD (red) and ERS (blue) for subject S2 for electrode position C3 and Cz (a) right foot ME, (b) left foot ME, and (c) right foot MI

C. *ERD/ERS Quantification*

Table 1 presents results of band power changes (ERD and ERS) of the most reactive mu and beta components in Hz for the electrode positions C3, Cz and C4 for the two ME (left foot, right foot) and two MI (left foot, right foot) tasks. For the mu frequency range, most reactive components ranged between 8 and 11 Hz for the ME/MI tasks. For the beta frequency range, most reactive components ranged between 12 to 29 Hz for the ME/MI tasks. Both mu and beta reactive frequency components were found at all central electrode positions.

The maximum ERD occurred at electrode position corresponding to Cz for left foot ME/MI in beta frequency range. For the right foot ME/MI maximum ERD was witnessed at position C3 in beta frequency range. Whereas maximum ERS for left foot ME/MI was visible at electrode position Cz corresponding to beta frequency range. For the right foot ME/MI the maximum ERS was visible at electrode position C3 in beta frequency range. Hence it can be clearly extracted that for the left foot ME/MI tasks ERD and ERS are maximum at electrode position Cz, which correlate to the already established findings reported in the literature [14]. For the right foot ME/MI the maximum ERD and ERS occur at electrode position C3 reflecting a contralateral dominance.

IV. DISCUSSION

In general both the ERD and ERS were visible for S1 and S2 as shown in *Fig. 6* to *Fig. 8*. *Fig. 6* shows an exemplary ERD/ERS time curve at 8 Hz mu rhythm for S1 performing left foot ME at electrode position C3. An ERD is prominent around 300 milliseconds after the visual cue display. About 1 second after the subject stopped executing an ERS can be seen at second 5.7.

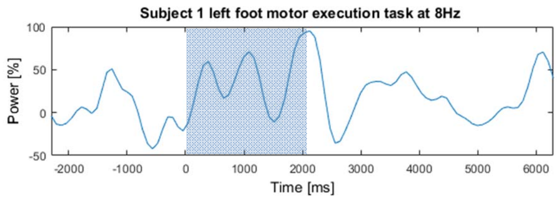

Fig. 6. ERD/ERS time curve obtained from left foot ME task for S1 at electrode position C3 for 8 Hz mu rhythm. Shaded area indicates cue display

Fig. 7 shows an exemplary ERD/ERS time curve at 14 Hz beta rhythm for S1 performing right foot MI at electrode position Cz. An ERD starts shortly before the end of visual cue display and continues until 800ms after the cue. An ERS is prominent around second 3-4 and at the end of the trial at second 6.

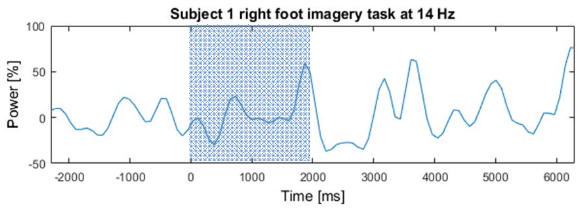

Fig. 7. ERD/ERS time curve obtained from right foot MI task for S1 at electrode position Cz for 14 Hz beta rhythm

Fig. 8 shows the exemplary ERD/ERS time curve at electrode position C3 averaged over two runs for S2 at 9 Hz. Averaging was conducted over two runs of ME and two runs of MI for the left foot. A prominent ERS at the end of the trial was obtained. A small ERD was obtained starting around 400 milliseconds after the cue display.

Based on the results it can be drawn that left and right foot discrimination task based BCI is valid both for ME as well as MI. Both subjects showed a percentage power increase and decrease for ERD and ERS respectively. This enables the implementation of a brain controlled bionic foot which is an interdisciplinary research area of socio-technical neurorehabilitation systems and addresses research questions in the field of intelligent robots and rehabilitation systems, and cognitive modeling of user adaptability. These questions are in accordance to some of the research areas addressed by CogInfoCom [15] as the augmented social intelligence, cognitive info-communication channels and industrial engineering aided by CogInfoCom.

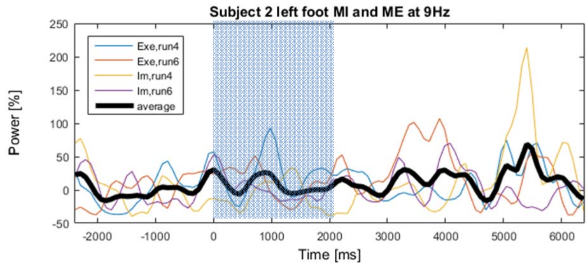

Fig. 8. ERD/ERS time curve obtained from left foot averaged over 2 runs for ME and MI task for S2 at electrode position C3 for 9 Hz mu rhythm

V. CONCLUSIONS

According to literature the MI/ME at electrode position Cz should enhance the foot area mu or beta rhythm respectively. However due to lack of literature available about the left and right foot tasks discrimination this study was based on distinguishing the left and right foot ME and MI tasks. Following that several results could be concluded. Our results overall suggest that, a BCI based on left and right foot ME/MI discrimination can be developed, despite the location of foot's motor area representation which is deep within the interhemispheric fissure of the cortex. The topographic maps reflected an interesting enhancement in the hand area high beta rhythm (beta ERS) representation during the individual left and right foot ME tasks. And a similar pattern was observed during low mu ERD and high beta ERS rhythms for right and left foot MI tasks individually followed by a contralateral dominance of the cortex for ERS patterns at position C3 during right foot MI task. The mean percentage of most reactive bands for ERD were not as high as expected, because of limited training sessions and less participants involved in the study. The main contribution of the conducted research, presented here, is the introduction and the trial of the new BCI concept for enabling the control of a robotic foot. In the future we aim to proceed this work by incorporating more subjects and classifying the left and right foot tasks for both ME and MI sessions to be used as a CogInfo Communication tool establishing a platform for neurorehabilitation in controlling BCI based robot applications for LL.

ACKNOWLEDGMENT

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TABLE 1(A) *MU* AND (B) *BETA* FREQUENCY BAND POWER CHANGES FOR MOST REACTIVE ERD -ERS FOR ME AND MI TASKS CALCULATED WITH BOOTSTRAP (α=0.05)

(a)	Left foot										Right foot								
	C3			Cz			C4				C3			Cz			C4		
ME	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	ME	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)
S1	8	-41	50	10	-25	30	8	-31	62		11	-41	52	10	-39	52	11	-38	49
S2	9	-37	52	9	-37	49	8	-33	54		9	-35	47	9	-43	32	8	-28	63
MI										MI									
S1	9	-49	90	8	-50	51	10	-57	65		11	-47	74	11	-50	80	10	-60	52
S2	9	-39	76	9	-45	41	9	-42	42		9	-32	117	9	-33	103	9	-36	82
Mean	8.8	-41.5	67	9	-39.3	42.8	8.8	-40.8	55.8		10	-38.8	72.5	9.8	-41.3	66.8	9.5	-40.5	61.5
SD	0.5	5.3	19.4	0.8	10.9	9.5	0.9	11.8	10.3		1.2	6.7	31.9	0.9	7.1	31.1	1.3	13.7	14.9

(b)	Left foot										Right foot								
	C3			Cz			C4				C3			Cz			C4		
ME	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	ME	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)	Hz	% (ERD)	% (ERS)
S1	27	-44	75	29	-42	127	25	-53	39		14	-47	66	22	-48	68	12	-44	60
S2	17	-48	54	26	-57	70	22	-44	72		14	-57	72	28	-44	60	20	-48	79
MI										MI									
S1	26	-52	109	14	-56	83	21	-51	83		17	-60	78	20	-31	71	15	-43	61
S2	15	-40	86	28	-42	88	17	-41	98		24	-43	80	24	-41	71	24	-39	76
Mean	21.3	-46	81	24.3	-49.3	92	21.3	-47.3	73		17.3	-51.8	74	23.5	-41	67.5	17.8	-43.5	69
SD	6.8	5.2	22.9	6.9	8.4	24.5	3.4	5.7	25		4.7	8	6.3	3.4	7.3	5.2	5.3	3.7	9.9

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