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A Quality Parameter for the detection of the intentionality of movement in patients with neurological tremor performing a finger-to-nose test.

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***Abstract*— The identification of the intentionality of movement is a key-aspect for the development of brain-computer interfaces (BCIs) applicable to daily life in neurological patients. We present a novel method of processing of electroencephalography (EEG) signals for the extraction of movement intention in neurological patients with upper limb tremor. This method is based on event-related EEG desynchronization, considering α (8-12Hz), β (13-30Hz), and γ (30-40Hz) bands. We have analyzed the EEG signals from the sensorimotor areas of 4 neurological patients presenting an upper limb tremor (grade 1 to 3/4) and executing successive finger-to-nose movements. A Quality Parameter (QP) for the detection of intentionality of movement has been extracted, by considering: (a) the changes in the β^2/α and β/α ratio (representing bursts of β-γ frequencies) during the pre-movement period; (b) an appropriate threshold predicting the movement; (c) the number of movements executed. This QP allows the prediction of the voluntary movement with a probability between 70% and 90%. This method could be implemented in a wearable BCI to detect the intentionality of movement and could be used, for instance, to trigger the electrical stimulation in selected muscles of upper limbs with the aim of blocking the emergence of tremor.**

I. INTRODUCTION

Recent studies aim to develop and validate a new treatment for upper limb tremor based on the combination of Functional Electrical Stimulation (FES) [1]-[2] with a Brain-computer interface (BCI). It is anticipated that a BCI-driven detection of voluntary movement can be used to trigger the FES, which is applied using a matrix of electrodes embedded in a wearable textile. Tremor would be selectively cancelled during a voluntary movement without interfering with the movement itself, thus resulting in smooth and accurate movements.

Different neural signals have been proposed for BCIs, such as electroencephalographic (EEG) recordings [3]-[4], slow negative potential shifts [5], and evoked potentials [6]. These last years, the attention has been put on spectral features of the EEG during the period preceding movement [7]. Indeed, EEG activity before the beginning of a movement is characterized by a decrease in the power of the α band (8-12Hz) and an increase in the β (13-30Hz) and γ (30-40Hz) bands. This phenomenon is known as event-related desynchronization/synchronization (ERD/ERS) [8].

In order to use the neural signals to control an electronic device improving the patient's motor performances, the analysis and the classification of these signals must be computed in real time [9]. However, the classification of EEG signals is challenging, because it has to be performed on a single-trial basis and not on averages of recordings.

We aim to suggest a Quality Parameter (QP) for the detection of the intention of movement in real-time. The QP takes into account (a) the changes in the β^2/α and β/α ratios, representing bursts of β or γ frequencies related to motor preparation of voluntary movements, (b) the appropriate threshold indicating which peaks of ratio are actually followed by a movement (and therefore may be considered as a predictor of movement), and (c) the number of movements executed.

II. MATERIALS AND METHODS

A. Patients description

Acquisition of data was carried out on 4 neurological patients following approval of the local Ethical Committee. Patients were affected by: Parkinsonism of vascular origin (n=1), Parkinson's disease (n=1), Essential tremor (n=1) and post-traumatic brain injury (n=1). Male/female ratio was 3:1. Mean age of the patients was 62±20 years. The patients were right-handed and presented with upper limb tremor of grade 1 to 3/4. The ADL-T24 score range was 4-17/24. Schwab and England ADL score ranged from 50 to 100%.

B. Experimental set-up

Patients were comfortably seated and equipped with an EEG conventional cap with the following location of EEG electrodes (10-20 system): FC3, FCz, FC4, C5, C3, C1, CZ, C2, C4, C6, CP3, CPZ, and CP4 (POz: ground; linked ear-lobes: reference). The patients maintained the eyes open. Artifacts were minimized by restraining head movements, keeping jaw and face relaxed and by avoiding swallowing or blinking during the recordings. Artifact rejection was applied by visual inspection of traces. EEG signals were sampled at 256 Hz (re-sampling at 1000 Hz for synchronization purposes) and band-pass filtered at 0.5-60 Hz. IMU sensors (gyroscopes) were used. Two gyroscopes were located on the anterior face of the upper limb at about 4

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cm above and below the elbow, respectively. The patients executed sequences of "finger-to-nose" movements cued by acoustic orders. The finger-to-nose task consists in touching the nose with the index finger, keeping the index on the nose for about one second and coming back to the thigh (starting position). After (1) hearing an acoustic signal, the patient (2) prepared himself mentally for the execution of movement and (3) performed the task. The dominant arm was studied. During a single run, the task was repeated about 10 times. Patients were first trained in order to perform the task correctly. Each patient executed a maximum of 6 runs. The nomenclature used for the recorded files is “pppFNnn" standing for patient’s code, task executed ("Finger-to-nose") and run number, respectively.

C. *Signal analysis*

Upsampled EEG data were processed with a Hamming window of 256 samples, an overlap of 250 in the time domain. Spectrograms were computed at the frequencies from 1 Hz to 40 Hz with Goertzel algorithm using a short time Fourier Transform. A one-sided power spectral density (PSD) matrix was then obtained with (1):

$$P = \frac{2\left|S(i,j)\right|^2}{Fs \sum_{n=1}^{L} \left|w(n)\right|^2} \qquad (1)$$

P is then containing the PSD of each segment for the frequency range 1-40 Hz, w(n) denotes the Hamming window function and Fs is the sampling frequency (1000 Hz).

Three time intervals were studied: pre-movement period, movement period, post-movement period. The pre-movement period (lasting 2 seconds) was defined according to the acoustic order given to the patients and to the detection of the beginning of movement via the gyroscopes.

The α, β and γ frequency bands were compared by calculating β/α and β^2/α ratios. PSD in a β-γ frequency band was divided by the PSD in the α frequency band, according to (2).

$$ratio(t) = 10 \log_{10} \frac{\sum \beta_f^n(t)}{\sum \alpha_{f'}(t)} \qquad (2)$$

Where $n = \{1,2\}$ depending on the ratio considered (squared or not).
f is the interval of β-γ frequencies (e.g.: from 26 to 33 Hz).
f' is the interval of α frequency (e.g.: from 8 to 10 Hz).

To extract these sub-bands, the following intervals in the α, β and γ frequency bands were first studied: 8-12Hz (8Hz, 9Hz, 10Hz,11Hz,12Hz), 8-10Hz, 10-12Hz, 13-40Hz, 13-26Hz, 26-40Hz, 13-20Hz, 20-26Hz, 26-33Hz, 33-40Hz, 13-16Hz, 16-20Hz, 20-23Hz, 23-26Hz, 26-30Hz, 30-33Hz, 33-40Hz. Therefore, each β-γ interval was compared with the α intervals. A total amount of 105 couples of intervals were thus analyzed. By applying (2) to the EEG power spectra from all the EEG channels and the successive runs, we obtained *ratiograms* which are spectrogram-like representations of EEG activities on the skull. An alternative technique using a fitting procedure has also been tested. Data were filtered and processed with a level 12 polynomial fitting in order to build an artificial EEG signal supposed to produce a smoother signal for spectral processing.

D. *Threshold and Quality Parameter*

The peaks (β/α and β^2/α ratios) higher than a defined threshold were considered as indicators of a potential voluntary movement, given that they represent the detection of the cortical motor preparation of the movement (Fig. 1).

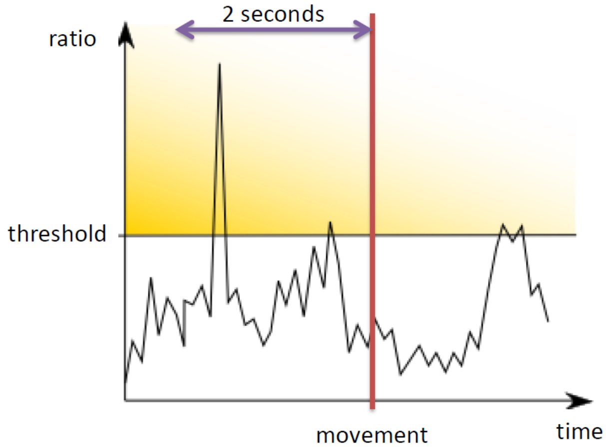

Fig. 1. Schematic representation of the thresholding procedure. Note the peaks (for an arbitrary ratio amongst the 105 ratios processed) higher than the threshold occurring in the pre-movement period.

Two methods were applied to determine the appropriate threshold. These methods were designed to detect peaks in ratiograms:

-a first static method was to define the threshold as a percentage of the maximum ratio over time. We tested the effectiveness of the threshold fixed at 40%, 50% and 55% of the highest ratio.

$$T = \max(ratio(t)) \forall t \qquad (3)$$

-a second statistical method was to define the threshold considering the mean and the standard deviation of the ratios:

$$T = mean(ratio(t)) + (K \times std(ratio(t))) \forall t \qquad (4)$$

where *std* stands for standard deviation, and *K* is a constant coefficient. Note that the mean and the std are global to the whole record. We tested: mean+4std, mean+4.5std, mean+5std, mean+5.5std.

All the values of ratios higher than the threshold and occurring within a pre-movement time window of 2 seconds were counted and divided by all the values superior to the threshold occurring outside the pre-movement window. This calculation was applied to each EEG channel and the maximum value was retrieved. Such parameter was expected to represent an index of prediction of a voluntary movement. However, this value was found to be unreliable. Indeed, this method could result in a high probability of movement also in the case when only one single movement is effectively executed along the run, thus providing an erroneous prediction (false positive). To solve this issue, the number of movements detected was added in order to adjust the sensitivity of the index and to obtain a robust value, considering that this kind of error would compromise the procedure for the definition of the threshold. We thus defined a QP as the geometric mean of the probability of movement (true positives) and the number of movements executed. A good QP has a value equal or higher than 70% [10]-[11]. Therefore, a run presenting a probability of voluntary movements of 100% (meaning that each peak of the ratio is followed by a movement) and of 18% of movement detected (meaning that the patient did not executed the task after each order) -as logically expected- is associated with a low quality parameter ($QP = \sqrt{100 \times 18} = 42\%$).

III. Results

Fig. 2 shows the ratiogram from the run 001FN04 (total duration of about 2 minutes). In this case, the sub-bands 8-10Hz and 26-40Hz have been selected to compute the β^2/α ratio.

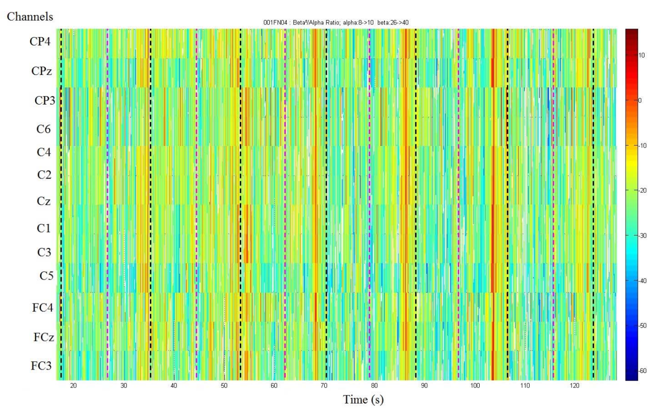

Fig. 2. Ratiogram of the β^2/α ratios. Sub-bands selected: 8-10Hz and 26-40Hz. The figure shows the changes in the values of the ratios (color scale) over time (X axis) and along the 13 EEG channels studied (Y axis). The magenta dotted lines indicate the acoustic order and the black dotted lines the movement performed. Note that the increases of ratios occur mainly in the pre-movement period (in yellow-red).

A total of 17 runs were analyzed (see session II.B and Fig. 3). The values of the best QP obtained were higher than 70% in almost all the cases studied (Fig. 3), although an intra-patient variability was found. These values have been selected among the QP obtained with the 2 methods for calculating the threshold and the different ratios of sub-bands (β^2/α and β/α). The mean QP was 82±12% (median= 83.5%) for the β/α ratio and 79.5±10,4% (median= 80%) for the β^2/α ratio. We found no significant difference between the QP calculated from β/α ratio and β^2/α ratio ($p = 0.502$).

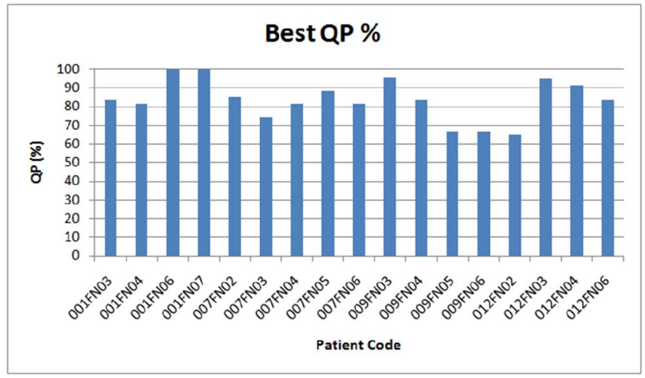

Fig. 3. Overview of QP for all the runs. Each patient executed several runs of successive finger-to-nose movement. The figure shows the best QP obtained.

Regarding the fitting procedure of EEG traces, the error was very close to zero. However, the fitting influenced the data processing in a variable manner, either improving or worsening the results for the QP along the different runs performed by the patients.

The different methods used for computing the threshold influenced the values of QP with an inter-patient and intra-patient variability. The highest QPs were found when the selected sub-band of frequency included the 30-35Hz. A strong correlation (r=0.97) was identified between the QP and the ratios obtained from β-γ sub-bands, progressively shifting towards high frequencies divided by α sub-bands (i.e. 13-16Hz/α, 16-20Hz/α, 20-23Hz/α, 23-26Hz/α, 26-30Hz/α, 30-33Hz/α, 33-40Hz/α). A sub-band of interest is more difficult to identify for the α band. However, the entire α band and its sub-bands never provided low values of QP. Figure 4 illustrates a way of localizing (in the frequency domain) the preparation of movements, with the highest QP's.

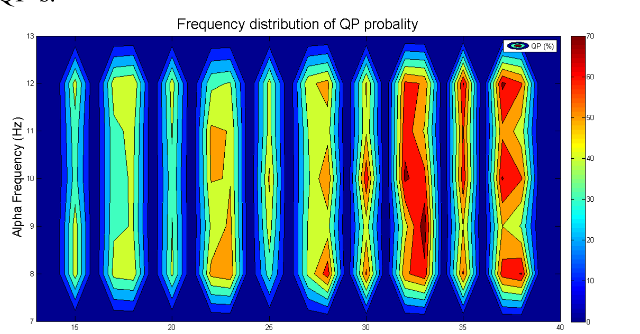

Fig.4. Illustration of the QP probability maps with a color code. The frequencies in the beta-gamma band are given on the X axis. The Y axis corresponds to the alpha band. Hot spots are clearly identified between 30 and 40 Hz, whereas a sub-band of interest is more difficult to identify for the alpha band.

An illustrative map of the QPs computed from the signals at the different EEG channels is shown in Fig. 5. As expected, the best values for prediction of movement have been found in C1-C3 channels (right-handed patient performing a movement with the right upper limb).

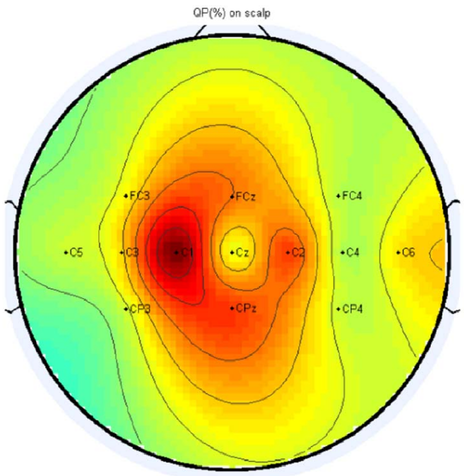

Fig. 5. Mapping of the QPs. QP is higher in the EEG signals recorded from the C1-C3 channels. This means that signals from this area (red) provide a higher probability to efficiently predict the intention of movement.

IV. Discussion

We present a novel method to predict the intentionality of movement in neurological patients presenting tremor in the upper limbs. We have extracted a "Quality Parameter" (QP), defined as the geometric mean of the probability of movement prediction (based on the changes in ratios of sub-bands according to the ERD/ERS phenomenon) and the number of movements detected. We propose that values equal or higher than 70% correspond to a good QP [10]-[11]. QP values even greater than 90% were observed in some runs performed by 3 of the patients. However, an inter-patient and intra-patient variability was found and further evaluations with a larger number of patients and runs per patient are required. The complexity of EEG recordings in patients with tremor performing upper limb movements should not be underestimated. The fitting step improved the results only in some of the signals analyzed, but had also deleterious effects in other cases. This procedure would result in an increase of the processing time in a real time device without improving the final results. However, a fitting module could still be taken into consideration for those patients who beneficiate from this method, in a case-by-case situation.

During the experiments, patients were asked to focus their attention on the execution of the task, and to execute the movement after an acoustic signal. Therefore the selected time window of 2 seconds was an appropriate interval for the laboratory use. In daily life, movements are most often performed in a semi-automatic way and their analysis may require a shorter time window. These are 2 limitations that need to be considered. QP parameter has been defined as a geometric mean in order to force both the true positive stimulation rate (in case of FES application) and the percentage of detected movements to be high enough to obtain a good QP value. The threshold step uses a global standard deviation (see II.D.). In practice, the std could be segmented with the same time frames described in section II.C. Moreover, adaptive algorithms could be implemented to take into account variations of the std and, thus, to adapt to different kinds of activities that have different ratio profiles. We suggest that the choice of the thresholding method and the convenient sub-band ratio for the application of QP in the framework of a BCI-driven system should be made for each patient, depending on the disorder.

V. Conclusion

The QP is a promising index in the field of the ERD/ERS-based methods to detect the intention of movement for future BCI applications. This parameter could be also used to process EEG recordings from wearable dry electrodes. Devices developed for the treatment of motor disturbances, such as a wearable FES system for the modulation of the upper limb neurological tremor, might benefit from this approach. Moreover, the analysis presented here could be considered as one part of a more complex process for the detection of movement intention, which would take into account other parameters of predictions, in particular parameters extracted from the cortico-kinematic and the cortico-muscular coherence (multi-modal approach with redundant information sources).

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