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Wavelet and Region-Specific EEG Signal Analysis for Studying Post-Stroke Rehabilitation

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Abstract—**Post-stroke monitoring is a crucial step for properly studying the progress of stroke patients. The rehabilitation process consists of exercise regimes that help in constantly engaging the affected part of the brain leading to faster recovery. The work here studies the effectiveness of the rehabilitation regime by investigating several parameters that can play important role in observing the immediate effect of the exercises. Various parameters from different wavelet coefficients were extracted for monitoring rehabilitation for up to 90 days. Energy and waveform length show maximum variation when monitoring pre and post-exercise changes. The parameters were correlated with clinical(FMA) score. Centroid Index gave high correlation value for beta band (r = -0.559). Alpha band on the other hand showed a good correlation with all the extracted features, maximum being -0.6988 with energy. So for monitoring post-stroke rehabilitation alpha and beta bands should be focused. Region-specific analyses were also done to monitor changes in different parts of the brain.**

Keywords—Stroke, rehabilitation, EEG, wavelet, occipital, Q-EEG

I. INTRODUCTION

Stroke has been a leading cause of death and disability for past few decades. The death rate due to stroke is very high worldwide. One of the survey by WHO states that it is leading cause of disability in adults. The improper supply of oxygen leads to sensory, motor, speech loss and even paralysis. Majority of the patients affected by stroke have limb motor function loss [1]. Rehabilitation is required to help these patients to regain the lost motor function [2]. The idea behind rehabilitation is to engage that part of the brain regularly so that recovery is faster and brain neuroplasticity takes place at faster pace. The therapies suggest exercises that mimic daily life activities [3]. The therapies have advanced to the extent where robots assist patients to perform exercises. There are even trained systems that help to move the limb according to the exercises fed in them [4]. There are also several Virtual Reality (VR) games that are interactive and help patients perform exercises while enjoying the game [5].

To study the effect of these therapies it is crucial to continuously monitor the patients for any progress in motor recovery [6]. Electroencephalogram (EEG) is one such important tool that can help us in monitoring the progress. EEG has been successfully used in BCI neuro-feedback systems in the rehabilitation process.

There are many studies that discuss important useful EEG parameters for studying motor rehabilitation in stroke patients. Quantitative EEG (Q-EEG) is one such domain that contains various parameters to quantify EEG signal in time and frequency domain [7]. Researchers have also used various band powers as input feature to monitor rehabilitation. The power of alpha band is found to be higher for healthy subjects than that for stroke patients [8]. Brain Symmetry Index(BSI) is one such parameter that quantifies symmetry of left and right hemisphere of the brain [9]. The studies till now have reported parameters by comparing healthy vs stroke subjects. But for properly studying the rehabilitation progress it is important to study the same subject at different time points. In our previous work [10], we extracted some features and correlated it with FMA score. The results were quite promising but as EEG is a non-stationary signal we extended our study to see variation in various EEG sub-bands. The proposed novel EEG feature namely Centroid Index (CI) was computed and correlation was done with the long-term database for studying the efficacy of post-stroke rehabilitation. We also extracted some other parameters that can be used as clinical indices in future.

II. MATERIAL AND METHOD

A. Subjects

A total of 30 post-stroke subjects with upper limb impairment were recruited in this study. The target of this study was to collect data up to 90 days. During the data collection process, 10 subjects dropped out in the middle; 12 subjects did not show up for the follow up schedule and 3 subjects did not come for day 90 data collection. So, this study was done with 5 post-stroke subjects (male) having upper limb impairment. They had blockage in frontal, occipital and central part of the brain. The baseline clinical data about subjects is mentioned in Table I. The left hemisphere of the subjects was effected that lead to impaired movement of right hand. Three subjects out of five had stroke in the occipital region of the brain.

TABLE I. CLINICAL BASELINE DATA

Variable	N = 5
Age (mean±SD) years	61±10.6
Baseline Fugl Meyer Assessment (mean±SD)	94.8±30.6
Diabetes	3(21.4%)
Hemoglobin, gm%	12.4±2.3

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B. EEG Data Acquisition

All the subjects were given proper information about the experiment and informed consent was obtained. The study was thoroughly reviewed and approved by the Ethics Committee at Christian Medical College, Ludhiana. The experiment was conducted in the Department of Neurology, Christian Medical College (CMC), Ludhiana, India. For acquiring EEG data, the subjects were asked to sit in a relaxed position and the exercises were performed with the help of a physiotherapist. The whole data acquisition is shown in figure 1. The data recording process was carried out on Day 1, Day 2, Day 7, Day 30 and Day 90 for all 5 subjects. EEG data was recorded using *g.HIamp* biosignal amplifier (g.tec medical engineering GmbH, Austria) having 64 gel-based electrodes. The device was set to 256 Hz sampling rate, 50 Hz notch filter, 0.5-40 Hz bandpass filter. The electrodes were placed according to 10/20 electrode international system (see Fig. 5(f)).

Start	Pre-exercise relaxation	Motor Imagery (5 trials)	Motor Execution (5 trials)	Post-exercise relaxation	End

Figure 1. Data recording session

C. Signal Pre-processing

The baseline was corrected and Common Average Referencing (CAR) was applied to reduce the noise in the acquired EEG signals. At last Independent Component Analysis (ICA) was done to remove ocular artifacts. All the pre-processing and feature extraction was done offline using *MATLAB* (The MathWorks, Inc.) and EEGLAB toolbox. For extracting features; few electrodes were used namely: FC1, FCz, FC2, C5, C3, C1, Cz, C2, C4, C6, CP3, CP1, CP2, CP4 (see fig 5(f)). For feature extraction pre-exercise relaxation and post-exercise relaxation data was used. The proposed method is shown in fig. 2.

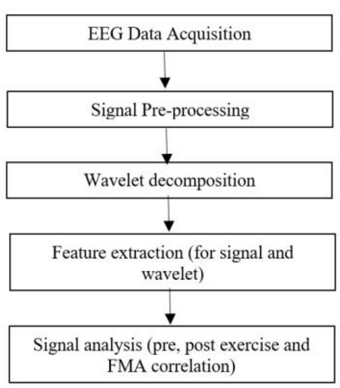

Figure 2. Proposed Method

D. Feature Extraction

The features were extracted from wavelet coefficients for different EEG sub-bands i.e. delta (0.5-4Hz), theta (4-8Hz), alpha (8-12Hz), beta (12-30Hz), gamma (30-40Hz). A six level wavelet decomposition was done. Approximation coefficient was used for delta band and detail coefficients were used for rest of the sub-bands. Features mentioned in Table II were extracted.

TABLE II. FEATURES EXTRACTED FROM THE DATA

Features	Formula
Entropy	$H(x) = -\sum_{i=1}^{n} P(x_i) log_b P(x_i)$ (1) *where P(x) is the Probability Mass Function*
Energy	$E_x = \sum_{n=1}^{N} \lvert x(n) \rvert^2$ (2)
WaveformLength (WL)	$WL = \log_{10}(\sum_{i=1}^{n-1} \lvert x_{i+1} - x_i \rvert)$ (3)
Centroid Index (CI)	$CI = \sum_{n=1}^{N} n * x^2(n) / \sum_{n=1}^{N} x^2(n)$ (4)

III. RESULTS AND DISCUSSION

A. Analysis on Wavelet coefficients

Energy, Entropy, CI and WL features were extracted for each sub-band's wavelet coefficients. Figure 3 shows methodology on immediate effect of post-stroke rehabilitation regime on Day 1, through wavelet coefficient features using mean and standard deviation. Fig. 3(a1) (a4) show that energy of delta and beta bands decrease immediately after exercise. The energy of gamma band (see fig. 3(a5)) shows drastic change in the energy. Entropy changes are much more prominent in alpha, beta and gamma bands (see fig. 3(b3-b5)). Centroid Index values decrease for each band except for delta band which shows increase after exercise. The decrease in the CI values tells us that the subject is responding quickly when asked to perform an action. Waveform Length on the other hand shows promising results. An immediate increase in the feature value can be seen in all the bands except for beta where the WL values drop (see fig. 3(d1-d5)). As WL is a measure of complexity of the signal; an increase in its value marks rehabilitation.

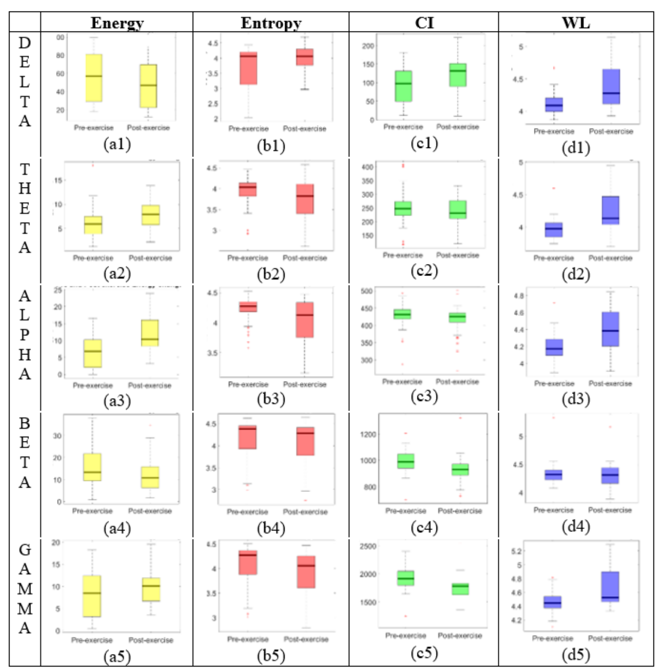

Figure 3. Pre and post exrcise effect on different wavelet band for Energy, Entropy, SL, WL features on Day 1

The clinical assessment of motor impairment was done using Fugl-Meyer Assessment (FMA) score. Table III shows the correlation coefficient (r) between change in FMA score (ΔFMA) vs change in EEG parameters (ΔFeatures) for each wavelet band using 25 data samples (5 subjects * 5 data-points). The ΔFMA score indicates clinical improvement which was correlated with the derived features: Energy, Entropy, CI, WL. From the table it can be seen that all the band except delta show high correlation with energy. Alpha band shows a correlation of 0.6988 ($p < 0.001$) with energy, beta band on the other hand shows high negative correlation ($r = -0.6684$) indicating energy of alpha band increases and that of beta band decreases with rehabilitation. Entropy of each band decreases with rehabilitation except for delta band. Beta and alpha band show high negative correlation with Centroid Index telling quick response of subject with respect to exercise onset. Beta band gives a correlation value of -0.559 with a very low p-value. Waveform length shows high positive correlation with delta, theta and alpha bands.

TABLE III. CORRELATION WITH ΔFMA FOR DIFFERENT WAVELETS

	Energy		**Entropy**		**CI**		**WL**	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Delta	-0.283	0.171	0.355	0.08	0.439	0.028	**0.571**	0.0028
Theta	**0.5451**	0.0048	-0.414	0.03	-0.419	0.036	**0.593**	0.001
Alpha	**0.6988**	0.0001	**-0.486**	0.01	**-0.486**	0.014	**0.588**	0.002
Beta	**-0.6684**	0.0003	-0.429	0.03	**-0.559**	0.0036	-0.309	0.13
Gamma	**0.5003**	0.0109	**-0.461**	0.02	-0.292	0.1567	0.298	0.15

B. *Analysis for Motor Cortex and Occipital region*

Power Spectral Density (PSD) analysis was done for specific regions of the brain to monitor their changes in attention. Figure 4 shows zoomed in (7-11 Hz) PSD of the channels from motor cortex region which generates impulses responsible for execution of movement. Channels C3 and C2 show peaks at 8Hz whereas C1, C4 and Cz have peaks at 9Hz. From the plots it can be seen that PSD for the motor cortex region increases as we move from day 1 to day 90.

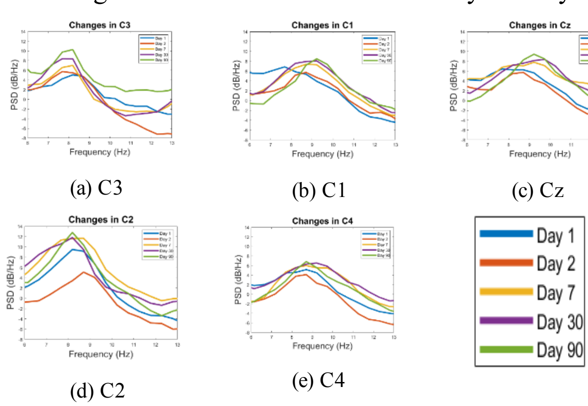

Figure 4. PSD analysis for Motor Cortex region

Figure 5 shows changes in the Occipital channel (O2) of the brain. The changes were observed just after exercise for each day from O2 channel. Some studies reported significant changes in occipital region for alpha rhythm [11] but an analysis on before and after exercise is not explored. The PSD analysis from O2 clearly shows that before exercise (blue line) subjects were less attentive but just after one exercise session significant changes were seen and the subjects were more active (red line).

Topo-plots were studied to see changes in each band. It can be seen in figure 6 (a)(b), prominent changes are seen in the frontal lobe of the brain for delta band which is responsible for attention and voluntary movements. Changes were also observed in the theta frequency range for parietal and primary motor cortex region of brain (see fig. 6(c)(d)). There were changes in occipital and frontal lobe of the brain for alpha frequency (see fig. 6(e)(f)). Figure 6(g)(h) shows pre-exercise and post-exercise changes in the temporal and parietal region of the brain for beta frequency. The inactive temporal region of the brain shows sign of activity after exercise. Activity in the temporal and central region of the brain for beta band marks alert and focused subjects.

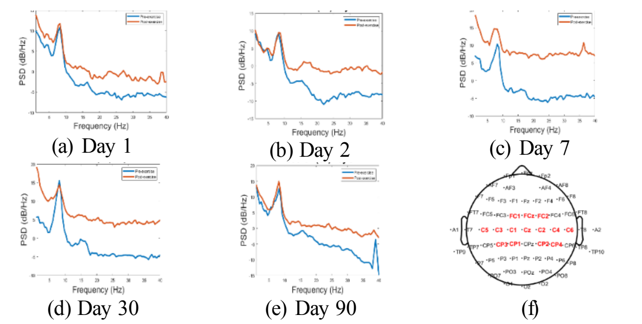

Figure 5. Pre and post exrcise effect on channel O2 from day 1 to day 90.

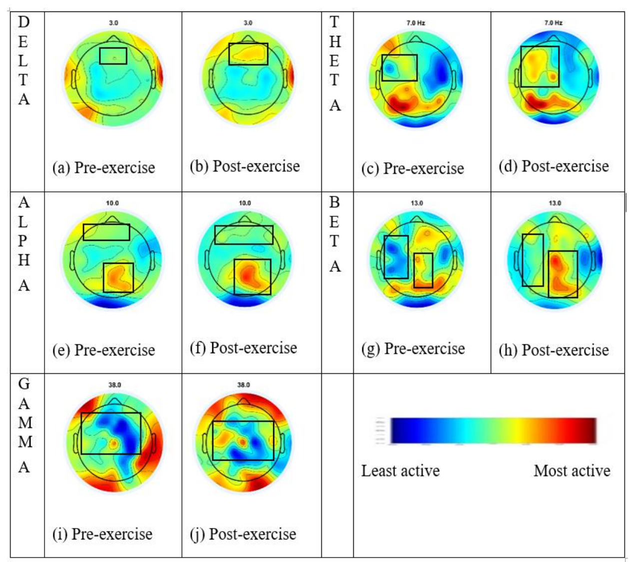

Figure 6. Topoplots of pre and post exercise for each sub-band

C. *Analysis for hemisphere symmetry Q-EEG parameters*

Q-EEG parameter like Delta-to-Alpha ratio (DAR), Delta-to-Theta ratio (DTR) and Power Ratio Index (PRI) were calculated to monitor brain symmetry. The parameters were calculated for frontral-central, central and central-parietal region of the brain using equation 5, 6 & 7; the x-axis is arranged in the manner that left and right hemisphere are separated by Cz electrode. In figure 7 we can see that the values in each channel decreases as we move forward in our rehabilitation regime. Day 1 has the highest values and as the subjects' undergo motor rehabilitation; values decrease. Also we can see that there were more fluctuations between left and right hemispheres of the brain during first day of analysis (seen in blue line) and the symmetry/fluctuations decreased with rehabilitation progress (seen in green line). All three parameters show similar trend.

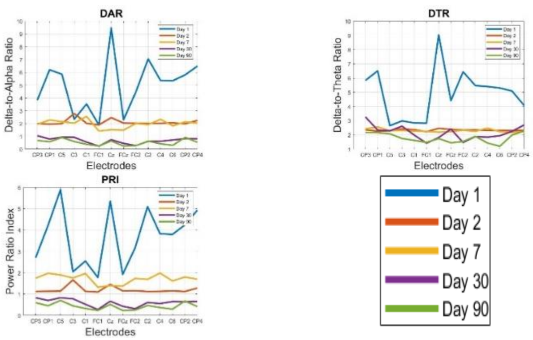

Figure 7. Q-EEG parameters

$$DAR = \frac{\delta}{\alpha} = \text{Delta-to-Alpha Ratio} \tag{5}$$

$$DTR = \frac{\delta}{\theta} = \text{Delta-to-Theta Ratio} \tag{6}$$

$$PRI = \frac{\delta+\theta}{\alpha+\beta} = \text{Power Ratio Index} \tag{7}$$

IV. CONCLUSION

The study here focused on studying pre-exercise and post-exercise effect on stroke patients. Another aim of the study was to present some potential parameters that can help us in monitoring rehabilitation process in long run. The above analysis was done on wavelets to see the effect of exercises in individual bands. Energy decreased for theta and delta band whereas an increase was observed in the other three bands. Entropy and waveform length also showed immediate change in values for each band. The correlation results of these features for each band shows that energy (except for delta band) can act as a marker for monitoring rehabilitation as it shows good correlation. Entropy can be used if we want to see effects in alpha and gamma bands. Waveform length also shows high correlation for delta, theta and alpha bands; so WL can be seen as a potential marker for studying post-stroke rehabilitation. CI shows good variation in alpha and beta band. Also, alpha and beta band show the maximum variation.

The motor cortex region showed rehabilitation in the alpha band range. The occipital region of the brain showed immediate positive affect of exercise regime. Frontal, occipital and temporal regions of the brain showed most significant change in activity for alpha and theta band range. The inactive region became active just after one session of the exercise regime. To study the symmetry changes between left and right hemisphere of the brain Q-EEG parameters were extracted up to 90 days. The asymmetry between left and right of the brain reduced with rehabilitation and similar pattern was seen for all three Q-EEG parameters.

Of all the bands, alpha band shows good variation with all the extracted features. High correlation values were also found with beta band for energy and CI feature. So for further studies alpha and beta bands can be focused for monitoring rehabilitation. Frontal, temporal and occipital regions should also be explored in further studies. In future more EEG parameters could be added for intra-subject analysis to understand quantitatively the efficacy of post-stroke rehabilitation.

APPENDIX

Institutional ethical clearance: 201808386/IECCMCL/RENEWAL-APPRVL/IMPRINT (Dated 28/8/2018).

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