DETECTING NONLINEAR DETERMINISM OF EEG SIGNALS IN PARKINSON'S DISEASE (PD)

Amir H. Meghdadi[1], Reza Fazel-Rezai[1,2], and Martin J. McKeown[3]
[1]*Department of Electrical and Computer Engineering, University of Manitoba,*
[2] *Institute for Biodiagnostics, National Research Council (NRC), Winnipeg,*
[3] *Brain Research Centre, University of British Columbia*

I. INTRODUCTION

The Parkinsonian state is defined by widespread oscillations in both cortical and subcortical brain structures. Usually these oscillations can only be detected by electrodes that have been invasively placed in the brain for the purpose of treatment via Deep Brain Stimulation (DBS). Here, we investigate using determinism in non-invasively acquired, scalp-based EEG signals as a marker for the widespread changes known to occur in the brains of subjects with PD. The method is based on smoothness analysis of reconstructed trajectories in the embedding space calculated from principal components of the signal [1][2], and, as we have shown previously, is robust to additive noise [1].

Previous studies have investigated correlation dimension, using a spatial embedding method, in EEG recordings from PD, but results have been inconclusive. A lower correlation dimension has been estimated for EEG of PD subjects [4], yet during the execution/imagining of a complex motor task, dimensionality is higher for PD subjects compared to normal subjects [3]. The correlation between the power of signal in beta band and correlation dimension previously described [4] may be indicative of the widespread oscillations seen in PD alluded to earlier.

Rather than estimating fractal dimension, which can be misleading as filtered noise can also exhibit finite fractal dimension[6], here we propose using a direct measure of determinism. The utilized method in this paper first uses singular value decomposition (SVD) to break up the time series into its principal components and then uses surrogate data analysis to test for determinism of each component. An overall index of determinism is then calculated for each short time segment of the signal. Surrogate methods [9] can then be used to determine the statistical significance of the results.

We found that the average index of determinism has higher variability in EEG segments of normal subjects compared to that for PD subjects. Moreover, comparing the index of determinism for PD subjects when they are on/off medication shows that medication increases the level of determinism in general. The results for different channel locations are also compared and shown on topographic maps of the scalp. The results suggest that determinism is higher in parietal areas of the scalp.

II. A METHOD FOR DETECTING DETERMINISM FOR SHORT TIME SERIES

The method is shown in Figure 1 and briefly explained here (please see [1] for a more detailed information). Assume $x(t)$ is the sampled time series of a variable in a deterministic dynamical system. The reconstructed trajectory in m-dimensional embedding state space is defined by the following points (state vectors) [5]

$$\vec{\mathbf{x}}_{\mathbf{t}} = \left(x(t), x(t-T), x(t-2T), \cdots, x(t-(m-1)T)\right)^{tr} \quad (1)$$

where T is the time lag between selected samples of the time series and tr denotes transpose operation.

These vectors are placed in subsequent columns of a matrix X named as trajectory matrix. The SVD of the trajectory matrix X can be written as $X = USV^{tr}$ where S is the diagonal matrix of singular values $\{\sigma_k\ , k = 1,2,...,p\}$ each establishes a principal component; V is the matrix of corresponding singular vectors; and $U = [\vec{u}_1 \ \ \vec{u}_2 \ \ \cdots \ \ \vec{u}_p]$ is a linear transformation which transforms the trajectory matrix X into Y as follows:

$$Y = U^{tr}X = SV^{tr} = [\sigma_1\vec{v}_1 \ \ \sigma_2\vec{v}_2 \ \ \cdots \ \ \sigma_P\vec{v}_P]^{tr} \quad (2)$$

For each component k, the projection of the transformed trajectory matrix Y on its k^{th} dimension is defined as the time series $x_k = \sigma_k\vec{v}_k$ that is regarded as one component. A standard time delay embedding method is then applied to each component to obtain a trajectory matrix of the component. Then, an index of determinism, which we name here smoothness index [8], is calculated for each component: CSI_k. Finally, the *compensated component smoothness index* ($CCSI$) is defined as the weighted average of all CSI_k as follows.

$$CCSI = \left(\sum_{k=1}^{P} \sigma_k^2 \times CSI_k \right) / \sum_{k=1}^{P} \sigma_k^2 \qquad (3)$$

Calculation of the smoothness index is based on a comparison between the smoothness of the signal trajectory and the average smoothness of its surrogates, where it is believed that smoothness implies determinism [7][10]. Full details about how the smoothness is calculated are given elsewhere ([8][1]. The smoothness index (and consequently the proposed *CCSI*) is a scalar value between 0 and 1. In the ideal case, the index should be very small (close to zero) for a deterministic system and very large (close to 1) for a stochastic system. In practice, however, a tolerance margin around 0.3 is considered and the level of determinism typically varies between 0.3 and 0.7 when signal and noise are mixed together. A block diagram of the method is shown in Figure 1.

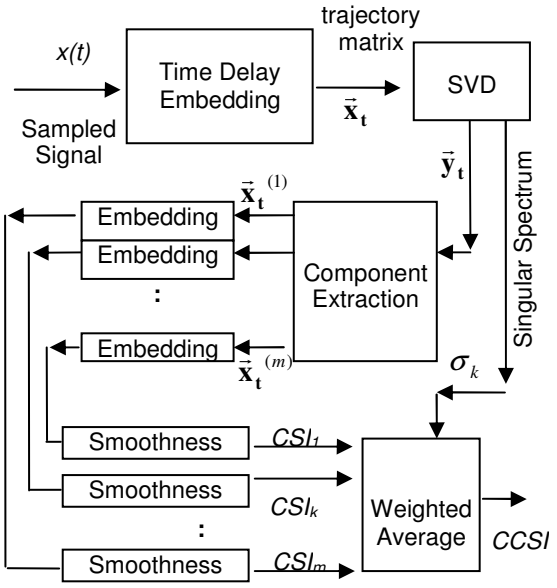

Figure 1: Block diagram of the method.

IV. DETERMINISM OF EEG FROM HEALTHY AND PARKINSON'S DISEASE SUBJECTS

The above method of detecting determinism was applied to time series of digitally recorded scalp EEG signals. Signals were recorded from 10 patients with clinically definite PD and 10 age-matched control subjects with no active neurological disorders. Exclusion criteria included atypical Parkinsonism, dementia, depression, obsessive compulsive disorder, schizophrenia and other related psychiatric conditions. Subjects on antidepressants, sleeping tablets, and dopamine blocking agents were also excluded from the study. All patients had mild to moderately severe PD with mean symptom duration of 7.8 ± 3.4 years. All patients were taking levodopa (mean daily dose 501 ± 206 mg), with an average morning dose of 148 ± 68 mg. Other medications included dopamine agonists, trihexyphenidyl, and amantadine. All patients had withdrawal of antiparkinson medications overnight for at least 12 hours before the EEG study. The mean Unified Parkinson's Disease Rating Scale (UPDRS) motor score during "off-levodopa" state was 27 ± 8. The study was approved by the ethics committee of the University of British Columbia.

Subjects underwent a continuous tracking task by using a joystick in response to visual stimuli that was designed for another study. PD patients underwent two EEG studies, one during 'off' state and the other after levodopa challenge. They were tested in the 'off' state after overnight withdrawal of all antiparkinson medications for at least 12 hours. At the end of the first EEG study, they were given immediate release Sinemet® at a dose equivalent to their usual morning dose of levodopa. They then had a rest for 40 minutes before repeating the second EEG study. All control subjects underwent only one EEG study

The EEG signals were digitally recorded with a sampling rate of 128 Hz during each study for 24 minutes. Signals were initially recorded with reference to both mastoids but later converted to a common average montage (CAR) to remove existing baseline artifacts. Channels PG1, PG2, FP1 and FP2 were excluded in calculation of the average because of the blink artifact. Signals were band pass filtered between 0.5 and 40 Hz. A moving window of length 10 seconds was used and the CCSI was calculated for all the channels during each window. The embedding dimension was set at *m=9* and the number of surrogate series used was *N=13*. The time delay used for reconstructing the attractor of each principal component was automatically selected to be the delay for which the autocorrelation of the signal drops to 1/e of its maximum.

The variations of the CCSI over time for all three groups of experiments (Normal control subjects, PD subjects off medication and PD subjects on medication) are shown in Figure 2 - Figure 4. Subject 3 in the healthy control group was excluded because it was an outlier. Distance between plots were reduced to 0.3 to show them all in one figure. The average and standard deviation of CCSI for all the signal segments in all channels (around 30000 segments for each group) were calculated for each group and the results are shown in Table 1 and the histogram of CCSI values are shown in Figure 5 for each group.

Table 1: The average and standard deviation of the CCSI values for each group of subjects

		mean	Std
Normal Subjects	N	0.68	0.18
PD Patients off Medication	PA	0.69	0.15
PD Patients on Medication	PB	0.63	0.15

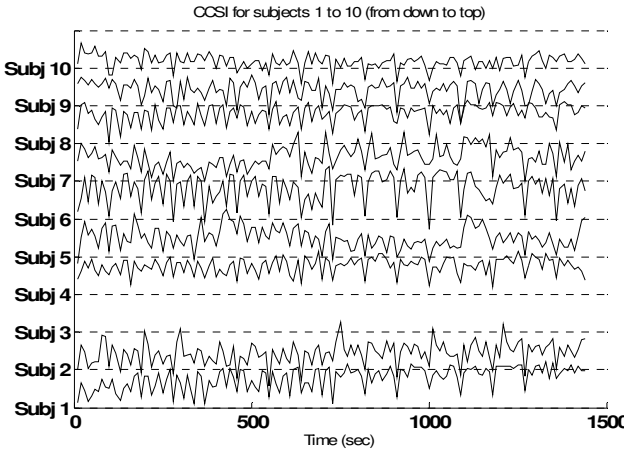

Figure 2: Variation of the average CCSI for all the normal subjects.

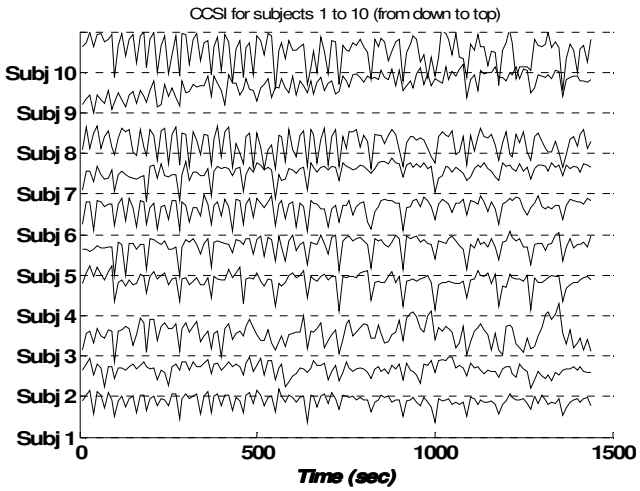

Figure 3: Variation of the average CCSI for all the PD subjects (off medication).

The effect of medication on each individual subject was also studied by calculating the average index of determinism among all channels for each PD subject. The results in Figure 6 demonstrate that when PD subjects are on medication, CCSI is generally lower (more deterministic) compared to the case when they are off medication.

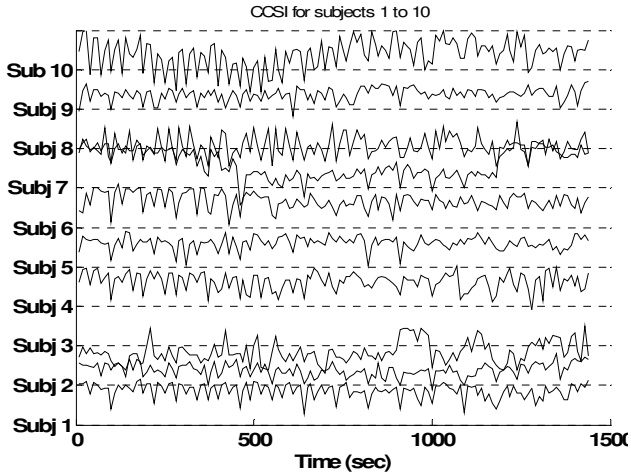

Figure 4: Variation of the average CCSI for all the PD subjects (on medication).

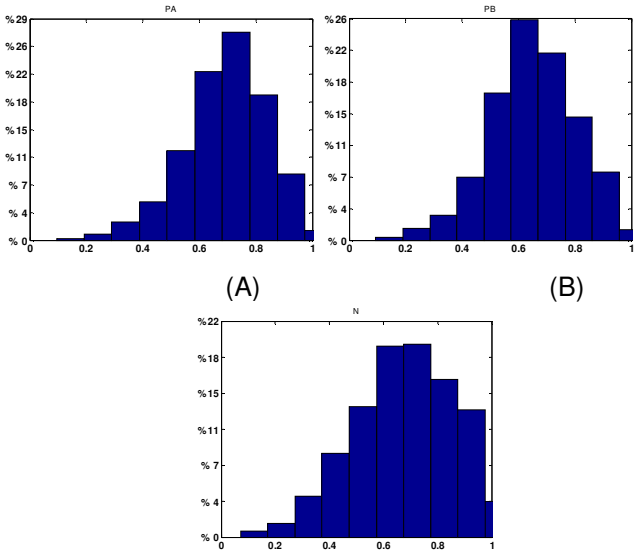

Figure 5: Histogram of the CCSI values for all the channels of all the subjects in each group, A (off medication), B(on medication), C(Healthy).

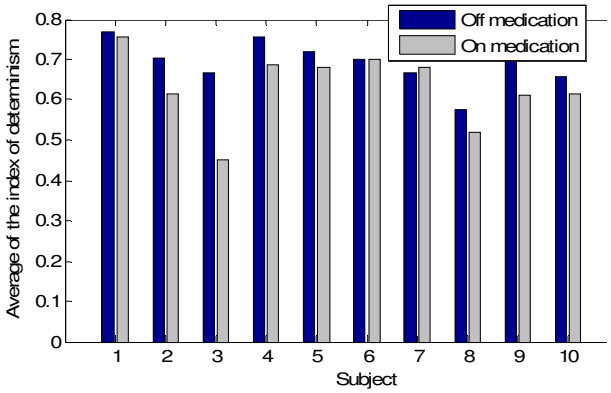

Figure 6: Comparison of the average CCSI between ON and OFF medication for each PD subject.

For each subject, the average of the CCSI during the whole experiment is also calculated for each channel separately. Topographic maps of the index values for two subjects as an example are shown in Figure 7 to Figure 9. Darker areas represent more deterministic regions.

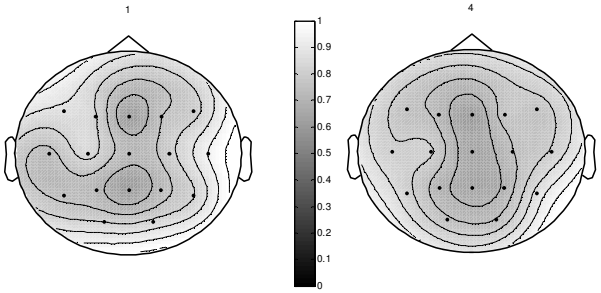

Figure 7: Topography of the CCSI on the scalp shown as an example for two normal subjects.

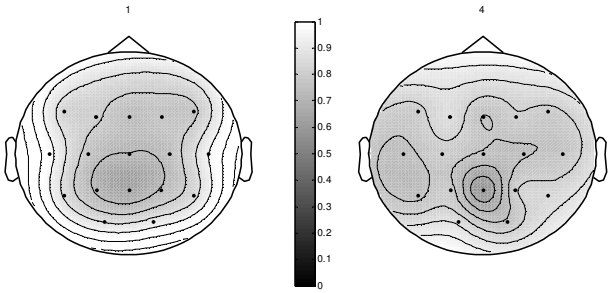

Figure 8: Topography of the CCSI on the scalp shown as an example for two PD subjects off medication (PA)

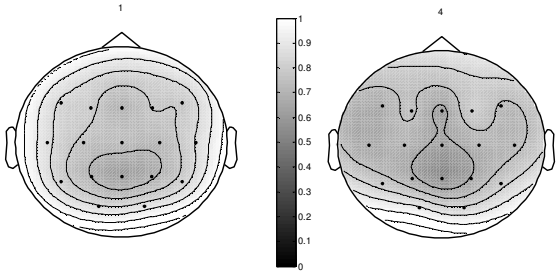

Figure 9: Topography of the CCSI on the scalp shown as an example for two PD subjects on medication (PB)

V. SUMMARY AND CONCLUSIONS

A measure-based approach in quantifying the level of determinism with respect to principal components based on trajectory smoothness analysis was used for characterizing EEG signals of patients with PD. We can conclude that:

- Patients with Parkinson disease (off medication) have slightly less deterministic EEG than normal patients in general. However, this difference is not significant and more statistical tests are needed to verify this finding.
- In most of the cases (8 out of 10 subjects), the patients had more deterministic EEG when they are on medication.
- Variability of the level of determinism is slightly higher for EEG of normal subjects compared to PD subjects (whether on or off medication).
- Generally, parietal areas near to electrode Pz have more deterministic EEG signals. The correlation between the brain condition and distribution of determinism on the scalp requires more investigation.

ACKNOWLEDGEMENTS

Financial supports from Manitoba Health Research Council, MITACS Canada and the National Parkinson's Foundation (USA) are gratefully acknowledged.

REFERENCES

[1] A. H. Meghdadi, R. Fazel-Rezai and Y. Aghakhani, "A Method for Detecting Nonlinear Determinism in Normal and Epileptic Brain EEG Signals," *The 29th Annual International Conference of the Engineering in Medicine and Biology Society (EMBS)* , pp. 2008-2011, 2007, Lyon, France.

[2] A. H. Meghdadi, R. Fazel-Rezai and Y. Aghakhani, "Seizure prediction by nonlinear smoothness analysis of scalp EEG recording," *Proceedings of the 30th Canadian Medical and Biological Engineering Conference*, June 16-19, 2007, Toronto, Canada

[3] V. Muller, W. Lutzenberger, F. Pulvermuller, B. Mohr and N. Birbaumer, "Investigation of brain dynamics in Parkinson's disease by methods derived from nonlinear dynamics," *Exp. Brain Res.*, vol. 137, pp. 103-110, Mar. 2001.

[4] C. J. Stam, B. Jelles, H. A. Achtereekte, S. A. Rombouts, J. P. Slaets and R. W. Keunen, "Investigation of EEG non-linearity in dementia and Parkinson's disease," *Electroencephalogr. Clin. Neurophysiol.*, vol. 95, pp. 309-317, Nov. 1995.

[5] F. Takens, "Detecting strange attractors in turbulence", Dynamical systems and turbulence, Lecture Notes in Mathematics, Springer-Verlag, vol. 898, pp. 366-381, 1981.

[6] P. E. Rapp, A. M. Albano, T. I. Schmah and L. A. Farwell, "Filtered noise can mimic low-dimensional chaotic attractors, *Physical Review E.*, vol. 47, pp. 2289-2297, Apr. 1993.

[7] L. W. Salvino and R. Cawley, "Smoothness implies determinism: A method to detect it in time series," *Physical Review Letters.*, vol. 73, issue 8, pp. 1091–1094, Aug. 1994.

[8] J. Jeong, J. C. Gore and B. S. Peterson, "A method for determinism in short time series and its application to stationary EEG," *Biomed. Eng. IEEE Transactions on*, vol. 49, issue 11, pp. 1374–1379, Nov. 2002.

[9] T. Schreiber and A. Schmitz, "Surrogate time series," *Physica D*: vol. 142, issues 3-4, pp. 346-382, Aug. 2000.

[10] G. J. Ortega and E. Louis, "Smoothness implies determinism in time series: A measure based approach," *Physical Review Letters*. vol. 81, issue 20, pp. 4345–4348, Nov. 1998.