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Recurrence Plots Visualize Task Periods in Noisy NIRS data

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Abstract– NIRS (Near infra-red spectroscopy) is a spectroscopic device with which brain activity can be measured non-invasively and low restrictedly. However, the obtained data are easily contaminated with noise. In addition, NIRS data, in principle, contain two unknown constants, therefore, the analysis of NIRS data is not well established. In this study recurrence plots are adopted to visualize task period in NIRS data. In addition, we examined the difference of brain activity between task period and non-task period using recurrence plots. As a result, it is shown that recurrence plots can visualize a task period in noisy NIRS data. Moreover, it was found that there are statistical differences in recurrence plots between task period and non-task period. The proposed method is robust to noisy NIRS data, hence it is suggested that recurrence plots contribute to the better practical use of NIRS.

1. Introduction

NIRS (Near infrared spectroscopy) is a device with which activation of the cortical surface can be measured. Using with different wavelengths of near infra-red light, absorbing ratio of the light can be measured [1]. Measurement with NIRS is non-invasively and low constrainedly, so subject can be patient.

2. NIRS

2.1. NIRS data

When neurons of the cortical surface activate, they require oxygen sufficiently much. Oxygen is transported in brain vessels, combined with oxygen-transporting protein which is called hemoglobin. As a result, the oxygenated hemoglobin concentration increases on the cortical surface. These changes gains the absorption of near infra-red light that is emitted from the extra cranial light source. With different wavelengths of near infra-red light, the relative oxygenated hemoglobin concentration changes can be calculated [2]. The formula of NIRS data is described below.

In principle, NIRS data contain two unknown constants. One is baseline *B*, which is the initial state of measurement. The other is optical path factor (*OPF*). NIRS data can be described as follows.

$$y(t) = B + OPF*x(t) + noise, \qquad (1)$$

where $x(t)$ is a time series of hemoglobin concentration changes from baseline and $y(t)$ is time series obtained with NIRS.

Neurons in the brain are activated even in a steady state so initial value of NIRS data is indeterminate. In addition, *OPF*s are different in measuring points, wavelengths of near infra-red light and subjects. That's why the analysis of NIRS data is not well established yet.

Two examples of NIRS data is shown in Fig. 1. In this measurement, the task is performed five times (20-40sec, 80-100sec, 140-160sec, 200-220sec, 260-280sec). It is difficult to estimate the task period from time series at a glance.

2.2. Model-based Analysis

Despite of many advantages in NIRS measure-ments, however, data analysis obtained by NIRS is not well established.

In the earlier researches with NIRS data analysis, subtraction between task period and non-task period was used. This method can extract the difference between those periods, but it still contains OPFs, so data measured in different points cannot be compared directly with each other [1].

Followed by subtraction, model-based analysis was reported. One of the major researches is about hemodynamic reactive function (HRF) [3]. This method depends on HRF (such as Gaussian and derivative family) and sometimes useful for static measurement (e.g. visual perception or cognitive tasks). However, it stands on the hypothesis that the error term obeys normal distribution.

In this study, we embedded NIRS data into high dimensional space and depicted the recurrence plots in reconstructed space.

3. Recurrence Plots

3.1. Embedding into high dimensional space

To extract the structure of time series, embedding in high dimensional space is done.

In this study, time delay τ is defined as the smallest positive integer that gives the minimal mutual information. Embedding dimension d is defined with a false nearest neighbor (FNN, threshold is 15).

3.2. Recurrence Plots

Recurrence plots are one of the powerful methods for characterizing time series [4] [5] [6], which enable us to extract the hidden structure of attractor embedded in high dimensional space.

Recurrence plots are primarily defined as a binary matrix of which all the elements are classified under the threshold. In broader definition, recurrence plots include a distance matrix whose elements consist of the distance among elements in the reconstructed space.

In this study, we adopted recurrence plots as distance matrix for the purpose of clinical use including BCI (brain computer interface), because recurrence plots as distance matrix are sometimes used in clinical research [7] [8].

4. Experimental Design

4.1. Subjects and Methods

Twenty-two healthy subjects participated in the experiment. They were all right-handed and were asked to grasp their hands during task period. One session consisted of three periods, pre-task period (20 sec), task period (20 sec) and post-task period (20 sec). Each measurement consists of five repetitive sessions. It is well known that left primary motor cortex (M1) activates in grasping [9], thus measuring point of NIRS was located corresponding to left M1 in each subject.

All the measurements were done with OMM-3000 (Shimadzu Corp., sampling rate 130ms) in accordance with the tenets of the Declaration of Helsinki and under the approval of the Ethics Committee of Tokyo Denki University. After the explanation of the nature and possible consequences of the study, written informed consent was obtained from all subjects.

4.2. Analysis of NIRS data

After acquiring raw NIRS data, we embedded them in a high dimensional space. On the other hand, we performed signal averaging over raw data, and calculated time delay τ and embedding dimension d for signal averaging data. Recurrence plots were depicted to visualize the hidden structure among three periods.

Furthermore, to validate the difference among three periods, histograms were constructed from signal averaging data. Then the average, median, mode (position of bin), AUC (area under the curve), skewness and kurtosis were calculated in three periods.

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5. Results

5.1. Embedding into high dimensional space

Raw NIRS data were embedded into high dimensional space. The averaged results of time delay and embedding dimension were $\tau = 2.1 \pm 1.0$ and $d = 5.6 \pm 0.6$.

5.2. Signal averaging

Signal-averaged NIRS data were embedded into reconstructed space. The averaged results of time delay and embedding dimension were $\tau = 2.1 \pm 1.0$ and $d = 4.3 \pm 0.5$. We checked recurrence plots in the reconstructed space. The results of characteristic subjects (#3 and #4) are shown in Fig. 2, which visualize the difference between the task period and the non-task period. Compared with Fig. 1, these results indicate better visualization of the task period.

5.3. Histogram

To validate the difference between task period and non-task period, we extracted the recurrence plots of each period, and constructed the histograms (the total number of bins is 40).

At first, maximum of each histogram was calculated. It was found that the maximum ranged widely (from .0240 to 0.568), therefore, with the aim of normalization, we divided individual recurrence plots' data with their maximum and treated the statistics. The results are shown in Table 1.

Secondly, to extract the difference among periods, we performed one-sided t-tests under the significance $\alpha = .05$. The results are shown in Table 2.

Between pre-task period and task period, there found the difference significantly. It was found that the average, median, AUC (area under the curve) and the number of bin which gives the mode were significantly larger in task period than in pre-task period, and that the skewness was significantly smaller in the period than in pre-task period. There found no difference significantly in the kurtosis between these two periods.

Surprisingly, there found no significant difference in the statistics listed above both between task period and post-task period, and between pre-task period and post-task period.

6. Discussions

6.1. Main idea of the study

In previous study, the embedding of NIRS data in high dimensional space has been reported [10] [11].
However, the research about recurrence plots based on the reconstructed attractor has not been reported yet.

6.2. Theoretical background

NIRS data contains two unknown constants, the baseline and the optical path factor (OPF). In this study, effect of a baseline is cancelled by calculating recurrence plots. In addition, by standardization, the effect of OPFs was removed. This standardization enables us to compare the data not only within a subject but also among subjects.

Aside from the baseline and the optical path factor, the data obtained with NIRS is easily contaminated by noise. Above all, physiological noise (such as heartbeat, pulsation and respiration), scalp blood flow and motion artifact are the representative ones. However, these physiological noise are regular, so they are expected to appear as a regular striped patterns in the recurrence plots. Scalp blood flow can be treated as constant [12], so it does not affect recurrence plots. Furthermore, the examiner checked postures of the subjects during measurements, so motion artifact does not do much harm the obtained data (sampling rate 130ms).

6.3. Recurrence plots as a result

Recurrence plots allow us to estimate the difference not only within a period but also between two or more periods. In Fig. 1, NIRS data obtained from characteristic subjects (#3 and #4) does not seem to have the structure in their time series, although, in Fig. 2, their recurrence plots has their own texture. In subject #3, the texture seems to be rather smooth, but it differs within each period. On the contrary, in subject #4, it is easy to see the different contrast between task period and non-task period. The former indicates the difference in intra-period structure, and the latter indicates the difference in inter-period structure, especially the difference in amplitude between periods.

6.4. Histograms of recurrence plots

It was shown that there is no significant difference in kurtosis among three periods (one-way ANOVA, $F = 3.14$, $d = (2, 63)$, $p = 0.61$). In this study, all the calculation were done with MATLAB2014, in which kurtosis of normal distribution is defined as three. Therefore it is suggested that, in each period, the histogram obeys the normalized-like distribution, and that, in accordance with periods, the distribution shifts horizontally and changes mesoscopically.

There found a significant difference in the average (<.01), median (<.01), number of bin that gives mode (<.05), AUC (<.05) and skewness (<.05) between pre-task period and task period. The reasons are as follows. The brain activates with fluctuation even in a steady state [12]. On the contrary, the motor task such as grasping is the collection of wired control of muscles, so the fluctuation in the task period is greater than that in pre-task period. Therefore, the average, median, the number of bin that gives the mode, and AUC are larger in task period than pre-task period.

The skewness in histogram is significantly smaller in task period than in pre-task period. This is because fluctuations of the data in task period are larger than those in pre-task period because of the motor control, and the range of data in task period spreads wide horizontally.

There are no significant difference both between pre-task period and post-task period, and between task period and post-task period in the statistics examined above. The reason why no difference exists in both pairs is that hemodynamic response fades out and go back to the steady state in at most ten seconds after neuronal activation quits.

6.5. For further study

Measurement with NIRS is excellent in versatility. If the analysis method is getting better, the application of NIRS will spread widely. Our proposed method is useful for noisy NIRS data, especially for the out-put type brain computer interface (BCI).

7. Conclusion

To visualize the task period in noisy NIRS data, we performed an embedding into high dimensional space and reconstructed the attractor. Then we depicted recurrence plots and found that task periods could be visualized in recurrence plots. Furthermore, there found the significant difference between task periods and non-task periods with testing histograms based on the recurrence plots. The proposed method is robust to noisy NIRS data, so recurrence plots is powerful tool for visualizing task periods in noisy NIRS data.

Acknowledgments

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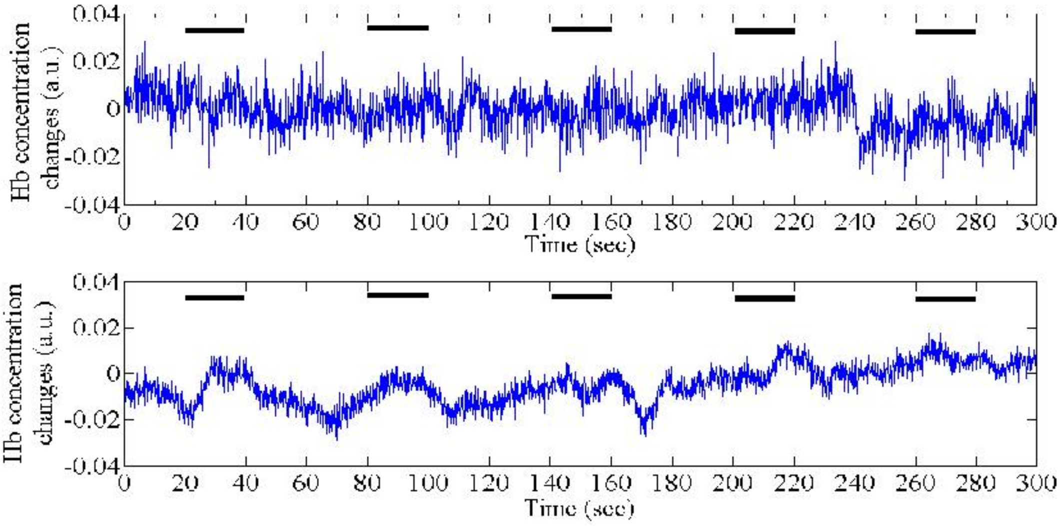

Fig. 1. Examples of NIRS data. Horizontal axis indicates time and vertical axis indicates oxygenated hemoglobin (Hb) concentration changes in arbitrary unit (a.u.). Black bold lines in the figures indicate the task periods. It is difficult to estimate the task period from time series at a glance. Upper row: subject #3, lower row: subject #4.

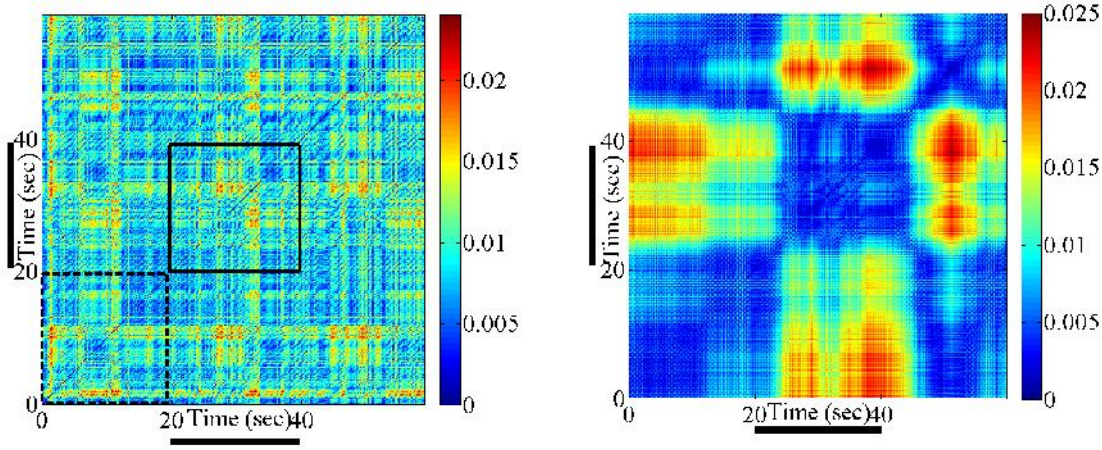

Fig. 2. Recurrence plots of signal averaging in representative subjects. Black lines along with each axis indicate task period. Left (subject #3): Recurrence plots seems to be smooth but the textures differs from task period (bold line square) and pre-task periods (dotted line square). Right (subject #4): Contrast in recurrence plots is obvious.

Table 1 Statistical results with elements in recurrence plots after standardization. Kurtosis of normal distribution is three in MATLAB 2014, and there is no difference among periods (one-way ANOVA, F = 3.14, d = (2, 63), p = 0.61).

	Average		Median		Skewness		Kurtosis		AUC		Mode	
	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std
pre-task	0.31	0.07	0.30	0.07	0.34	0.18	3.18	0.36	6749.6	1635.7	11.9	3.1
task	0.33	0.06	0.32	0.06	0.34	0.22	3.09	0.22	7198.1	1275.7	12.6	3.1
post-task	0.33	0.06	0.32	0.06	0.39	0.24	3.14	0.30	7119.3	1196.3	12.5	2.9

Table 2 Post hoc paired t-tests of each period (α=.05). There is no significant difference between task period and post-task period, and pre-task period and post-task period.

	Mean		Median		Skewness		AUC		Mode	
	t	p	t	p	t	p	t	p	t	p
pre<task	2.56	<.01	2.41	<.01	-0.48	<.05	2.17	<.05	1.73	<.05
task<post	0.05	n.s.	-0.12	n.s.	1.03	n.s.	-0.29	n.s.	-0.23	n.s.
pre<post	1.57	n.s.	1.31	n.s.	0.74	n.s.	1.22	n.s.	0.89	n.s.