Detection of changes in connectivity based on joint recurrence plots

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Abstract–Recently it is reported that the brain activation derives not only from the region solely but also among the network of the brain. In this study, we adopted recurrence plots and joint recurrence plots for NIRS (near infra-red spectroscopy) data to detect the difference in functional connectivity between motor execution and imagery. We examined the functional connectivity among the three regions in both right and left hemispheres, (1) pre-motor area and supplementary motor area (PM+SM), (2) primary motor area (M1) and (3) primary sensory area (S1). Furthermore, global recurrence plot was calculated to detect the changes in functional connectivity between rest and task.

As a result, in motor execution, functional connectivity changes are detected significantly between left M1 and left S1, between left M1 and right PM+SM and between left S1 and right S1. In motor imagery task, more functional connectivity changes are found among six regions. Our study shows that joint recurrence plots could be a useful tool for detecting the functional connectivity and discriminating the difference between motor execution and imagery.

1. Introduction

Traditionally, there are many devices developed with which the brain activity can be measured, and many researches have been done to report the functions in the brain. In past researches, the activation of the brain was often reported. Recently many studies about functional or effective connectivity have been reported to detect the network in the brain with various kinds of devices, such as EEG (electroencephalogram), MEG (magnetoencephalo-gram), fMRI (functional magnetic resonance imaging), and NIRS.

NIRS is a spectroscopic device with which the brain activity can be measured non-invasively and low-restrictedly. There are so many researches with NIRS, however, the analysis of NIRS data is not well established. In this study, we adopted recurrence plot and joint recurrence plot to detect the changes of functional connectivity in NIRS data. Furthermore, we examined the dynamic connectivity changes with global recurrence plot in motor execution and imagery tasks.

2. Recurrence plots for NIRS

2.1. NIRS

NIRS refers as near infra-red spectroscopy with which the brain activity can be measured. Using two or three wavelengths of near infra-red light, the relative hemoglobin concentration changes from the baseline can be measured [1]. The optical pathway of near infra-red light is shown in Fig.1.
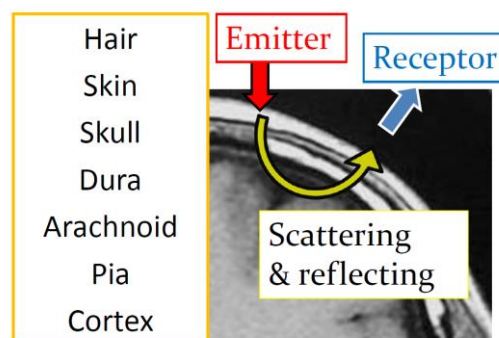

Fig.1. Optical pathway of near infra-red light.
Near infra-red light travels from the emitter to the receptor.

When near infra-red light travels from the emitter, it goes through hair, scalp, skull, dura, arachnoid, pia mater, cortex, reflecting and scattering repeatedly, then it goes out of the scalp and reaches to the receptor. The intensity ratio of near infra-red light decreases less than micro order. With modified Lambert Beer's Law, the relative changes of hemoglobin concentration in cortex blood flow from the baseline is measured [1].

There are many advantages in NIRS. The measurement with NIRS is non-invasive and low-constrained. Moreover, NIRS is relatively small and portable compared to other devices such as fMRI and MEG. There is no need for shielding nor strong magnetic fields, so subjects can be infants or in/outpatients. In recent studies, multi-modality is reported, for example, recording simultaneously with fMRI [2], with EEG [3] or with MEG [4]. For clinical usage, many studies have been reported in the department of neurosurgery, rehabilitation and psychic medicine [5].

2.2. Recurrence plot

Recurrence plot is one of the useful methods for time series analysis [6] [7]. For a single time series, recurrence plot is defined as a symmetrical binary matrix, which is based on the distance among the elements of the time series. The definition of recurrence plot is stated below.

Let x(t) be a time series. With a threshold r, recurrence plot $R_{ij}(x(t))$, the symmetrical binary matrix, is defined as follows.

$$R_{ij}(x(t)) = \begin{cases} 1 & if \; d(x(i),x(j)) < r, \qquad r : \text{threshold} \\ 0 & otherwise. \end{cases}$$

Recurrence plot can visualize the inner structure of single time series. If threshold r is given, recurrence plot is uniquely defined as a binary matrix. Therefore, there exists one to one correspondence between the inner structure of time series and its recurrence plot.

For physiological data, analysis with recurrence plot has already reported in EEG [8] or fMRI [9].

2.3. Joint recurrence plot

For a single time series, as explained above, recurrence plot is defined. Moreover, based on the recurrence plots, joint recurrence plot is defined for two time series [10].

Let X(t) and Y(t) be two time series, joint recurrence plot is defined as follows.

If the threshold r is given, recurrence plot of X(t), Y(t) can be obtained, R_X, R_Y, respectively.

Fig.2. Joint recurrence plot.
The symbol '.*' denotes a multiplication element by element in matrices.

If we see 1s at the same coordinate in both matrices of the right side of the formula in Fig.2, then place 1 for the corresponding coordinate in the left side, otherwise, place 0. Let m be the number of the elements in the triangle shown in Fig.2. Then calculate the ratio of 1s in the triangle in each matrix. If two time series X(t) and Y(t) are independent, then their recurrence plots R_X and R_Y are also independent. Therefore the ratio of 1s in each matrix in

the right side follows the binomial distribution. Moreover, if m is sufficiently large, the binomial distribution can be approximated by the normal distribution. After we standardized and performed z-test, if null hypothesis is rejected, then functional connectivity exists between two time series.

As mentioned above, if two time series X(t), Y(t) and threshold are given, JR_{XY} is defined as a binary element of which the value is one or zero. If we have two or more time series, by collecting all the results of calculation through every pair of time series, we can get the joint recurrence plot for the set of these time series. It is easy to see that joint recurrence plot is defined as a symmetrical binary matrix.

In this study, the threshold r for recurrence plot is given so that the probability of p and q in Fig.2 is equal to 0.05, and for joint recurrence plot, the significant level of the z-test is given by 0.10[10].

2.4. Global recurrence plot

By calculating joint recurrence plot, we can detect the static connectivity between two or more time series. Furthermore, with joint recurrence plots, global recurrence plot can be defined [11]. For long-term multiple time series, if the distance between the joint recurrence plot is given, we can detect the dynamic network changes with global recurrence plots as a binary matrix.

If we divide long-term multiple series into several segments, the joint recurrence plots can be obtained in each segments individually. Joint recurrence plots can be replaced with undirected graphs. After checking the difference between the graphs, the global recurrence plot can be obtained with the Hamming distance.

3. Experimental design

3.1. Subjects and methods

Eleven healthy subjects participated in the experiment. All of them have no neurological disorder and are judged as right-handed with Edinburgh Handedness Inventory. Measurements with NIRS were done in the quiet and lighted room appropriate for the experiments. We adapted the block design, which consists of pre-task period (20s), task period (20s) and post-task period (20s). With pacing visual stimuli on the PC monitor, subjects are asked to execute grasping or to image grasping hands during task periods. In each session, the block design was repeated five times. Through one session, the subjects was asked to perform the same task. For every subject, two measurements (motor execution or imagery) were done, however, the order of the task was pseudo-randomized. The experimental design is shown in Fig.3.
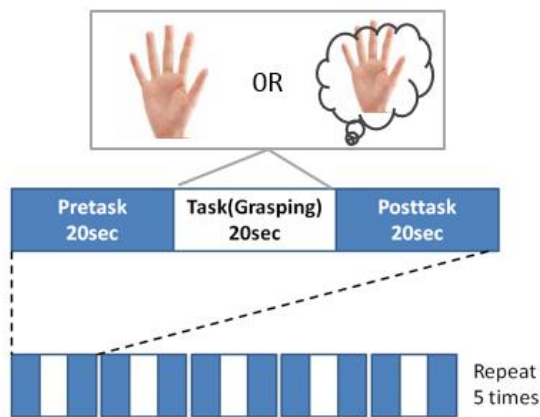
Fig.3. Experimental design.
Each block consists of pre-task period (20 sec), task period (20sec) and post-task period (20sec).

In a motor task, it is well known that primary motor area in contralateral hemisphere activates significantly, so we adapted the center of the measuring point to C3 in international 10-20 system. Moreover, we estimated the projection onto the cortical surface of the measuring point with 3D digitizer (FASTRAK, POLHEMUS) and NIRS-SPM [12] [13] [14] [15].

 NIRS data was obtained with Foire-3000 (Shimadzu Corporation, Kyoto, Japan, the sampling rate: 130ms). Data analysis was done with MATLAB2012 (MathWorks).

Each experiment was performed according to the tenets of the Declaration of Helsinki and under the approval of the Ethics Committee of the Tokyo Denki University. Written informed consent was obtained from all the subjects after the explanation of the nature and possible consequences of the study.

3.2. Data analysis

After we acquired the coordinates of measuring points with 3D digitizer, we chose six measuring points as nodes, each of which corresponds to (1) pre-motor area (PM) and supplementary motor area (SM), (2) primary motor area (M1) and (3) primary sensory area (S1) in both right and left hemispheres (Fig.4).
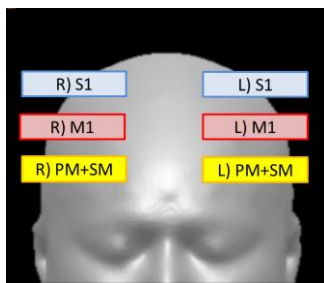

Fig.4. Selection of the measuring points.
PM: premotor area, SM: Supplementary motor area,
M1: Primary motor area, S1: Primary somatosensory area.

Each time series contains 2307 time points in raw NIRS data. According to the intervals of rest and task, we divided the time series into 15 segments in all and, to avoid the influence of boundary between rest and task, we chose 100 consecutive points from 50th point of segment. To improve the signal to noise ratio, signal averaging was calculated and, as a result, we obtained three signal-averaged segments (pre-task period, task period and post-task period) in each measuring point. Then we calculated the recurrence plots and the joint recurrence plots of each subject's data.

Furthermore, global joint recurrence plot was checked in all subjects to detect the changes in networks of functional connectivity with Hamming distance equal to 2[11].

To detect the network changes statistically between pre-task period and task period, we performed paired binomial test (significant level=0.001) for joint recurrence plots.

4. Results

At first we check the functional connectivity in each subject. In motor execution, significant functional connectivity was found between left M1 and left S1, between left S1 and right S1 and between right PM+SM and left M1.

On the other hand, in motor imagery task, the functional connectivity was found between among left hemisphere, between left PM+SM and right M1, between left PM+SM and right S1, between right M1 and right S1 and between right M1 and left S1.
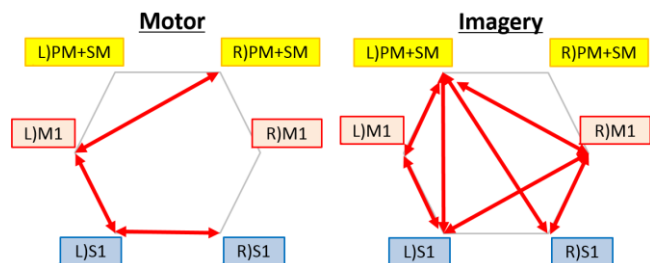

Fig.5. Connectivity changes between rest and task.
Red arrows indicate the existence of the changes
in connectivity between rest and task.

The result of global recurrence plot in characteristic subject is shown in Fig.6. The horizontal and vertical red lines indicate the time at which subject began to grasp or imagine grasping. In motor execution, four of five red lines coincided with the beginning of the task. On the contrary, in motor imagery task, the coincidence is not obvious compared to motor execution. Therefore, it is suggested that the changes in functional connectivity could be detected with global recurrence plot.
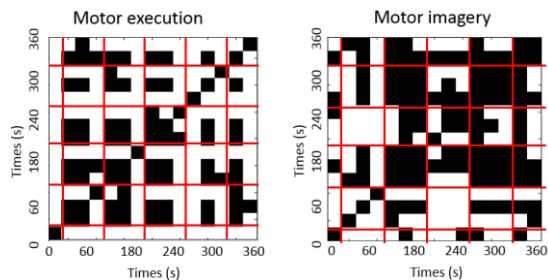
Fig.6. Global joint recurrence plot of subject #1. Horizontal and vertical red lines indicate the beginning of motor execution or imagery.

5. Discussions

It is well known that the contralateral cortical region around C3 activates both in motor execution and imagery. Moreover, premotor area plans to control the movement or controls motor area directly and bilaterally [16]. All the subjects participating in our study are right-handed, then as we expected, in motor execution, our results shows that connectivity changes between left M1 and left S1 and between right PM+SM and left M1. On the contrary, as for motor imagery, more connectivity changes in left PM+SM are detected. Generally, subjects are not accustomed to perform such motor imagery tasks, so our results do not conflict. In addition, between left M1 and left S1, the connectivity changes emerged in both motor execution and imagery. In our study, subjects are asked only to imagine grasping regardless of their ways of imagery, in other words, by visual or by haptic. So our results might reflect their tactics, however, further study will be needed.

Recurrence plot, joint recurrence plot and global recurrence plot are cost-effective method, so these techniques can be appropriate for the online calculation. Therefore, our study shows that these techniques can be a useful tool for detecting functional connectivity changes or discriminating motor execution task from motor imagery task on-line including brain machine interface (BMI) or rehabilitation program.

6. Conclusions

To detect the difference in functional connectivity between motor execution and imagery in NIRS data, we adopted joint recurrence plot which is based on the recurrence plots. Furthermore, the global recurrence plot was calculated. As a result, in motor execution, functional connectivity is detected significantly between left M1 and left S1, between left M1 and right PM+SM and between left S1 and right S1. In motor imagery task, more functional connectivity is found between. Furthermore, the global recurrence plot in characteristic subject partly reflected the changes in functional connectivity from rest period to task period in motor execution. Our study shows that the joint recurrence plot can be a useful tool for detecting the functional connectivity and discriminating the difference between the motor execution and imagery. Moreover, it is suggested that the global recurrence plot could contribute to detect the changes in functional connectivity in motor execution.

References

[1] A. Torricelli et al., "Time domain functional NIRS imaging for human brain mapping", NeuroImage, 85, 28-50, 2014.

[2] M. Okamoto et al., "Multimodal assessment of cortical activation during apple peeling by NIRS and fMRI", NeuroImage, 21, 1275-1288, 2004.

[3] S. Fazil et al., "Enhanced performance by a hybrid NIRS-EEG brain computer interface", NeuroImage, 59,519-529, 2002.

[4] T. Aihara et al., "Cortical current source estimation from electroencephalography in combination with near-infrared spectroscopy as a hierarchical prior", NeuroImage, 59, 4006-4021, 2012.

[5] H. Obrig, "NIRS in clinical neurology - a 'promising' tool?", NeuroImage, 85, 535-546, 2014.

[6] P. Eckmann et al., "Recurrence plots of dynamical Systems", Europhysics Letters, 5, 973-977, 1987.

[7] N. Marwan et al., "Recurrence plots for the analysis of complex systems", Physics Reports, 438, 237-329, 2007.

[8] G. Ouyang et al., Clin. Neurophy., 2008.

[9] M. Biamciardi et al., NeuroImage, 2007.

[10] Y. Hirata & K. Aihara, "Identifying hidden common causes from bivariate time series: A method using recurrence plots", Phys. Rev. E 81, 016203, 2010.

[11] K. Iwayama et al., "Characterizing global evolutions of complex systems via intermediate network representations", Scientific Reports, Vol. 2, 423, 2012.

[12] J.C. Ye et al., "Statistical parametric mapping for near-infrared spectroscopy", NeuroImage, 44, 428-447, 2009.

[13] K.E. Jang et al., "Wavelet-MDL detrending for near-infrared spectroscopy (NIRS)", Journal of Biomedical Optics, vol. 14, no. 3, 1-13, 2009.

[14] S. Tak et al., "Quantification of CMRO2 without hypercapnia using simultaneous near-infrared spectroscopy and fMRI measurements", Physics. Med. Biol. 55, 3249-3269, 2010.

[15] A.K. Singh et al., "Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI", NeuroImage 27(4), 842-851, 2005.

[16] D.A. Rosenbaum, "Human motor control", Academic Press, 2010.