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Analysis of Brain Activities due to Differences in Running Shoe Properties

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***Abstract*—**Many of the ever-growing elderly population require exercise, such as running, for health management. One important element of a runner's training is the choice of shoes for exercise; shoes are important because they provide the interface between the feet and road. When we purchase shoes, we may instinctively choose a pair after trying on many different pairs of shoes. Selecting the shoes instinctively may work, but it does not guarantee a suitable fit for running activities. Therefore, if we could select suitable shoes for each runner from the viewpoint of brain activities, it would be helpful for validating shoe selection. In this paper, we describe how brain activities show different characteristics during particular task, corresponding to different properties of shoes. Using five subjects, we performed a verification experiment, applying weight, softness, and flexibility as shoe properties. In order to affect the shoe property's differences to the brain, subjects run for 10 min. Before and after running, subjects conducted a paced auditory serial addition task (PASAT) as the particular task; and the subjects' brain activities during the PASAT are evaluated based on oxyhemoglobin and deoxyhemoglobin relative concentration changes, measured by near-infrared spectroscopy (NIRS). When the brain works actively, oxihemoglobin and deoxyhemoglobin concentration drastically changes; therefore, we calculate the maximum values of concentration changes. In order to normalize relative concentration changes after running, the maximum value are divided by before running maximum value as evaluation parameters. The classification of the groups of shoes is expressed on a self-organizing map (SOM). As a result, deoxyhemoglobin can make clusters for two of the three types of shoes.

***Keywords*—**Brain activities, NIRS, PASAT, running shoes.

I. INTRODUCTION

BY 2050 at least 2 billion people in the world will be older than 60 years old [1]. An increasing number of the ever-growing elderly population requires exercise for health management.

In particular, walking and running are prevalent because it is very easy for elderly persons to train in these activities. A runner's shoe is an important element of exercise because shoes provide an interface between the foot and the road. If runners do not put on shoes that suit their own foot properties, the shoes will hurt the legs of runners. Furthermore, because foot shock can affect brain activity [2], properties of the shoes, such as weight, softness, and flexibility can make running a safer and healthier exercise, prolonging a healthy life and decreasing health costs for the elderly. When consumers purchase shoes, they often try on a few pairs and make a selection; that selection may indeed be instinctive, but such a purchase may not always be the most suitable and healthy option. Therefore, selecting suitable shoes for each runner according to the runner's brain activities can result in a much better shoe selection for the runner's activities.

In order to evaluate brain activities, various measurement devices have been applied for researches such as electroencephalography (EEG) [3], [4], magnetoencephalography (MEG) [5], [6], near-infrared spectroscopy (NIRS) [7], [8], positron emission tomography (PET) [9]-[11] and functional magnetic resonance imaging (fMRI) [12]-[14].

In this paper, we experimentally verify how the properties of weight, softness, and flexibility of shoes affect brain activities during a particular task. Oxyhemoglobin / deoxyhemoglobin concentration change—measured by NIRS— is used to evaluate brain activities, and to set the paced auditory serial addition task (PASAT) as a working task in this experiment.

II. METHOD

A. Subjects and Shoe Properties

We carried out experiments to verify how brain activities show different characteristics when subjects wear shoes with different properties. This study includes five male subjects (Subjects 1–5). Table I shows subjects' ages and athletic experiences.

We provided the subjects with three types of shoes - A, B, and C - with different values of weight, softness, and flexibility, respectively. Table II compares weight, softness, and flexibility for the three shoes. Regarding all properties, shoes B and C are normalized by shoe A's properties. Shoe B is the most light, soft, and flexible of the three shoes; and shoe C is the most heavy, hard, and firm.

B. Paced Auditory Serial Addition Task (PASAT)

This study employed PASAT to the subjects as external stimulation. PASAT is a neuropsychological test applied to evaluate sustained attention and working memory. In the PASAT, single digits are auditorily provided every second; and subjects have to immediately add each new digit to the prior digit; and answer orally. Sixty-one total digits are provided for 1 min. The test score of the PASAT is evaluated by the total number of correct sums.

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TABLE I
SUBJECTS' AGES AND ATHLETIC EXPERIENCES

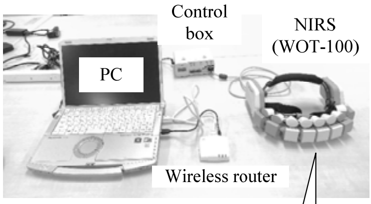
Subject	Ages	Athletic experiences
1	Thirties	Running Bicycle Skiing
2	Twenties	Baseball
3	Twenties	Baseball
4	Twenties	Short-distance race
5	Forties	Running Bicycle

TABLE II
SHOE PROPERTIES

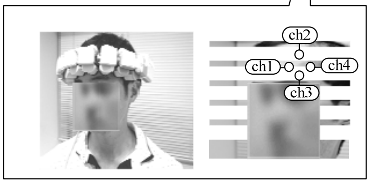
	Shoe A	Shoe B	Shoe C
Weight	100 %	91 %	144 %
Softness	100 %	87 %	128 %
Flexibility	100 %	73 %	385 %

C. Experiment System

In this paper, we focus on brain activities on the left side of the frontal lobe, which is related to working memory [15]-[17]. Therefore, we measure oxyhemoglobin and deoxyhemoglobin concentration change on the left side of the frontal lobe by using NIRS (HITACHI WOT-100). Figs. 1 (a) and (b) show experiment equipment and how the subjects attach the NIRS on the head. We could obtain four channels of data—ch1, ch2, ch3, and ch4—at different places on the left side of the frontal lobe, as shown in Fig. 1 (b). Each channel can provide both oxyhemoglobin and deoxyhemoglobin concentration changes as a time-series waveform with a 0.2 s sampling interval. The wireless connection sends the measured data to the PC in real time.



(a) Experimental system



(b) Attachment place of each channel

Fig. 1 Experimental system

D. Experimental Procedures

In order to compare the effect of shoe properties on brain activities, the subjects conducted PASAT before and after running. Before running, PASAT was conducted for a subject wearing one type of shoe and brain activities was measured by NIRS. After the PASAT was completed, the subjects started running at a steady pace for 10 min, keeping their heart rate at approximately 140 pulses/min. The subjects took 15 min of rest after running to decrease the heart rate to its previous rate, before the run; the PASAT was then conducted again. We performed this set of procedures three times, once for each type of shoe. During these experiments, no subjects were informed about the shoe properties.

E. Signal Processing for the Data Measured by NIRS

Here, we describe the signal processing flows for evaluation.

As shown in Fig. 1 (b), the measurement of four signals by the NIRS is numbered from ch1 to ch4. Let i be channel number of NIRS; and let $S_i^{\mathrm{Pre}}(k)$ ($i = 1, 2, 3, 4$) be the measurement signal before running. Here, k represents discrete time ($k = 1, 2, 3, \ldots N$) with sampling interval $dt = 0.2$ s. Similarly, let $S_i^{\mathrm{Post}}(k)$ ($i = 1, 2, 3, 4$) be the measurement signal after running. When the brain works actively, oxihemoglobin and deoxyhemoglobin concentration drastically changes; therefore, we calculate the maximum values of $S_i^{\mathrm{Pre}}(k)$ and $S_i^{\mathrm{Post}}(k)$ for all four channels. Let $max\{\, S_i^{\mathrm{Pre}}(k)\ \}$ and $max\{\, S_i^{\mathrm{Post}}(k)\ \}$ be maximum values of $S_i^{\mathrm{Pre}}(k)$ and $S_i^{\mathrm{Post}}(k)$ respectively. Furthermore, because the measured signals of oxyhemoglobin and deoxyhemoglobin concentration measured by NIRS are relative concentration change from start time of measurement, comparisons $max\{\, S_i^{\mathrm{Pre}}(k)\ \}$ and $max\{\, S_i^{\mathrm{Post}}(k)\ \}$ between different subjects are inadequate. Hence, for evaluation, we apply a normalized parameter $P_i(k)$ defined as

$$P_i(k) = \frac{max\{S_i^{\mathrm{Post}}(k)\}}{max\{\, S_i^{\mathrm{Pre}}(k)\}} \tag{1}$$

F. Evaluation Using the Self Organized Map

Because brain activities include complicated factors, a nonlinear judgment method is required to evaluate how brain activities change when wearing different shoes by using maximum values P_1-P_4. Therefore, a brain activity evaluation by P_1-P_4 was calculated using a self-organizing map (SOM), which is capable of nonlinear judgment and of two-dimensional mapping. This map will be the shoes' model to collectively judge the maximum values P_1-P_4, and to determine the equivalent shoe group of subjects' P_1-P_4. SOM is an unsupervised neural network model that comprises two layers: *input* and *output*. In order to make a brain activity map, the SOM learns P_1, P_2, P_3, and P_4, of subjects with different shoes. The input layer has four neurons, where feature vectors ($\boldsymbol{x} = [P_1\ P_2\ P_3\ P_4]$) are input. The output layer has neurons m_l ($l = 1, 2, \ldots, v$), where v stands for the total number of neurons, which are positioned on a two-dimensional coordinate. The position vector of each neuron on the coordinate is defined as $\boldsymbol{r}_l$. A neuron m_l on the output layer is connected to all three neurons on the input layer, and its weight vector is defined as $\boldsymbol{w}_l = [w_{P1,l}\ w_{P2,l}\ w_{P3,l}\ w_{P4,l}]$. The default value of the weight vector is provided randomly. The Euclidean distance $d(l) = \|\boldsymbol{x} - \boldsymbol{w}_l\|$ between the feature vector $\boldsymbol{x}$ input into the input layer, and the weight vector $\boldsymbol{w}_l$ of neuron m_l in the output layer are calculated in terms of each l. The neuron number c (□ l), where $d(l)$ is the minimum, is defined as the winner neuron m_c, and its position vector as $\boldsymbol{r}_c$. When the number of learning is q ($= 1, 2, \ldots, Q$), the weight vector of the winner neuron m_c and the weight vector of its neighborhood neuron are updated using the following equation:

$$\boldsymbol{w}_l(q+1) = \boldsymbol{w}_l(q) + h_{c,l}(q)\,[\boldsymbol{x} - \boldsymbol{w}_l(q)] \qquad (2)$$

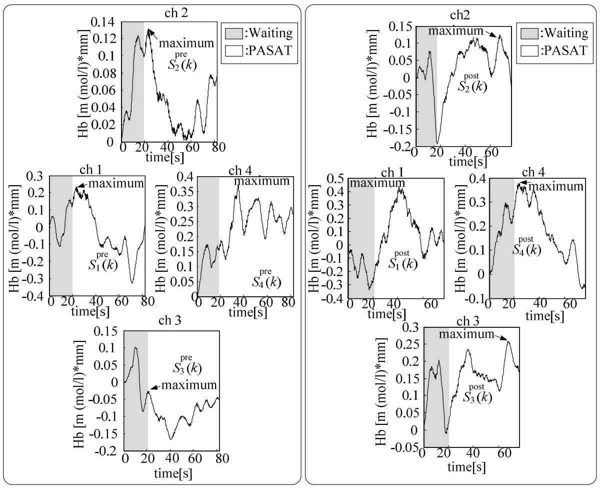
where h_{cl} (q) is a neighborhood function, here, numbers of neurons v and learning of SOM Q are set to 400 and 100, respectively.

III. Results and Consideration

Compared to oxyhemoglobin and deoxyhemoglobin concentration changes, deoxyhemoglobin concentrations were more affected by different shoe types. Hence, we can apply deoxyhemoglobin concentration to evaluate brain activities. Fig. 2 is an example of deoxyhemoglobin concentration of subject 4 wearing shoes A. Fig. 2 (a) shows four channels $S_1^{\mathrm{Pre}}(k)$, $S_2^{\mathrm{Pre}}(k)$, $S_3^{\mathrm{Pre}}(k)$, and $S_4^{\mathrm{Pre}}(k)$, before running; and Fig. 2 (b) also shows the deoxyhemoglobin concentration of four channels $S_1^{\mathrm{Post}}(k)$, $S_2^{\mathrm{Post}}(k)$, $S_3^{\mathrm{Post}}(k)$, and $S_4^{\mathrm{Post}}(k)$, after running. Figs. 3 and 4 show results of shoes B and C, respectively. Regarding all graphs in the figure, PASAT was conducted between 20 and 80 s. Before 20 s represented gray areas in the figures are waiting time for PASAT. Therefore, in almost all graphs, deoxyhemoglobin concentration drastically changes after 20 s. For shoe A, compared in Figs. 2 (a) and (b), before running, $S_1^{\mathrm{Pre}}(k)$, $S_2^{\mathrm{Pre}}(k)$, and $S_3^{\mathrm{Pre}}(k)$ decreased; and $S_4^{\mathrm{Pre}}(k)$ increased from 20 s. After running, however, $S_1^{\mathrm{Post}}(k)$, $S_2^{\mathrm{Post}}(k)$, and $S_3^{\mathrm{Post}}(k)$ increased and $S_4^{\mathrm{Post}}(k)$ decreased. For shoe B, as shown in Figs. 3 (a) and (b), both $S_4^{\mathrm{Pre}}(k)$ and $S_4^{\mathrm{Post}}(k)$ had negative values during PASAT. For shoe C, as shown in Figs. 4 (a) and (b), $S_1^{\mathrm{Post}}(k)$ and $S_4^{\mathrm{Post}}(k)$ showed clearly periodic characteristics, although $S_1^{\mathrm{Pre}}(k)$ and $S_4^{\mathrm{Pre}}(k)$ did not show periodic characteristics. Regarding all three types of shoes, we calculated normalized parameters P_1, P_2, P_3, and P_4. Similarly, for all subjects, P_1, P_2, P_3, and P_4 are also obtained for the SOM classification.

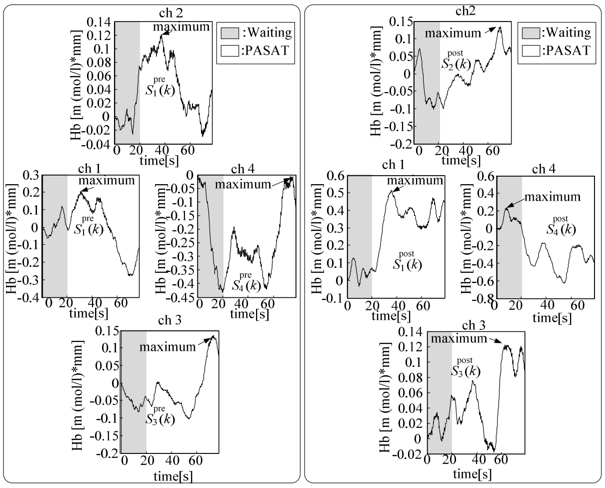
For three types of shoes and five subjects, feature vectors $\boldsymbol{x}$ are provided by each set of P_1, P_2, P_3, and P_4; and $\boldsymbol{x}$ are input to the SOM. Figs.5 and 6 show the U-matrix and the component map of P_1, P_2, P_3, and P_4, respectively. The labels in the SOM represent subject number and shoe type. As shown in Fig. 5, a shoe A group and a shoe C group made clusters of each group. The elements belonging to a shoe B group are dispersed on the U-matrix map.

As shown in Fig. 6, component maps of ch1 and ch4 are similar graduations on the map; and ch2 and ch3 are shows similar graduations. As mentioned previously, $S_1^{\mathrm{Post}}(k)$ and $S_4^{\mathrm{Post}}(k)$ showed clearly periodically characteristics although $S_1^{\mathrm{Pre}}(k)$ and $S_4^{\mathrm{Pre}}(k)$ did not show the characteristics in the case of shoe C. This may affects the result of SOM classifications.



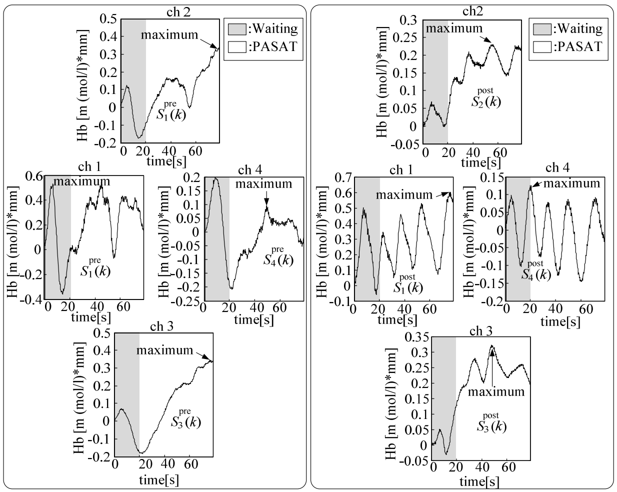
(a) Before running (a) After running

Fig. 2 Deoxyhemoglobin concentrations for shoe A



(a) Before running (a) After running

Fig. 3 Deoxyhemoglobin concentrations for shoe B



(a) Before running (a) After running

Fig. 4 Deoxyhemoglobin concentrations for shoe C

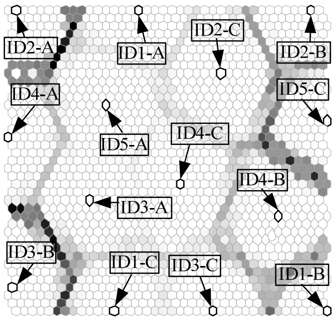
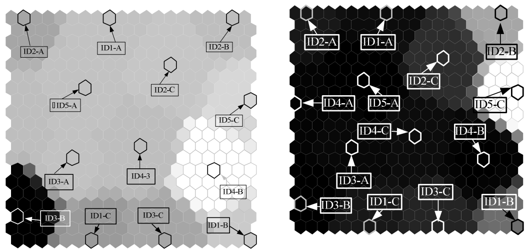
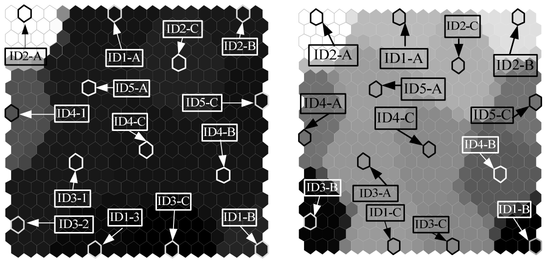


Fig. 5 Results of U-matrix of SOM



(a) Component map of ch1

(b) Component map of ch2



(c) Component map of ch3

(d) Component map of ch4

Fig. 6 Components maps of SOM

IV. CONCLUSION

In this paper, we described how brain activities show different characteristics during particular task, through experiments with test subjects wear shoes with different properties.

We performed our verification experiment with five subjects. In the experiment, we applied weight, softness, and flexibility as the types of shoe properties. In order to insure shoe property difference in the brain, the five subjects ran for 10 min. Before and after running, subjects conducted PASAT as the particular task; and the subjects' brain activities during PASAT were evaluated by oxyhemoglobin and deoxyhemoglobin relative concentration changes measured using NIRS. When the brain works actively, oxihemoglobin and deoxyhemoglobin concentration drastically changes; therefore, we calculate the maximum values of concentration changes. In order to normalize relative concentration changes after running, the maximum value was divided by before running maximum value as evaluation parameters. The classification of the groups of shoes was expressed on a SOM. As a result, we found that deoxyhemoglobin can make clusters for any two of the three types of shoes. We hope to test our results on more subjects in future studies.

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