Independent Component Analysis of Finger Photoplethysmography for Evaluating Effects of Visually-Induced Motion Sickness

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Abstract. To evaluate the effects of visually-induced motion sickness that induces symptoms related to the autonomic nervous activity, we proposed a new method for obtaining the physiological index ρ_{max}, which represents the maximum cross-correlation coefficient between blood pressure and heart rate, with measurement of neither continuous blood pressure nor ECG but using finger photoplethysmography only. In this study, a blood pressure-related parameter was obtained using the independent component analysis of finger photoplethysmography. Two experimental trials in which subjects performed the Valsalva maneuver and then they watched a swaying video image were carried out to evaluate the adequacy of the proposed method. The experimental results have shown that the proposed method worked successfully as well as the conventional method.

Keywords: baroreflex, photoplethysmography, independent component analysis, visually-induced motion sickness.

1 Introduction

A human watching a moving image displayed on a wide-field display or screen often suffers from visually-induced motion sickness (VIMS) that induces symptoms related to the autonomic nervous activity such as nausea, vomiting, and dizziness. The previous study reported that the maximum cross-correlation coefficient (ρ_{max}) between blood pressure variability (*BP*) and heart rate variability (*HR*) whose frequency components were limited in the neighborhood of 0.1Hz was a useful index to evaluate the effects of VIMS on humans [1].

The present study has proposed a new method for obtaining ρ_{max} with measurement of neither continuous blood pressure nor ECG but using finger photoplethysmography (PPG) only. In this study, *HR* was obtained from the foot-to-foot-interval (*FFI*) of the PPG signal, and *BP*-related information was obtained from parameters extracted by

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using the Independent Component Analysis (ICA). And an experiment with the Valsalva maneuver and the presentation of visual stimulation which induces VIMS was carried out to provide the validity of the proposed method.

2 Method with ICA

The proposed method using the ICA is as follows. 1) Let $x_1(t)$, $x_2(t)$, …, $x_m(t)$ be m variables extracted from the PPG signal at time t. Define a feature vector $\boldsymbol{x}(t)$ as $\boldsymbol{x}(t)=[x_1(t), x_2(t), \ldots, x_m(t)]^T$ and define $\boldsymbol{X}$ *as* $\boldsymbol{X}=[\boldsymbol{x}(1), \boldsymbol{x}(2), \ldots, \boldsymbol{x}(t)]$. 2) Let $s_1(t)$, $s_2(t)$, …, $s_n(t)$ be n unknown physiological parameters which are independent of one another at time t. Assume that the feature vector $\boldsymbol{x}(t)$ is given by a linear combination of $s_1(t)$, $s_2(t)$, …,$s_n(t)$. Define a parameter vector $\boldsymbol{s}(t)$ as $\boldsymbol{s}(t)=[s_1(t), s_2(t), \ldots, s_n(t)]^T$. Define $\boldsymbol{S}$ as $\boldsymbol{S}=[\boldsymbol{s}(1), \boldsymbol{s}(2), \ldots, \boldsymbol{s}(t)]$. 3) Thus, the matrix $\boldsymbol{X}$ is given by $\boldsymbol{S}$ as follows:

$$\boldsymbol{X}=\boldsymbol{AS}$$

where, $\boldsymbol{A}$ represents an unknown constant mixing matrix consisting of coefficients of the liner combination. This equation shows that we need to estimate the independent component $\boldsymbol{S}$ and the mixing matrix $\boldsymbol{A}$ from the matrix of feature vectors $\boldsymbol{X}$. In this study, we used the ICA method in order to estimate $\boldsymbol{S}$ and $\boldsymbol{A}$. To separate linearly mixed independent source signals $\boldsymbol{X}$, we used a first fixed point algorithm (FastICA) presented by Hyvärinen and Oja [2] [3]. In addition, the number of feature variables m was set to 7 and the number of independent variables n did 4. Thus, $\boldsymbol{X}$ is 7×k matrix, $\boldsymbol{S}$ is 4×k matrix and $\boldsymbol{A}$ is 4×7 matrix, where k is the number of heart beat.

Figure 1 shows the example of feature variables. One of the feature variables is the normalized pulse wave area (*NPWA*) [4]. This parameter shows the mean value of the pulsatile component of arterial blood volume.

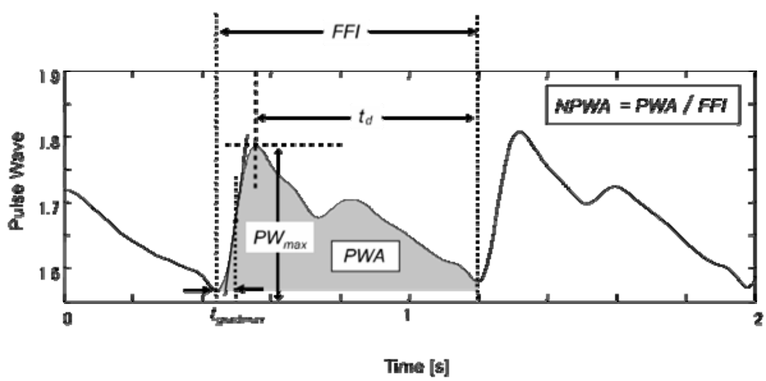

Fig. 1. Examples of feature variables and the definition of normalized pulse wave area (*NPWA*)

3 Experiment

In this study, healthy 15 subjects (12 males and 3 females, 23.6±2.6 yrs) participated in two consecutive trials. The first trial was the Valsalva maneuver to obtain the mixing matrix for each subject. The second one was the trial in which the subject watched the swaying video image.

3.1 Valsalva Maneuver

The Valsalva maneuver was performed by having the subject conduct a maximal, forced expiration against a closed glottis and keeping this condition for 1 minute. In general, baroreflex sensitivity of the subject on the Valsalva maneuver decreases and thus $\rho_{\max}$ decreases.

ECG, continuous blood pressure and finger PPG of the subject was measured during the trial. Fig. 2 represents the protocol of the trial.

3.2 Trial with Swaying Video Image

After the Valsalva maneuver, all the subjects watched the swaying video image. Physiological parameters measured in this trial were the same as in the Valsalva maneuver.

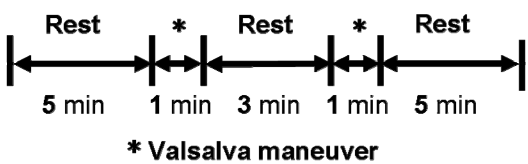

Fig. 2. The protocol of the Valsalva maneuver

Fig. 3. The protocol of the trial with the swaying video image

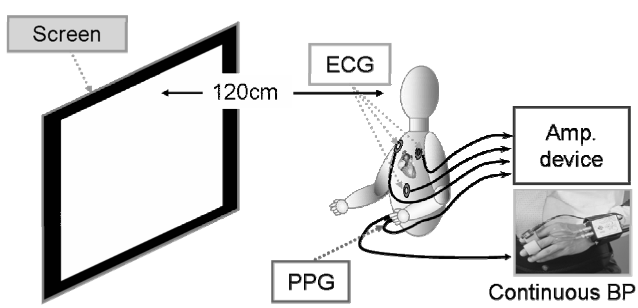

Fig. 4. Experimental set up. In the Valsalva maneuver, the subject received instructions by seeing text projected on a screen.

Figure 3 represents the protocol of the trial. After the second rest, the simulator sickness questionnaire (SSQ) [5] was charged on the subject. The total score (*TS*) of the SSQ is expected to show the intensity of VIMS. Fig. 4 shows the experimental set up.

4 Analysis

In the trial with the Valsalva maneuver, the beat-to-beat change was obtained from ECG. For each beat, the mean value of blood pressure and feature variables from PPG were calculated. The observed matrix $\boldsymbol{X}$ consists of feature variables from PPG. The mixing matrix $\boldsymbol{A}$ and independent component $\boldsymbol{S}$ were calculated with ICA for each subject. Let $\rho_{max}(BP)$, $\rho_{max}(NPWA)$ and $\rho_{max}(IC)$ denote ρ_{max} between *HR* and *BP*, ρ_{max} between *HR* and *NPWA*, and ρ_{max} between *HR* and an independent component (*IC*), respectively. *IC* used in calculating ρ_{max} was one that was most related to *BP* in all *IC*s.

In the trial with the swaying video image, the mixing matrix $\boldsymbol{A}$ obtained in the trial with the Valsalva maneuver was used to calculate *IC* for each subject. With the same way of analysis described above, $\rho_{max}(BP)$, $\rho_{max}(NPWA)$ and $\rho_{max}(IC)$ were calculated.

5 Results and Discussion

5.1 Valsalva maneuver

All subjects' data could successfully be obtained and analyzed in the Valsalva maneuver. Fig. 5 shows the change of $\rho_{max}(BP)$, $\rho_{max}(NPWA)$ and $\rho_{max}(IC)$. Each ρ_{max} is

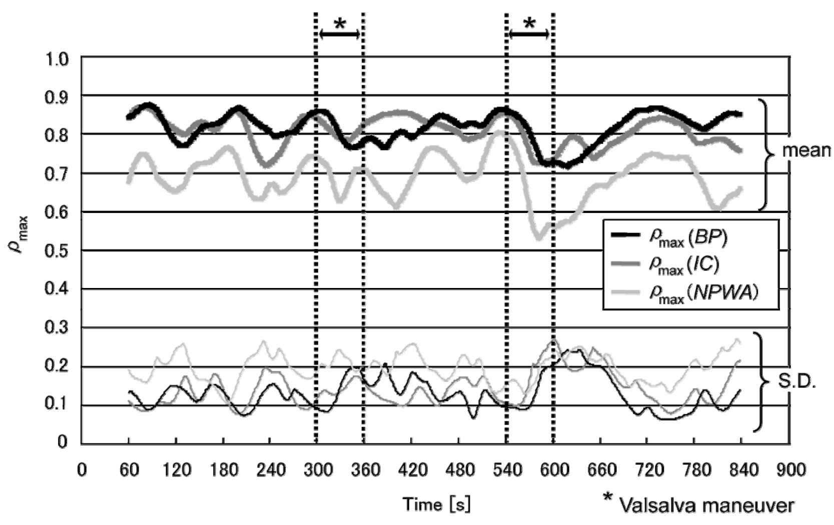

Fig. 5. Changes of ρ_{max}s averaged in all subjects in the Valsalva maneuver. $\rho_{max}(IC)$ represents ρ_{max} calculated by using *IC* which was the most *BP*-related component.

the value averaged in all subjects and the standard deviation (S.D.) was shown in the lower part of the figure.

This result revealed that $\rho_{max}(IC)$ changed similarly to $\rho_{max}(BP)$. However the change of $\rho_{max}(NPWA)$ obtained from only the PPG signal was dissimilar to that of $\rho_{max}(BP)$.

5.2 Trial with Swaying Video Image

Fourteen subjects' data out of 15 could successfully be obtained in this trial. From the result of the subjective evaluation based on the SSQ, the median *TS* of 14 subjects was 17.7. All subjects were divided into two groups: "Sick" and "Well" groups. Sick group consists of 7 subjects with *TS* higher than 17.7 and Well group consists of 7 subjects with *TS* lower than 17.7.

Figure 6 shows changes of $\rho_{max}(BP)$, $\rho_{max}(NPWA)$ and $\rho_{max}(IC)$ averaged in 14 subjects. In this figure, $\rho_{max}(IC)$ changed more similarly to $\rho_{max}(BP)$ than $\rho_{max}(NPWA)$. $\rho_{max}(IC)$ was calculated by using the mixing matrix obtained from the result of the Valsalva maneuver. Therefore, this result suggests that the mixing matrix obtained in an experiment can be used for data set obtained in the other experiment. However, the change of $\rho_{max}(IC)$ did not completely correspond to that of $\rho_{max}(BP)$. This result suggested that the change of *BP* by autonomic nervous activity in the experiment with the Valsalva maneuver did not necessarily correspond to that in the experiment with the swaying video image.

Figure 7, 8 and 9 show changes of $\rho_{max}(BP)$, $\rho_{max}(NPWA)$ and $\rho_{max}(IC)$ averaged in 14 subjects, respectively. In these figures, each ρ_{max} was compared between Sick and Well groups. The shadow shown in these figures represents the time interval in which the significant difference (p<0.05) between two groups was found by the Welch's t-test.

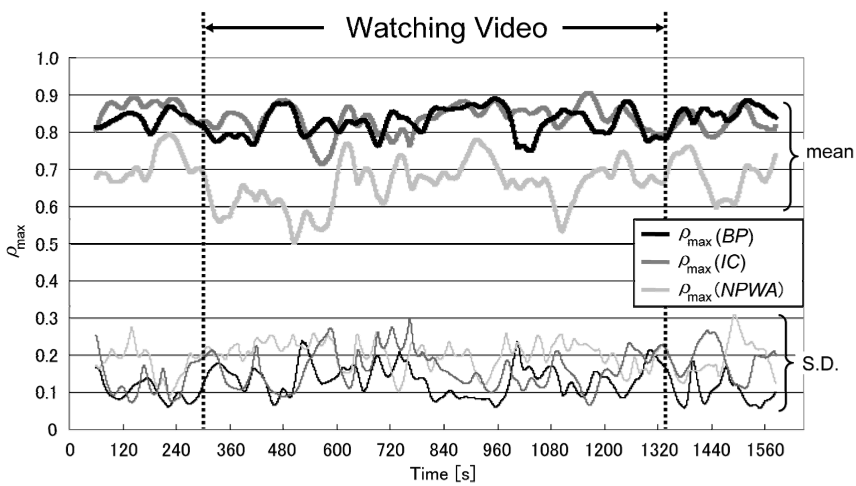

Fig. 6. Changes of ρ_{max} averaged in 14 subjects in the trial with the swaying video image. $\rho_{max}(IC)$ represents ρ_{max} calculated by using the mixing matrix obtained in the Valsalva maneuver.

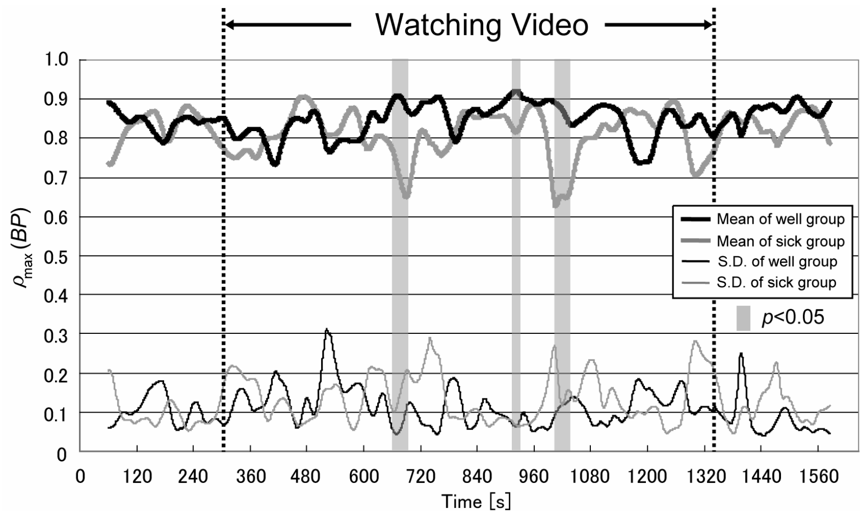

Fig. 7. Comparison in ρ_{max} using *BP* between Sick and Well groups in the trial with the swaying video image

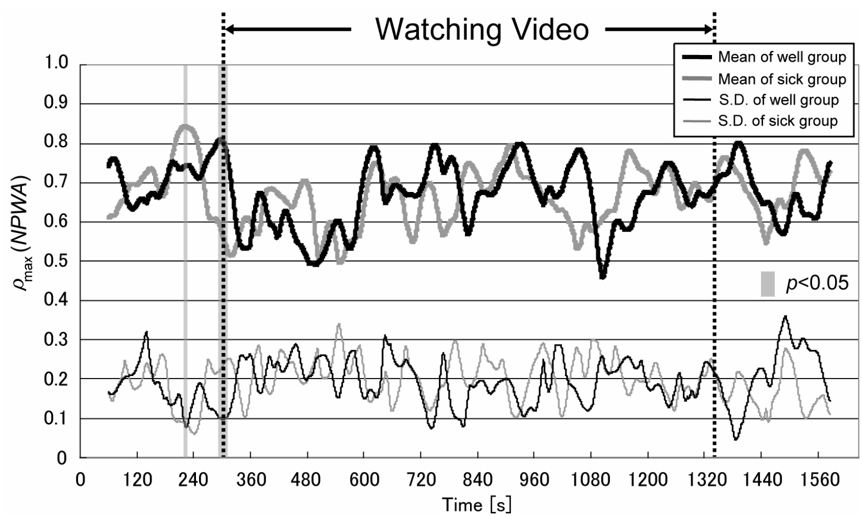

Fig. 8. Comparison in ρ_{max} using *NPWA* between Sick and Well groups in the trial with the swaying video image

These results imply that $\rho_{max}(BP)$ and $\rho_{max}(IC)$ of Sick group was lower than those of Well group in the presentation of the video image. However, there was no significant difference in $\rho_{max}(NPWA)$ between two groups in the presentation. This fact suggests

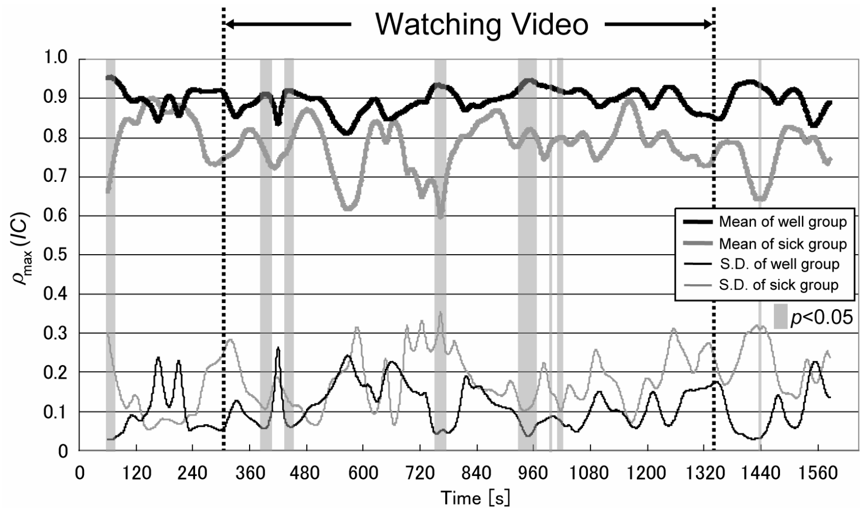

Fig. 9. Comparison in $\rho_{\max}$ using *IC* between Sick and Well groups in the trial with the swaying video image

that symptoms of VIMS were caused by watching the swaying video image and it seems that the effects of it was strong especially at about 720 s and 960 s. However, $\rho_{\max}(IC)$ did not necessarily correspond to traditional $\rho_{\max}$ using *BP*.

6 Conclusion

This study has proposed a method for extracting the blood pressure-related parameter from photoplethysmography using the independent component analysis. From the experimental result, it was ascertained that the proposed method could extract the independent component related to *BP*. In addition, the effects of visually-induced motion sickness could be estimated with independent component which was obtained by using the mixing matrix calculated in the Valsalva maneuver. However, the physiological index $\rho_{\max}$ using the independent component did not necessarily correspond to $\rho_{\max}$ using blood pressure. Thus, we need to reveal the physiological reason of this result.

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