A Heartbeat Interval Error Compensation Method Using Multiple Linear Regression for Photoplethysmography Sensors*

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***Abstract*— This paper presents an error compensation method for heartbeat intervals measured by a photoplethysmography (PPG) sensor. The objective of this work is to improve the accuracy of heart rate variability analysis (HRVA) using PPG, because a peak-to-peak interval (PPI) of the PPG has an error when compared with R to R interval (RRI) of electrocardiograph (ECG). This error is caused by several factors such as blood pressure fluctuation, body motion artifact, and body position. The proposed method predicts RRI using multiple regression analysis with time series of PPIs. The predicted RRI using the proposed method can also reduce the error of frequency characteristics, which are used for HRVA. Evaluation results with three subjects show that the proposed method achieved about 30% mean absolute error (MAE) reduction for predicted RRI and 17% mean absolute percentage error (MAPE) of LF/HF index of HRV analysis.**

Keywords—heart rate variability analysis, heartbeat interval, multiple linear regression, Photoplethysmography (PPG)

I. INTRODUCTION

Cardiovascular disease is one of the leading causes of death around the world. It is important to detect and prevent cardiovascular disease in the early stages to suppress the decrease in the working populations of aging societies. Continuous measurement of cardiovascular information in daily life is useful for early detection of such diseases. Therefore, wearable sensors have been developed to monitor cardio vascular information in daily life.

Photoplethysmography (PPG) is widely used in wearable sensors to detect a pulse wave. PPG sensors irradiate green or red light to the body surface and measure the amount of light absorption by hemoglobin related to the volume change of blood vessels. The heartbeat interval is obtained by detecting the peak from the waveform of these biological signals. Pulse wave detection methods from facial video images according to the same principle of PPG have also been proposed [1].

Unfortunately, there is an error between the pulse interval measured by PPG and the exact heartbeat interval measured by electrocardiograph (ECG). This error is mainly caused by factors such as body motion, arm movement, body position, relative position of blood vessel and heart, blood pressure, and hardness of the vascular wall. Consequently, even when the subject is in a state of rest, the pulse interval contains a time error.

The time error of the pulse wave interval affects the result of the biological signal processing using the heartbeat, such as heart rate variability analysis (HRVA) [2]. The heartbeat interval always fluctuates according to autonomic nervous activity, and it also shows peculiar features by heart disease. Therefore, it is expected that stress monitoring, drowsiness detection, and heart disease detection can be determined by the HRVA. Details of HRVA and the effects of time errors are described in Section II.

There are several prior studies of HRVA using the pulse intervals measured by PPG [3].

For healthy subjects at rest, HRVA using PPI has been shown to be effective [4]. However, as shown in Section II, the result of performing HRVA using RRI differs from the result of performing HRVA using PPI. When comparing the result of HRVA using PPI and the result of HRVA using RRI, the effect of respiration is greater in the case of using PPI [4]. For example, when the breathing interval is slow, the HF component increases, decreasing the LF component and the LF/HF ratio [5]. If the heart rate variability is analyzed using PPI, the results may be misleading. Therefore, in this research, we aim to improve the accuracy of HRVA by learning the error between PPI and RRI for each individual, rather than HRVA using PPI and predicting RRI.

II. HEARTBEAT INTERVAL ERROR IN PPG SENSOR

A. Cause of Heartbeat Interval Error

The observation of the pulse peak is measured by the PPG sensor, which is worn on the arm or wrist. There is a delay from the systole of the heart. This delay depends on the subject's blood pressure. Blood pressure always fluctuates due to various factors such as body movement, arm movement, posture,

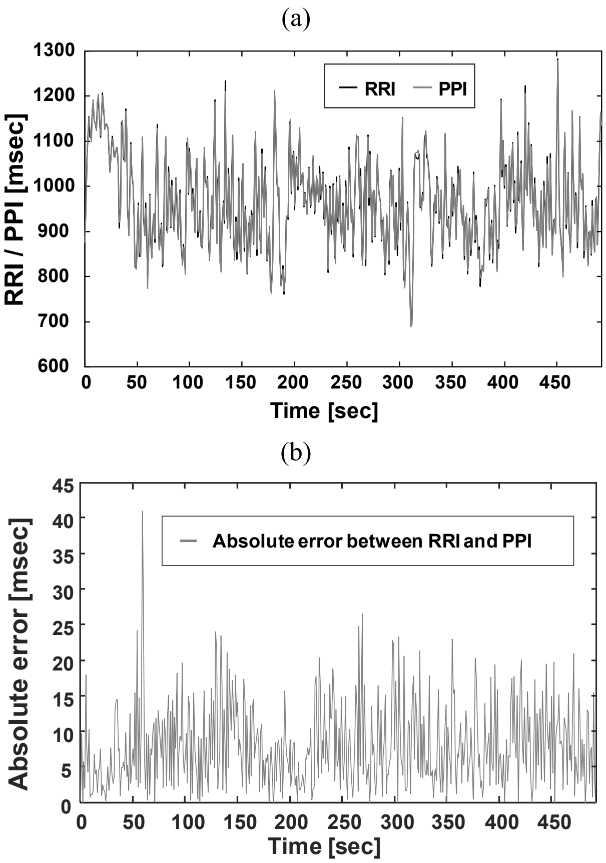

Fig. 1. (a) Time series of measured RRI and PPI, and (b) absolute error between RRI and PPI.

relative position of blood vessel and heart, blood pressure, and the hardness of the blood vessel wall [6].

The peak of the heartbeat waveform in ECG is called the R wave, and the R to R interval (RRI) is defined as the time interval between the R waves. Similarly, the time interval between the peaks of the pulse waveform in PPG is called Pulse-to-Pulse interval (PPI). Fig. 1 (a) shows the time series change of measured RRI and PPI, and the errors between them. Then, ECG for RRI and PPG for PPI are measured simultaneously with a 1-kHz sampling rate from healthy subjects (a 24-year old man). As shown in Fig. 1 (b), a few milliseconds error always occurs in the measured result. This is, because the pulse wave propagation time is not constant as described above [6].

B. *Effect of Heartbeat Interval Error in Heart Rate Variability Analysis*

The heartbeat interval always fluctuates because it is affected by the nervous system and endocrine system. The activity of these systems is always changing due to physical and mental stress, breathing, diet, posture, exercise, and various other factors. Furthermore, heart diseases also affect the fluctuation of heartbeat intervals. In other words, these systems and diseases can be observed indirectly by analyzing heart rate variability. This methodology is called HRVA [7]. In HRVA, the time series change of RRI is analyzed in the time domain and frequency domain [8, 9]. First, spline interpolation is adopted to time series data of RRI and resampled with a 1-Hz sampling rate. Next, a frequency analysis is adopted to the resampled RRI data. Low-Frequency components (LF) and High-Frequency components (HF) are used as indices of HRV in the frequency domain. The respective frequency ranges of the LF and HF are 0.05 Hz to 0.15 Hz and 0.15 Hz to 0.40 Hz. The sum of the power spectra in those frequency ranges is calculated. When the LF is larger than the HF, the sympathetic nerve is tensed. Conversely, when the HF is larger than the LF, the parasympathetic nerve is tensed. LF/HF, which is the ratio of LF to HF, is also used as an index of the balance between sympathetic nervous activity and parasympathetic nerve.

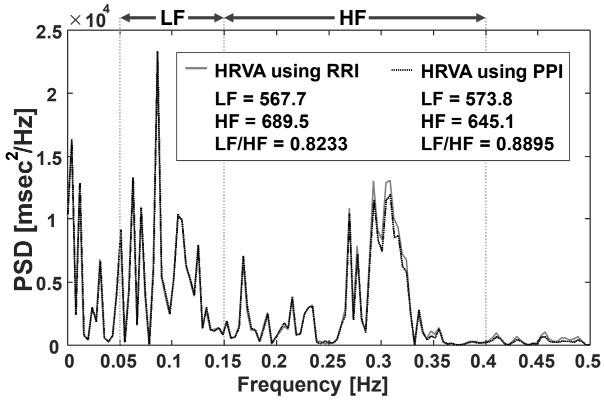

Fig. 2. HRVA results using RRI and PPI.

Fig. 2 shows an example of HRVA results using RRI and PPI. The same measured data of Fig. 1 are used RRI and PPI. As shown in Fig. 2, an error occurs between HRVA results using RRI and ones using PPI.

III. Error Compensation Method

As shown in Fig. 2, the error between PPI and RRI affects HRVA [2]. To compensate for the time error of PPI, we introduced a multiple linear regression analysis method. The time error is then predicted by the time series of PPI.

Multiple linear regression analysis is a mathematical method for modeling the relationship between variables. When the relationship between the dependent variable and one or more independent variables is linear, it is called linear regression. The linear regression equation is expressed by the following equation.:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_p x_p + \varepsilon \quad (1)$$

Here, b is regression coefficients, x is independent variables, ε stands for random error, and y signifies a dependent variable. It is called simple linear regression when $\mathrm{p} = 1$, and it is called multiple linear regression when $p \geq 2$ [10]. The value of the

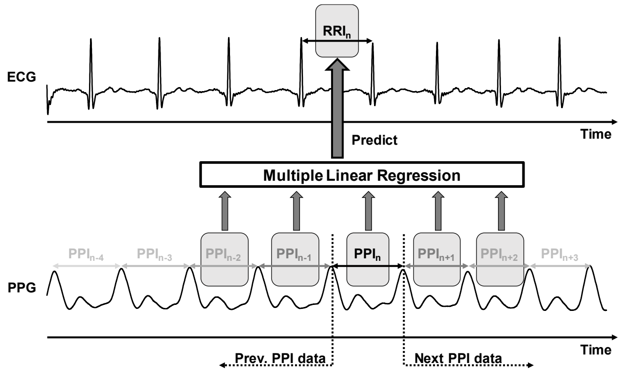

Fig. 3. Error compensation using time series of PPI

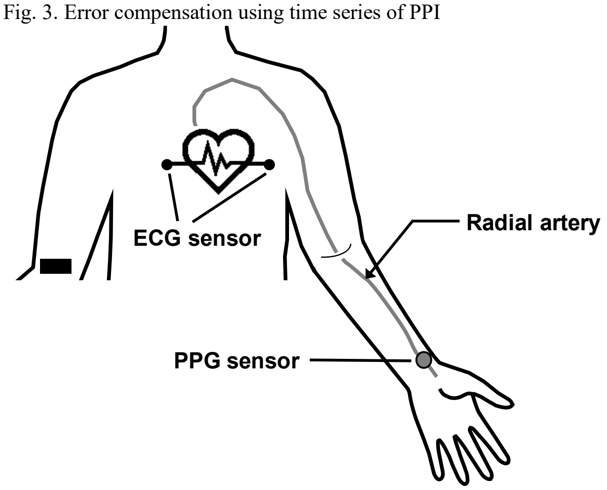

Fig. 4. Measurement setup: 2-electrodes ECG sensor and PPG sensor are measured simultaneously.

dependent variables can be predicted from the values of the plurality independent variables using the multiple linear regression equation. We used this method for time error reduction.

Fig.3 shows the concept image of RRI prediction using time series of PPI and the linear multiple regression model. Then, past and future PPI from time series data are used as independent variables.

As inference by linear multiple regression consists of a simple multiply-add operation, it is very useful under severe power limitation of a wearable device. When measuring PPG data, ECG data is measured as teacher data to obtain a linear multiple regression model for predicting heartbeat intervals.

IV. Performance Evaluation

A. Experimental Setup

To evaluate the proposed method, we measured the reference ECG [11] and PPG [12] with three subjects (23–25 year old healthy men). The ECG and PPG are measured simultaneously as shown in Fig. 4. In this study, the ECG data was measured with Ag/Cl electrodes pasted on the left and right sides of the chest. The PPG sensor was placed along the radial artery of the wrist. The sampling frequency was set to 1 kHz.

All subjects were sitting, and they moved their arms upwards and downwards slowly. Data are recorded for 6 min, twice at different times from each subject. The multiple regression model was created using the first-time measured data, and the inference was conducted using the second time measured data. We obtained mean average error (MAE) between the error predicted RRI from PPG and RRI from ECG as shown in (2). Here, L denotes data length.

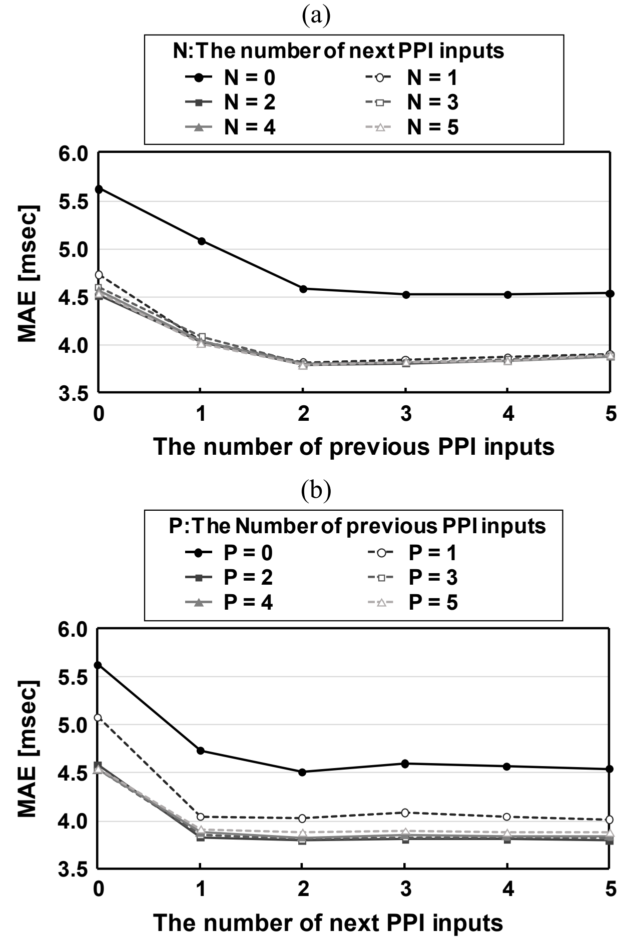

Fig. 5. Relationship between MAE and the number of input PPIs: *PPI*[*n* - *P*:*n*+*N*]. (a) The number of the next PPI *N* is fixed, and (b) the number of the previous PPI *P* is fixed.

The accuracy of LF/HF, which is one of the HRVA results described in Section II, is also evaluated. We obtained the relative error rate expressed by equation (3). Here, y_{ref} represents the LF/HF calculated from RRI, and y_{meas} represents the LF/HF calculated from PPI and predicted RRI.

$$MAE = \frac{1}{L}\sum_{n=1}^{L}|RRIpre_n - RRI_n| \qquad (2)$$

$$Relative\ error\ rate = \left|\frac{y_{meas} - y_{ref}}{y_{ref}}\right| \times 100[\%] \qquad (3)$$

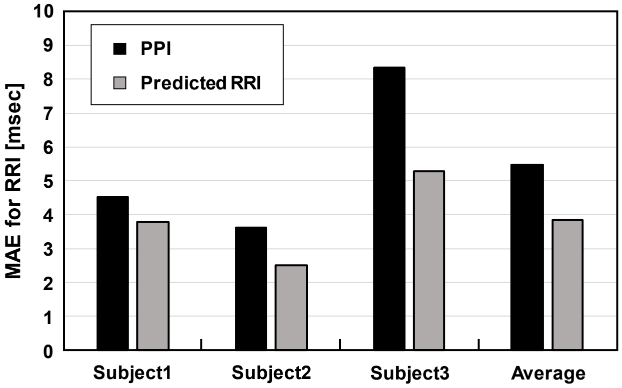

Fig. 6. Comparison of MAE of heartbeat interval.

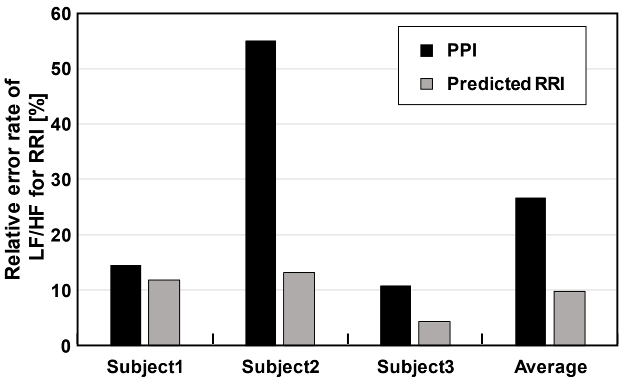

Fig. 7. Comparison of relative error rate of LF/HF.

B. Results

First, we evaluated the effect of independent variables of linear multiple regression. As shown in, Fig. 3, we used time series PPIs as independent variables. Fig. 5 shows the relationship between the number of input PPIs ($PPI[n - P:n+N]$) and MAE. Here, P and N respectively denote the number of previous PPI and the number of next PPI. According to this result, we chose $P = 2$ and $N = 1$ and these parameters are used in the following evaluation.

Fig. 6 shows a comparison of MAEs of heartbeat intervals between PPI and predicted RRI. Here, the MAE is calculated from true RRI measured by ECG. The MAE of predicted RRI is improved from 5.49 ms to 3.83 ms. This MAE is a sufficiently small value, because the HRVA requires less than 5 ms heartbeat interval error [13].

Finally, Fig. 7 shows the MAPE of LF/HF calculated by (3). As described in Section II, the LF/HF is the frequency characteristic of heartbeat interval, which is used in HRVA. The MAPE of LF/HF also improved in all of the subjects, and the results improved about 17% on average.

V. CONCLUSION

In this study, we proposed the heartbeat interval error compensation method for HRVA using PPG sensors. The proposed method can predict RRI only using time series of PPIs measured by PPG. The linear multiple regression model is used to calculate the prediction. To evaluate the proposed method, reference RRI and PPI are measured from three subjects using commercial ECG and PPG sensors. As a result, the MAE of heartbeat interval improved from 5.49 ms to 3.83 ms. Furthermore, the MAPE of LF/HF value, which is used in HRVA, also improved from 26.7% to 9.7%.

VI. ACKNOWLEDGMENT

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