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Estimating Heart Rate using Wrist-type Photoplethysmography and Acceleration sensor while running

Hayato Fukushima[1], Haruki Kawanaka[2], Md. Shoaib Bhuiyan[3] and Koji Oguri[4]

Abstract— **This study provides Heart Rate (HR) Estimation using wrist-type Photoplethysmogpraphy (PPG) sensor while the subject is running. We propose the algorithm to estimate heart rate for the wrist-type PPG sensor. Since body motion artifacts easily affect the arm portion, our method in this study also uses accelerometer built in the wrist-type sensor to improve the accuracy of heart rate estimation. Our method has two components. One is rejecting artifacts with the power spectrum's difference between PPG and acceleration obtained by frequency analysis. The other is the reliability of heart rate estimation, defined by the acceleration.**

Experimental results while our test subjects were running came closer to the holter Electrocardiogram (ECG) in high accuracy (r = 0.98, SD = 8.7 bpm). We, therefore, report the heart rate estimation method which has a higher degree of usability compared to existing methods using ECG.

I. INTRODUCTION

Monitoring heart rate (HR) during movement is important for preventing accidents caused by heart troubles. Besides, heart rate training is also getting popular nowadays [1]. In general, people monitor their heart rate during exercise by Electrocardiogram (ECG). However, existing methods have low degrees of usability because they need a sensor tied to the chest. Therefore, there is a need for heart rate monitoring methods having a higher degree of usability.

So, we estimate heart rate during exercise using Photoplethysmography (PPG), instead of ECG.

There are some early studies [2] for estimating heart rate using PPG. Earlier studies [3][4] tried using a finger ring type sensor, instead of a chest sensor. However, very few people wear rings while actually doing exercises. Imai [5] experimented using PPG sensor worn at an ear. They suffered from drawbacks like the earring-type sensor that needs the code linked to the analyzer, and the experiment was simulating running using a treadmill.

On the other hand, watches are necessary for lap time measurement in exercises such as in marathon. Therefore, this study's purpose is estimating heart rate while actual running is being occurred, using wrist-type sensor with a higher degree of usability than existing methods provide.

[1]Hayato Fukushima is with Graduate school of Information Science and Technology, Aichi Prefectural University, Japan `h.fukushima at bme.ist.aichi-pu.ac.jp`

[2]Haruki Kawanaka is with Faculty of Information Science and Technology, Aichi Prefectural University, Japan `kawanaka at ist.aichi-pu.ac.jp`

[3]Md. Shoaib Bhuiyan is with Faculty of Medical Engineering, Suzuka University of Medical Science, Japan `bhuiyan at suzuka-u.ac.jp`

[4]Koji Oguri is with Faculty of Information Science and Technology, Aichi Prefectural University, Japan `oguri at ist.aichi-pu.ac.jp`

However, the arm portion is greatly affected by movement artifacts. The waveform of PPG is easy to be distorted by body motion artifacts [6].

Therefore, we also propose the heart rate estimation algorithm using accelerometer to improve the accuracy.

II. PHOTOPLETHYSMOGRAPHY

PPG is the change of blood's volume in the capillary vessel. Oxygenated hemoglobin in the vessel absorbs green lights (wave length: 400 - 550 nm) more than other lights. Therefore, human blood looks like red. We can observe PPG noninvasively with irradiating LED (Light Emitting Diode) toward the capillary vessel in the skin, and receiving the reflected light at PD (Photo Detector) (Fig. 1).

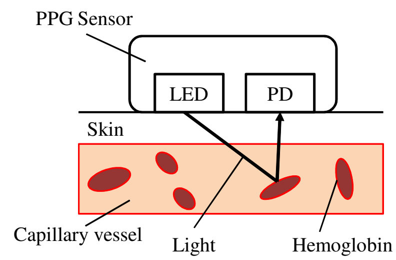
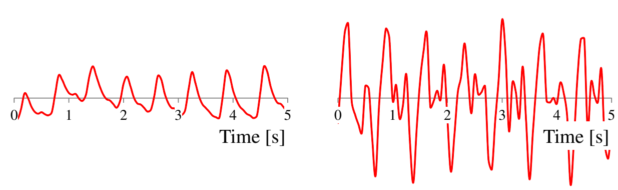


Fig. 1. Structure of detecting PPG by receiving the reflected light

Blood flows to capillary vessel at every beat of heart. This flowing is the main component of volume change. Thus, PPG is a biological signal whose periodicity is similar to that of ECG. In addition, this period corresponds to heart rate (Fig. 2a). Therefore, to estimate heart rate from PPG is to detect the fundamental frequency of PPG.



(a) Resting (b) Running

Fig. 2. Photoplethysmography (Normal and Affected by artifacts)

However, PPG is greatly affected by movement artifacts. In this study, wrist-type PPG sensor has a serious problem while the subject is running. The artifact caused by the runner shaking arm convolutes into PPG (Fig. 2b). Such artifact is periodic, and the frequency of the artifact is close to that of heart rate. Therefore, it is difficult to detect the frequency of heart rate from PPG while the subject is running.

III. METHOD

A. Outline of heart rate Estimation Algorithm

In this study, we estimate heart rate using wrist-type PPG sensor during exercise. We also use accelerometer built in a wrist-type sensor. The flowchart of heart rate estimation algorithm is shown in Fig. 3.

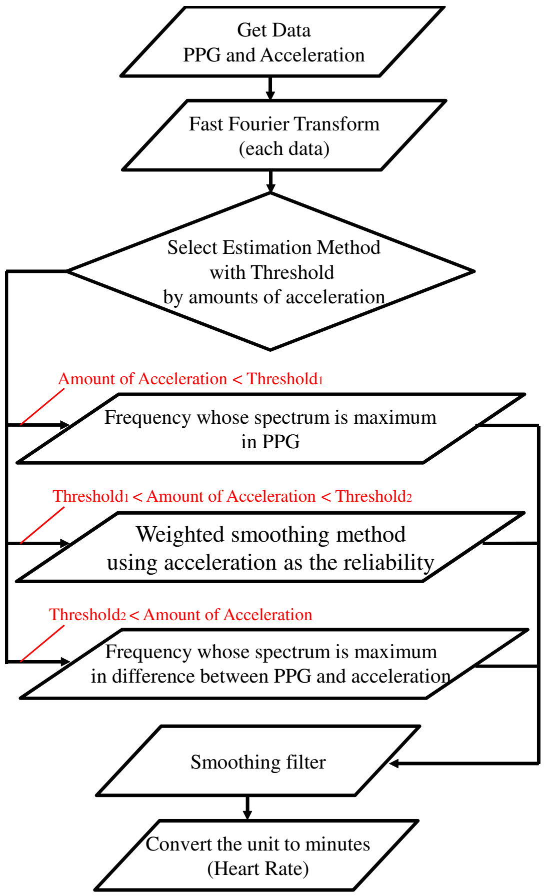


Fig. 3. Flowchart of heart rate Estimation Algorithm

In this study, we define the following three states from the magnitude of the measured acceleration amount.

1) Resting
2) Warming-up (Aperiodic motion)
3) Running

In each of these three states, the time and force of arm movement is different, so the estimation method can use the acceleration's integral absolute value (it has both positive and negative values) as a threshold to determine each of the above three states.

To estimate heart rate from PPG is to detect the frequency of PPG. Next, the estimated frequency passes through a smoothing filter. Finally, heart rate is determined after converting the time scale from seconds to minutes.

B. Estimation using Frequency Analysis

The frequency corresponding to heart rate can be detected as a peak from PPG with frequency analysis. In general, each biological signal has specific bandwidth of frequency. For example, heart rate has around 1.0 to 3.0 Hz or around 60 to 180 bpm (beats per minute). Thus, the frequency of heart rate can be detected by separating it from other measured biological signals (example, respiratory signal). Therefore, heart rate can be determined by detecting such frequency peaks in the band. While in the resting state, we can estimate heart rate by detecting the peak of frequency whose spectrum is maximum.

However, with frequency analysis of PPG while someone is running, the frequency of artifact caused by shaking of arms appears remarkably close to the band of heart rate. The reason is that the subject shakes arms within the range of [1.0 - 3.0] times while running. This makes determining the frequency of heart rate unconditionally difficult.

Therefore, we also use accelerometer to reject the artifact of shaking arm in this study. The artifact caused by motion appears in Acceleration as well as in PPG. Frequency sequences $X_{ppg}(f)$, $X_{acc}(f)$ are calculated by frequency analysis from PPG and acceleration respectively (red line in Fig. 4 shows X_{ppg}, and blue one shows X_{acc}). In addition, both power spectrums are normalized by dividing the maximum value of each spectrum. Each maximum value is set at 1.0.

In Fig. 4, the fundamental frequency of arm shaking artifact appears around 1.4 Hz, and 2.8 Hz which is the double of the fundamental frequency as peaks in both spectrums of PPG and acceleration. In contrast, the peak appears around 2.9 Hz in spectrum of only PPG. This peak corresponds to heart rate, compared with the correct value which is described in detail later.

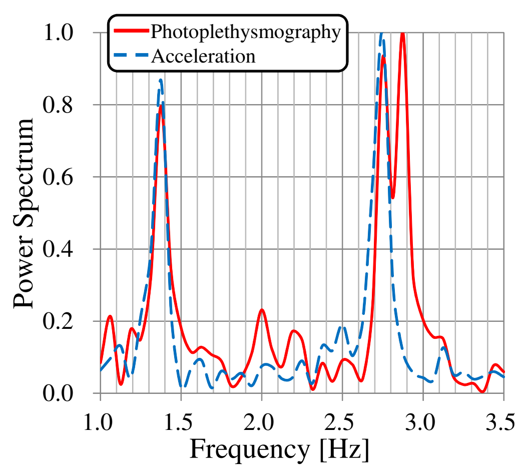


Fig. 4. Heart rate appears in Power spectrum of PPG only, not Acceleration.

Therefore, $D(f)$ which is the difference of spectrum between PPG to Acceleration is defined as (1). We detect the frequency of heart rate in the frequency sequence $D(f)$. The frequency whose spectrum is maximum in $D(f)$ is accepted as heart rate.

$$D(f) = \frac{X_{ppg}(f)}{\max\{X_{ppg}(f)\}} - \frac{X_{acc}(f)}{\max\{X_{acc}(f)\}} \quad (1)$$

With this method, heart rate frequency f_{HR} can be detected, and the artifact of shaking arms can also be rejected.

C. Method for Aperiodic Motion

While in aperiodic movement such as warming up, artifacts can't be detected in frequency sequences $X_{ppg}(f)$, $X_{acc}(f)$ as clear peaks. Therefore, we use the following method in such cases.

There are many kinds of warming up movements. The affected artifacts depend on movements. The larger the convoluted artifact is, the worse the PPG is distorted.

Therefore, the relative reliability to estimate is defined by measured $\mathrm{Acceleration}$ in this study. $\mathrm{Acceleration}$ is the absolute value. The reliability as coefficient is calculated by $\mathrm{Acceleration}(i)$ which is $\mathrm{Acceleration}$ at i, in *seconds*. $\mathrm{Reliability}\,(i)$ is defined as (2).

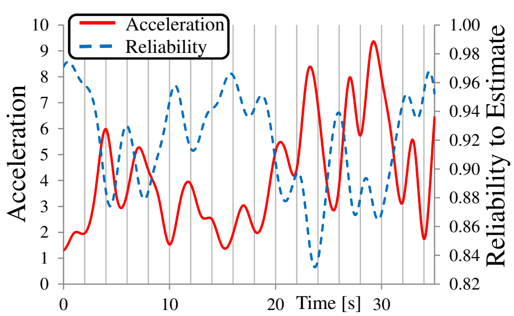


Fig. 5. Inverse relationship between Acceleration to Reliability for estimating heart rate during warming up

The smaller the $\mathrm{Acceleration}(i)$ is, the higher the $\mathrm{Reliability}\,(i)$ as coefficient is (Fig. 5). Thus, we estimate heart rate frequency f_{HR} with weighted smoothing the instantaneous heart rate frequency $f_{\mathrm{peaks}}\,(i)$ in (3).

$$\mathrm{Reliability}(i) = 1 - \frac{\mathrm{Acceleration}\,(i)}{\sum_{j=i-N}^{i} \mathrm{Acceleration}(j)} \quad (2)$$

$$f_{\mathrm{HR}} = \frac{\sum_{i=0}^{N-1} \mathrm{Reliability}\,(i)\, f_{\mathrm{peaks}}\,(i)}{\sum_{i=0}^{N-1} \mathrm{Reliability}\,(i)} \quad (3)$$

The instantaneous heart rate frequency $f_{\mathrm{peaks}}\,(i)$ is calculated by the difference of the time PPG's peaks happen. Wang [7] improved the accuracy by making signals to be decomposed to frequency bands.

Therefore, we also extracted the frequency band (around 1.0 - 2.0 Hz) which corresponded to heart rate to detect the difference of the time when peaks happen.

D. Post-Processing

We used the following smoothing filter at the post-processing to reject outliers. Such outliers are caused by motion artifacts having huge magnitude (example, jumping). We obtained heart rate once every second, whether exercising or not, for a total of 8,200 seconds. We used a time-window ($n = 120$ second) to calculate $\sigma\,(i)$ and $\overline{f}\,(i)$ at the time i, in *seconds*. $\sigma\,(i)$ is defined as (4). In the time series of estimated heart rate frequency, the average is $\overline{f}\,(i)$, and the standard deviation is $\sigma\,(i)$. Heart rate frequency is $f(i)$. If the difference between $f(i)$ to $\overline{f}\,(i)$ is greater than $\sigma\,(i)$, such $f(i)$ is determined to be an outlier. Then, the frequency is updated to $\overline{f}\,(i)$. This filter is non-linear. The updated frequency $f_{\mathrm{new}}\,(i)$ through the filter which rejects the outliers is defined as (5). Finally, the ultimate frequency f_{final} is defined as (6). f_{final} is calculated from smoothing $f_{\mathrm{new}}\,(i)$.

$$\sigma\,(i) = \sqrt{\frac{1}{n} \sum_{j=i-(n-1)}^{i} \left\{\overline{f}\,(i) - f\,(j)\right\}^2} \quad (4)$$

$$f_{\mathrm{new}}(i) = \begin{cases} f(i) & \left|f(i) - \overline{f}\,(i)\right| < \sigma\,(i) \\ \overline{f}\,(i) & \text{otherwise} \end{cases} \quad (5)$$

$$f_{\mathrm{final}} = \frac{1}{N} \sum_{i=0}^{N-1} f_{\mathrm{new}}(i) \quad (6)$$

Two examples of heart rate estimation results are shown in Fig. 6. The first, Fig. 6a, is not using the proposed filter at post-processing. There are some outliers when compared with correct values. In contrast, the other (Fig. 6b) using the proposed filter has no outliers, and it is more continuous than the one not using it.

IV. EXPERIMENT

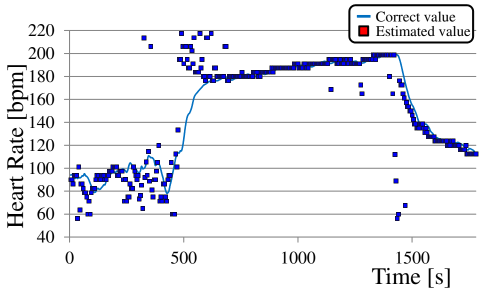
A. Condition

As part of the experiment, five test subjects (two females and three males, aged 21.4 ± 0.5) actually ran in the circuit course (one round is about 500 m), wearing wrist-type PPG sensor in left wrist (Fig. 7). LED to measure PPG is built on the back of the wrist-type sensor, and the accelerometer is built-in. The wrist-type sensor is a product made by Japanese corporation. The sensor's weight is about 27 g, and each signal is measured simultaneously (sampling rate: 16 Hz).

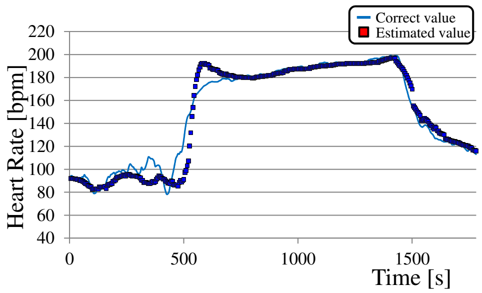
After obtaining informed consent from the test subjects, we conducted the experiments with the understanding that if anyone is at the limit of his/her physical strength, the experiment would be stopped. Before running, we instructed test subjects to rest and to warm up, and we estimated heart rate during then, too.

B. Definition of correct value of heart rate

Heart rate is defined as the number of times the heart beats in one minute. Measuring heart rate exactly is difficult because it takes so long. In practice, instantaneous heart rate calculated from the difference of time of beats is evaluated.



(a) heart rate estimation without using the proposed filter



(b) heart rate estimation using the proposed filter

Fig. 6. Effect of proposed filter for rejecting outliers

Fig. 7. Wrist-type Photoplethysmography sensor in this study (Acceleration sensor is also built in)

For comparison, test subjects also wore holter ECG sensor which is medical equipment (Cardy 303 pico, Suzuken Corp.) This holter ECG is able to detect R wave even during movement (sampling rate: 125 Hz).

We calculated heart rate from R-R Interval (RRI) with the holter ECG. The output of holter ECG is considered the correct value of heart rate in this study.

C. Result

An example of heart rate estimation results is shown in Fig. 8. The blue line shows the correct value calculated from holter ECG. Heart rate as calculated from PPG using our method in this study, but without using accelerometer is also shown as a comparison value (green line). The method also using acceleration (red line) in this study has higher accuracy than the comparison value affected by artifacts (green line).

The result of all subjects is that correlation coefficient $r = 0.98$, and the standard deviation of error SD = 8.7 bpm.

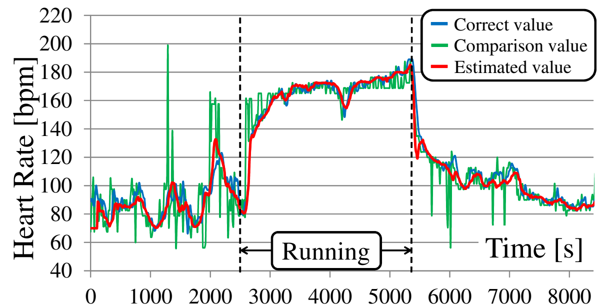


Fig. 8. Estimated value in this study (red line) is closer in accuracy to the correct value (blue line) than comparison value (green line).

V. CONCLUSION

This paper reports estimating heart rate using wrist-type PPG sensor while the test subject is actually running. The proposed method has a higher degree of usability compared to existing methods using ECG.

Estimation from PPG is difficult because the arm portion is greatly affected by movement artifacts. Therefore, we try rejecting such artifacts using also accelerometer to improve the heart rate estimation accuracy. With frequency analysis, clear peaks appear for both PPG and acceleration. We defined the difference of spectrum between PPG and acceleration, so we can reject the artifact with it. Thus, we can detect the heart rate frequency. Considering aperiodic artifacts and not many early studies, we defined the reliability with acceleration to estimate heart rate frequency.

As of the experiment, five test subjects ran in the circuit course, wearing the wrist-type sensor. The results were closer to holter ECG in high accuracy ($r = 0.98$, SD $= 8.7$ bpm). Therefore, we could make the algorithm of heart rate estimation for wrist-type PPG sensor.

REFERENCES

[1] J. Kim, M. hee Lee, H.K. Lee, K. Choi, S. Bang, and S. Kim, “Heart Rate Monitor for Portable MP3 Player,” IEEE Engineering in Medicine and Biology 27th Annual Conference, pp.5207–5210, 2005.

[2] T. Kosuda and I. Aoshima, “Development of the pulse rate measurement technology to reduce influence of motion,” The Horological Institute of Japan, vol.48, no.3, pp.42–51, 2004.

[3] T. Kimura, R. Ohsaki, and A. Iwata, “Wearable Pulse Wave Sensor,” The Institute of Electronics, Information, and Communication Engineers - MBE, vol.100, no.350, pp.43–49, 2000. Tech. Rep.

[4] Y. Kondo, K. Honda, and K. Tsubata, “Development of SEIKO PULSE GRAPH (Part of the Sensor),” The Horological Institute of Japan, no.160, pp.38–48, 1997.

[5] B. Imai, N. Shiozawa, and M. Makikawa, “Elimination of Motion Artifacts Mixed in Photoplethysmography Using an Accelerometer,” Japanese Society for Medical and Biological Engineering, vol.41, no.1, pp.148–155, 2006.

[6] M. Yarita and T. Tamura, Research into artifact removal from pulse oximeter signals, Ph.D. thesis, Chiba University, 2008.

[7] Q. Wang, P. Yang, and Y. Zhang, “Artifact Reduction based on Empirical Mode Decomposition (EMD) in Photoplethysmography for Pulse Rate Detection,” 32nd Annual International Conference of the IEEE EMBS, pp.959–962, 2010.

[8] A. Kusajima, K. Nakajima, T. Saito, and K. Sasaki, “Development of a Pulsation Sensor for Measurement of Photoplethysmogram through Clothing,” The Transactions of the Institute of Electronics, Information and Communication Engineers D, vol.95, no.4, pp.713–721, 2012.