Design of PPG-Based Heart Rate Sensor Enabling Motion Artifact Cancellation

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Abstract - We have proposed a photoplethysmography (PPG)-based heart rate sensor which is equipped with a normal PPG sensor and a motion artifact sensor to be able to cancel motion artifact induced during exercise. It has two critical design parameters such as the height of the motion artifact sensor and the distance between the motion artifact sensor and the normal PPG sensor. This paper tries to determine the two parameters by experiments with a subject.

I. Introduction

Heart rate (HR) sensing for men during exercise is important in the view-points of medicine, healthcare and sport physiology. According to the Karvonen formula [1], the maximum allowable heart rate (HR_{max}) can be calculated for any man/woman, and it is known that, for healthcare and effective training purposes, the heart rate during exercise should not go beyond 50%×his/her own HR_{max} for a normal man/woman whereas 75%×his/her own HR_{max} for an athlete. To prevent diseases such as sudden cardiac arrest and heat stroke during exercise, real-time HR sensing/monitoring is effective for players during training in amateur and professional sport teams and for pupils and students during physical training in schools.

One method of HR sensing is to measure the electrical activity of the heart, which is called “electrocardiography (ECG).” ECG puts several electrodes to the positions closer to the heart to directly measure the voltage generated by it. Figure 1 shows the HR during exercise sensed by an ECG put to a subject when he repeats a running and a resting alternatively. In the figure, the red curve shows the HR measured by Polar RS400, which is considered to be the reference, whereas several dots are the HRs sensed by the ECG. In the former half of the exercise, the ECG can give correct HRs, but in the latter half, it cannot give correct HRs any more. This is because the exercise gradually introduces sweat around the electrodes of the ECG and an electric current finally flows them due to the sweat, resulting in the wrong HRs. This is a fatal problem in HR sensing during exercise, so we threw this approach by ECG.

Another method of HR sensing is to indirectly measure the pumping activity of the heart. Photoplethysmography (PPG) is based on opto-electronic technique, which illuminates the skin using a light emitting diode (LED) and detects the intensity of the light changed by the blood volume pulse (BVP) under the skin using a photo detector (PD). The principle of PPG is like measuring the distance between the LED and PD via a blood vessel, so the light intensity is also changed by the change of the thickness of the tissue around the PPG sensor introduced by exercise, which is called “motion artifact (MA).” Especially when a PPG sensor wearer takes vigorous exercise, the spectral component of MA overlaps with that of BVP in the PPG output, so a nonlinear technique is required to cancel the MA.

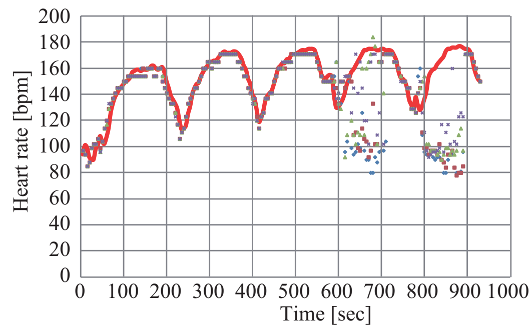

Fig. 1 HR sensing by ECG during an exercise.

PPG is a simple, unobtrusive and non-invasive technique, so we consider that it is only the method suited for HR sensing during exercise, but it is essential to cancel MA in the PPG output, in other words, to detect only MA. There have been several methods so far proposed in MA cancellation. One method uses two colors for LEDs; “near infrared red (NIR)” for detecting BVP and MA and “green” for detecting only MA [2], and another method uses an accelerometer for detecting MA [3]. We tested these methods in experiments with several subjects, but unfortunately we found they did not work effective for HR sensing during vigorous exercise.

We have proposed an MA cancellation for HR sensing [4], which is equipped with a normal PPG sensor (LED/PD) and a MA sensor (LED/PD). We can say that it is only the method of HR sensing effectively workable even during vigorous exercise. As shown below, the PPG-based HR sensor enabling MA cancellation has two design parameters such as the distance between the PPG and MA sensors and the height

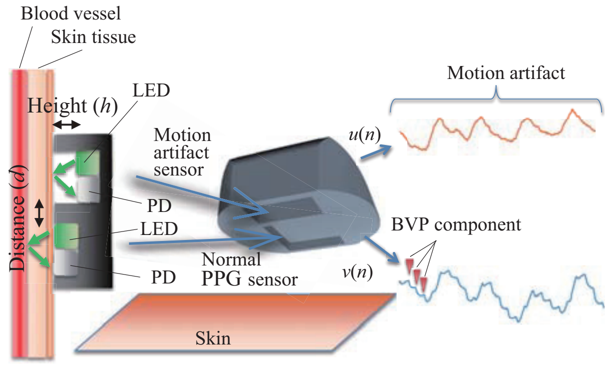

Fig. 2 Principle of the MA cancellation.

of the MA sensor. In [4], we have shown the principle of the MA cancellation but we have not discussed adequate values of the two design parameters. Therefore, in this paper, we try to determine the two design parameters by experiments with a subject.

II. Principle of the MA Cancellation

A. Position of the HR sensor

Our purpose of vital sensing is to wirelessly monitor vital data such as HR, energy expenditure (EE) and body temperature (BT) from a number of men during exercise spread in a large field [5],[6]. The EE can be calculated from the tri-accelerometer data put to a man, and in this case, the tri-accelerometer should be put to the lower part of the body to be able to sense the EE consumed for walking, running, sprint and jumping. Therefore, we decided to put a single device to the back waist position of a man for jointly sensing the HR, EE and BT.

B. Principle of the MA cancellation

Figure 2 shows the principle of the MA cancellation, which is equipped with two pairs of green LED/PD [4]. One LED/PD is used as a normal PPG sensor which directly contacts the skin of the sensor wearer. In this case, the light, which is injected into the skin tissue by the LED, is reflected by a blood vessel under it, so the PD output contains not only the BVP component but also the motion artifact component. On the other hand, the other LED/PD does not contact the skin, namely, there is a gap between the LED/PD and the skin, which is used as an MA sensor. In this case, the light is reflected by the surface or shallower part of the skin, so the PD output contains only the MA component (when either of the LED and PD touches the skin, the PD output contains some BVP component). Once the (BVP+MA) signal and the MA signal are obtained, we can use a simple adaptive filter algorithm to extract only the BVP component [7]. We do not go into its detail in this paper, so please refer [4].

C. Two critical design parameters

As shown in Fig. 2, there are two critical design

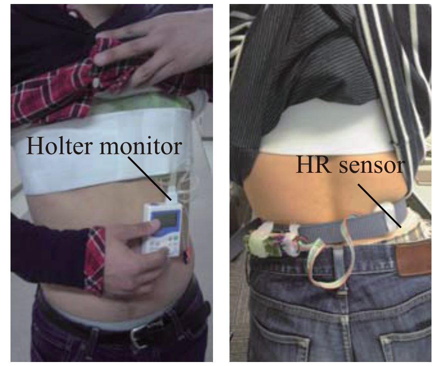

Fig. 3 A subject with a Holter monitor and the HR sensor.

parameters in the MA cancellation. One is the height (h) of the LED/PD in the MA sensor. Note that the two sensors should be placed closer in the sense that the MA component in the MA sensor can be more correlated with that in the normal PPG sensor. When h is smaller, for the MA sensor, the MA component is more correlated with that in the normal PPG sensor, but the light is injected into the skin with more power, so the PD output can contain some BVP component. On the other hand, when h is larger, for the MA sensor, the MA component is less correlated with that in the normal PPG sensor, but the PD output tends to not to contain the BVP component. Therefore, there must be the adequate value in h which can minimize the HR error.

The other is the distance (d) between the two sensors. When d is smaller, the MA components in the two PD outputs are more correlated, but there is more crosstalk between them. On the other hand, when d is larger, the crosstalk can be more reduced, but the two MA components is less correlated. Therefore, there must the adequate value in d which can minimize the HR error.

III. Experiments

To determine the adequate values of h and d, we conducted an experiment with a subject. Figure 3 shows the photos of the subject with the HR sensor. We put the HR sensor to the back waist position of the subject and at the same time a Holter monitor (a medical device to monitor ECG waveform) to the chest position of the subject. The HR sensor is composed of two image sensors with 12-bit resolution and 20 Hz sampling rate. Four types of covers for the HR sensor were made with a 3D printer. Figure 4 shows the four covers such as (1) d13 mm×h3.5 mm, (2) d13 mm×h6.0 mm, (3) d19 mm×h10 mm, (4) d30 mm×h10 mm. Note that the shortest distance is determined because of the size of the LED/PD device whereas the highest height is determined by the LED power. During three kinds of exercise such as fast-walking (4 km/h), running (10 km/h) and jumping (0.8-1.0 jump/sec), we stored the EGC waveform from the Holter monitor and the two PD output signals from the HR sensor. We analyzed the HRs using the obtained data in off-line after the experiments. For the adaptive filter for the HR sensor, we employed a normalized least mean

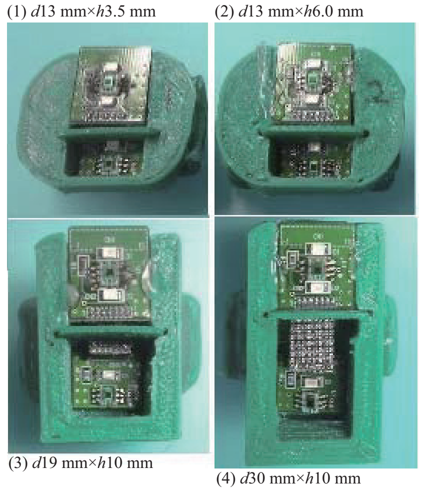

Fig. 4 Four types of the sensor covers.

squares (NLMS) algorithm with the number of taps of 30 and convergence parameter of 0.5.

IV. Results and Discussions

The HR sensing capability is measured as the improvement rate (*IR*), which is given by

$$IR = \frac{RMSE_{w/o\ \text{cancel}} - RMSE_{w/\ \text{cancel}}}{RMSE_{w/o\ \text{cancel}}} \times 100[\%] \qquad (1)$$

where *RMSE* means the root mean square error calculated with respect to the HR for the Holter monitor. Note that a better canceler should give a larger *IR*.

Figure 5 (a) shows the low (h=3.5mm and 6.0mm)-high (h=10mm) dependency on the *IR*. The lower MA sensor position gives better performance for the fast-walking and running, but the higher MA sensor position gives a better performance for the jumping. Figure 5 (b) shows the short (d=13mm)-long (d=19mm and 30mm) dependency on the *IR*. The short inter-sensor distance gives better performance for the fast-walking and jumping, and the performance of the short distance is comparable to that of the long distance for the running. Taking into consideration that for ball games such as football and rugby, the periods of walking and running are dominant and the sensor height affects the size of the HR sensor, we decided to select h=3.5mm and d=13mm.

Finally, Figure 6 shows the sensed HR by the proposed HR sensor for another experiment with the same subject; (a) for repetition of 2-minute running and 1-minite resting, (b) for repetition of 2-minute jumping and 1-nimute resting. In addition to the NLMS algorithm, this figure shows the performance by a recursive least squares (RLS) algorithm with the number of taps of 50 and forgetting factor of 0.99, but there was no large difference in the sensed HR between the NLMS and RLS algorithms. The proposed cancellation can work effective for the running and jumping; its performance agrees well with that of the Holter monitor. On the other hand, the conventional band pass filtering (BPF) can correctly sense the HR only for

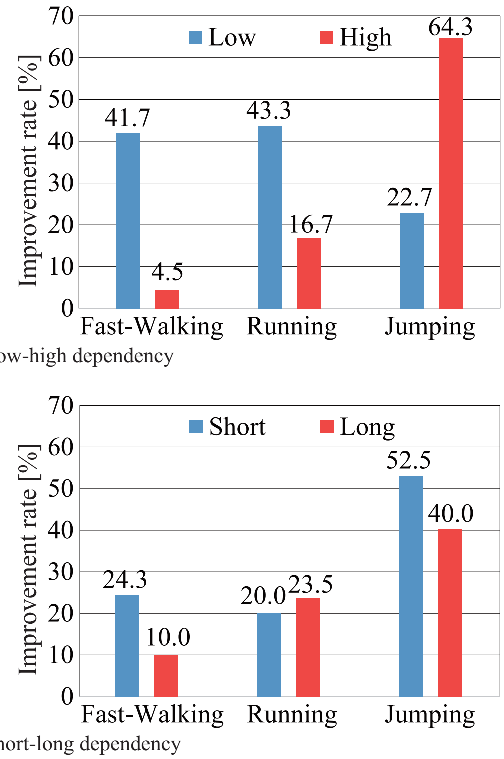

Fig. 5 Experimental results.

the case when the subject is taking a rest. For the case of running, the BPF gives a wrong HR of 170 [bpm (beats per minute)], which corresponds to its high-end cut-off frequency, on the other hand, for the case of jumping, the BFP gives a wrong HR of 50 [bpm], which corresponds to its low-end cut-off frequency.

V. Summary and Conclusions

In this paper, we presented a problem of motion artifact in heart rate sensing from a man during exercise and outlined our proposed motion artifact cancellation in PPG-based heart rate sensing as a solution for the problem. The proposed cancellation technique has two critical design parameters such as the height and distance of sensors, so we tried to determine adequate values of the two parameters by an experiment with a subject. By the experiment, we found the heart rate sensor with distance of 13mm and height of 3.5mm gives better performance for exercise such as walking and running. Finally, by another experiment where a subject repeats an exercise and a resting, we successfully demonstrated that even for the case of vigorous exercise when a conventional linear filtering technique cannot cancel the induced motion artifact, the proposed heart rate sensor can correctly sense the heart rate.

For determining truly adequate deign parameters, more experiments with more subjects are required. It is one of our future works. In addition, a smaller and light sensor cover is desirable. Implementing such a cover is another of our future works.

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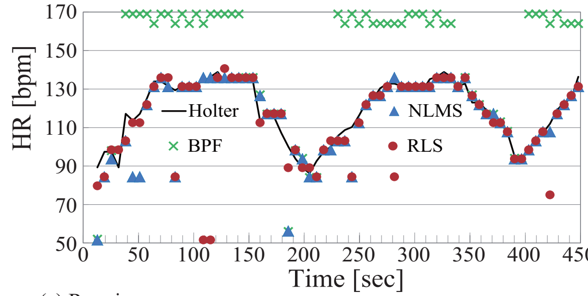
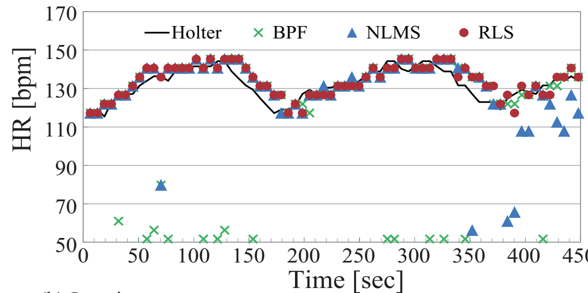


(a) Running



(b) Jumping

Figure 6 HR versus the time.