Communications

Photoplethysmogram Measurement Without Direct Skin-to-Sensor Contact Using an Adaptive Light Source Intensity Control

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***Abstract*—We developed a chair-attached, nonintrusive photoplethysmogram (PPG) measuring system for everyday life, unconstrained monitoring using nonskin-contacting sensor-amplifier circuits capable of emitting suitable light intensity adaptable to clothing characteristics. Comparison between proposed and conventional systems showed reasonable correlation and root-mean-squared error levels, indicating its feasibility for unconstrained PPG monitoring.**

***Index Terms*—Adaptive light intensity control, indirect contact sensor, photoplethysmogram (PPG) monitoring, unconstrained measurement.**

I. Introduction

The growing interest in health monitoring during daily life has lead to many studies on unconstrained biological signal measurements. Most of the systems for unconstrained measurement have used "fixed-on-environment" electrodes installed on appliances, furniture, or clothing [1]–[3] that require exposed skin for direct contact with sensors. However, people normally wear clothes with only a small area of bare skin exposed during their daily life and, therefore, the application scope for "fixed-on-environment" electrodes is limited. Thus, the ability to measure biological signals through clothing is required for the practical application of this kind of sensory system. Recent improvements in biological signal measuring through clothing have facilitated many applications for unconstrained biological signal monitoring in healthcare [4], [5]; however, despite these advances, there have been no attempts to measure photoplethysmogram (PPG) signals through clothing. Therefore, in this paper, we decided to explore this concept for PPG measurement.

II. Methods

According to the Beer–Lambert law of spectrophotometry, the intensity of light traveling through a uniform medium containing an absorptive substance decreases exponentially with the absorptive coefficient and the optical path length through the medium [6]. In conventional PPG measurements, light travels through various media, including skin pigmentation, bones, and venous and arterial blood. Since cloth can be thought of as an additive layer of light-absorptive medium, an output signal through cloth will be relatively weaker than that of conventional PPG measurement. Additionally, because of the various absorptive characteristics and optical path lengths of different cloth types, acquisition of an acceptable PPG signal through these materials necessitates the use of a high-intensity light source and a sensor that can vary according to cloth type.

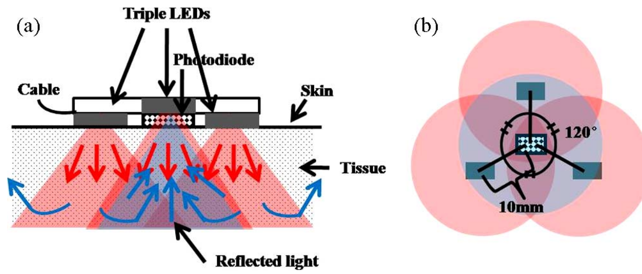

Fig. 1. Conceptual diagrams of the proposed PPG sensor with three light sources. (a) Frontal view. (b) Transverse view.

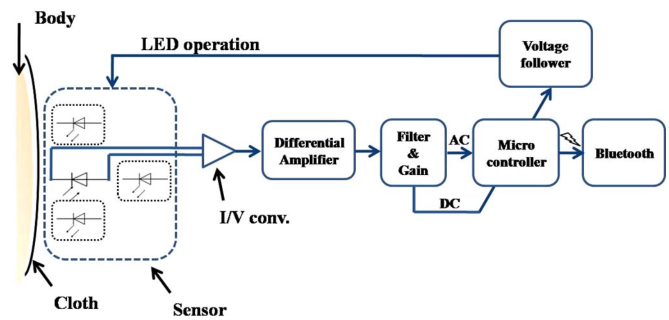

Fig. 2. Block diagram for the proposed PPG measurement system that includes an adaptive light intensity control function using dc components.

A. Hardware Design for PPG Measurement Over Clothing

A conventional reflectance PPG sensor consists of an LED unit and photodetector in parallel configuration. Since LEDs emit light in a circular pattern, the detected light represents a fraction of the total reflected light emitted toward the photodetector. To increase the incident light, we placed three LEDs (QEB421, 880 nm peak wavelength, Fairchild Semiconductor, San Jose, CA) symmetrically around the photodetector (HSDL-5400, Agilent Technologies, Palo Alto, CA) (see Fig. 1). Light emitted from each LED had its own circular pattern, and a portion of the light from each LED overlapped at the photodetector. The output signal from the sensor was converted into a voltage and amplified, then filtered with a bandpass of 0.05–10 Hz to separate the pulsatile ac component, and filtered with a low-pass cutoff at 0.1 Hz to separate the dc component. The ac and dc signals were digitized at 400 Hz using the microprocessor. The ac signal was digitized for Bluetooth communication and dc signal for adaptive control of the LED's light intensity. This PPG sensor was installed in the seat and back of a chair for the purpose of unconstrained measurement.

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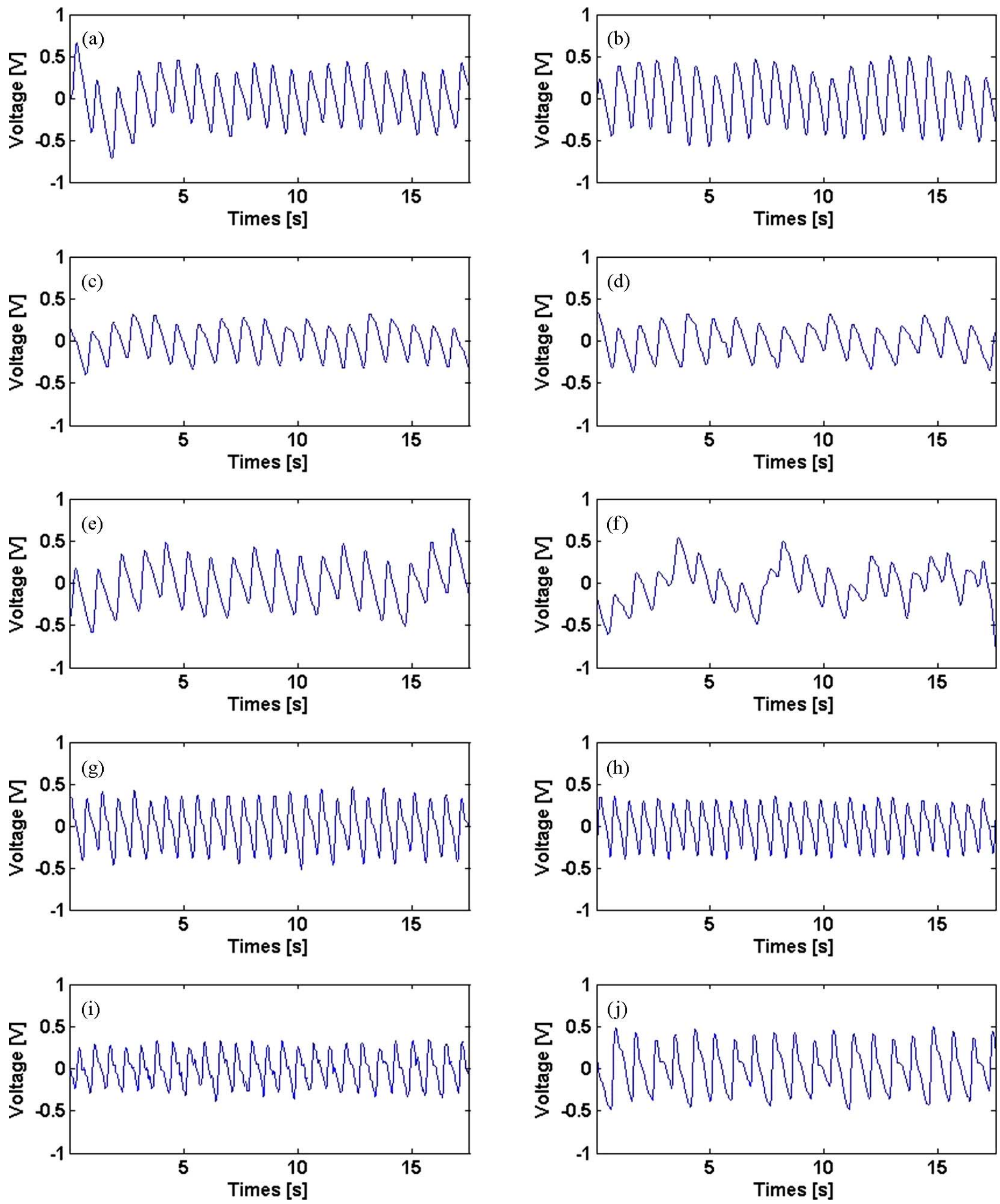

Fig. 3. Normalized PPG signal morphologies obtained by the presented method through: (a) white dress shirt, (b) black dress shirt, (c) white T-shirt, (d) red T-shirt, (e) blue T-shirt, (f) upper business suit at the back region, as well as (g) beige cotton pants, (h) dark blue cotton pants, (i) blue jeans, and (j) lower business suit at the thigh region.

B. Adaptive Light Intensity Control

Since clothing and human tissue, with the exception of pulsatile arterial blood, have a constant absorptive coefficient and light path length, the dc component is thus constant at a given measurement site with a given cloth type. In preliminary experiments, dc voltage was manually adjusted to control light intensity, and PPG measurements were attempted through white, blue, and red T-shirts, white and black dress shirts, beige and dark blue cotton pants, blue jeans, and a business suit via the chair-mounted sensors at the back and thigh of five different subjects. A microprocessor (Atmega128, Atmel, Systems Corporation, Chester Springs, PA) and digital-to-analog converter (DAC) (AD558, Analog Device, Norwood, MA) were used for light intensity control. LED light intensity was varied by controlling the microprocessor's digital input to the DAC. Our results showed that even though the level of light intensity and amplitude of acquired PPG signal was different for various cloth types, a stable ac PPG signal was acquired for all five subjects when the dc voltage was between 1.0 and 2.0 V. In the final version of the experiment, the adaptive light intensity was controlled using continuous monitoring of the dc voltage by the microprocessor. Lower and upper thresholds were set at 1.0 and 2.0 V, respectively, and LED intensity was controlled to match the dc voltage within this preset range. The configuration of the entire system is illustrated in Fig. 2.

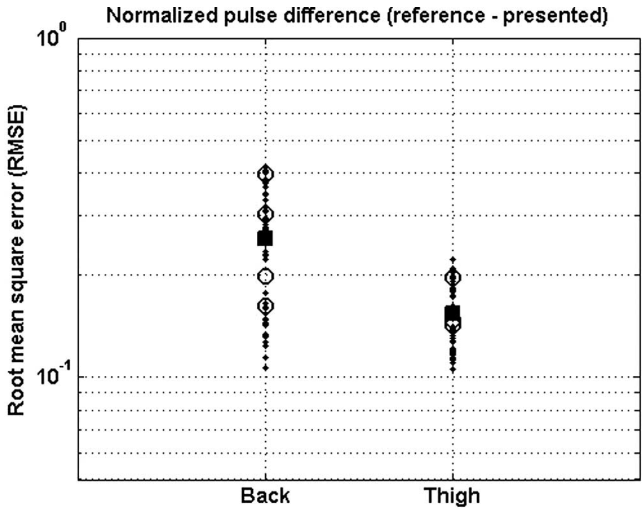

Fig. 4. RMS error for normalized pulse difference between PPG signals measured using reference and presented method. (x) Ten 6 s segments and (o) total 1-min data for each subject and (■) mean of all segment showed very low level of rms error.

C. PPG Signal Validations

In order to validate the proposed PPG measurement method, a conventional reflectance PPG sensor (NONIN 8000R, Nonin Medical, Inc., North Plymouth, MN) and physiological signal acquisition system (MP150, Biopac, Goleta, CA) were used to measure reference PPG signals on bare skin for comparison with the proposed PPG sensor. In order to remove the influence of other sources in the validation process, wired communication was employed, rather than wireless communication. The conventional Nonin sensor was directly attached to the skin on one side of the back or thigh. The through-the-clothing sensor was located on the opposite (contralateral) side. Both signals were digitized at 1000 Hz. Two types of analysis were employed for comparison of the two PPG signals: root-mean-square (rms) error for signal difference [see (1)] and cross correlation analysis (CC) for similarity [see (2)]. Recording was divided into ten segments (epochs) of 6 s (for a total of 1 min) and normalized within a range of -1 to 1. Data analysis was done for each 6 s epoch and also for the complete 1 min

$$\text{rms error} = \sqrt{\frac{\sum_{i=1}^{N} (\text{refppg}_i - \text{ppg}_i)^2}{N}} \quad (1)$$

where N is the epoch length, refppg is the normalized reference PPG pulses, and ppg is the normalized PPG pulses measured by proposed method

$$\text{CC} = \frac{F^{-1}[F(\text{refppg}) * F(\text{ppg})]}{\sqrt{(\sum_{i=1}^{N} \text{refppg}_i^2)(\sum_{i=1}^{N} \text{ppg}_i^2)}} \quad (2)$$

where refppg is the reference PPG pulses with mean removed, ppg is the PPG pulses measured by proposed method with mean removed, F is the Fourier transform, (*) is the complex conjugate, F^{-1} is the inverse Fourier transform, and CC is the normalized cross correlation between reference PPG and proposed PPG.

III. Results

Fig. 3 shows the PPG signal as measured through several types of clothing as follows: part (a) white dress shirt (0.36 mm), part (b) black dress shirt (0.28 mm), part (c) white T-shirt (0.66 mm), part (d) red T-shirt (0.69 m), part (e) blue T-shirt (0.61 mm), part (f) upper business suit (1.13 mm, 70% woolen and 30% rayon), part (g) beige cotton pants (0.52 mm), part (h) dark blue cotton pants (0.48 mm), part (i) blue jeans (1.03 mm), and part (j) lower business suit (0.42 mm, 70% woolen and 30% rayon), with the designed sensor configuration. All clothes except business suit were made of cotton. The results show ordinary PPG waveforms, including cardiac cycle, dicrotic notch, and respiratory induced baseline variation. The correlation coefficient between the PPG measured through the subject's clothes and the standard reflectance PPG measured at the contralateral location was greater than 0.9 in all cases. In the validation process, a very low level of rms error was obtained (see Fig. 4). RMS error was in the range of 0.1067–0.4186 for the back and 0.1058–0.2235 for the thigh. When complete 1-min data were considered, the maximum rms error level was also within the above range. The mean rms error for all segments was also very low, and was 0.2554 for the back region and 0.1536 for the thigh region. Examples of two PPG signals and corresponding ECG signals can be seen in Fig. 5(a). CC indicated very strong correlation between the two PPG signals, as shown in Fig. 5(b). For all measurement sites and their segments, maximum correlation lag was very close to zero. The cross correlation coefficient at zero lag was greater than 0.87 in all segments. The low rms error and high correlation-coefficient value implied a small difference and a significant similarity between PPG signals measured using a conventional and the proposed method.

IV. Discussion

Unlike electrical signals such as ECG, the PPG signal varies according to the measurement site with respect to upstroke timing, amplitude, and shape. However, according to Allen and Murray, bilateral PPG signals are relatively highly correlated [7]. In our paper, PPG signals obtained over clothing at the back and thigh region with the proposed PPG measurement method showed different characteristics but were highly correlated with reference signals obtained from bare skin at contralateral sites. Analysis showed a very low rms error and a very high correlation value. Our method also exhibited two dominant characteristics of the PPG signal: evidence of the cardiac cycle and respiration induced baseline variations.

PPG monitoring has been widely applied in ubiquitous healthcare because it can provide a variety of physiological information, such as heart rate, blood pressure, and respiration rate [8], [9]. However, PPG measuring systems currently in use do not satisfactorily comply with the concept of unconstrained monitoring because they require a certain level of the user's attention and cooperation; i.e., the user must consciously place the skin site to be measured onto the sensor. Our method that enables PPG measurement through clothing has potential for wholly unconstrained monitoring.

Although a PPG signal was detectable through clothing used in our experiments; however, a signal did not transmit through some clothes made of highly reflective materials such as polyester, despite maximum LED intensity. Possible transmission at maximum light intensity through clothing may have limits in terms of optical path length and absorption coefficients. However, it may be possible to detect PPG signals through thicker clothing if a PPG sensor with more LEDs or more photodiodes is used, or if an LED that can tolerate much higher forward current is developed and applied to our system.

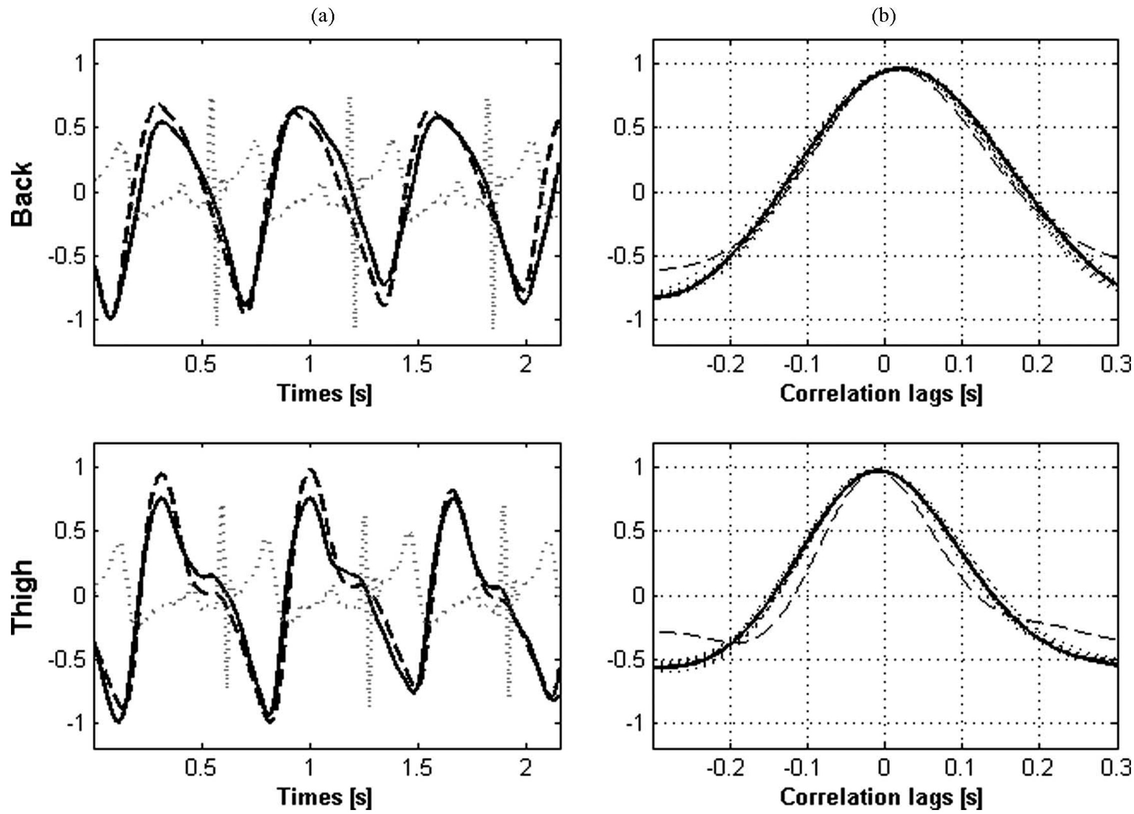

Fig. 5. (a) Example waveform of (dashed line) normalized reference, (solid line) proposed PPG, and (dotted line) ECG. (b) Cross correlation coefficients with respect to correlation lag for (dotted line) each segments, (dashed line) mean of all segment, and (solid line) total 1-min data.

V. Conclusion

Using the proposed system, PPG was successfully measured, without direct skin contact, in subjects sitting on a chair wearing casual clothes or a business suit. Our results demonstrate the potential of this technique for PPG applications, such as heart rate, respiration monitoring, and beat-to-beat blood pressure estimation with ECG. In addition, our basic configuration could be expanded to include a pulse oximeter for oxygen saturation determination through clothing by adding other LEDs and sensors utilizing red wavelengths.

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