DE GRUYTER Current Directions in Biomedical Engineering 2025;11(1): 555-558

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Effects of Wrist Sensor Placement on PPG Signal Quality

https://doi.org/10.1515/cdbme-2025-0241

Abstract: Photoplethysmography (PPG) is a key sensing modality in wearable devices for monitoring cardiovascular parameters. Despite widespread use, wrist-based PPG measurements often suffer from signal degradation due to anatomical variability and suboptimal sensor placement. This study investigates the influence of sensor positioning on PPG signal quality at the dorsal wrist. A custom-designed sensor array comprising eight photodiodes and multiple green LEDs was employed to perform synchronized multi-position recordings in 20 subjects. Signal quality was quantified using a signal-to-noise ratio (SNR) surrogate derived from band-limited root mean square values. Results demonstrate that a centrally located distal photodiode (PD2) consistently showed the highest SNR across subjects. Configurations utilizing additional LEDs moderately enhanced signal quality, while combining photodiodes increased signal amplitude without corresponding improvements in SNR. These findings highlight the critical role of sensor placement and emitter configuration in optimizing PPG acquisition.

Keywords: photoplethysmography, pulse oximetry, sensor design, wearables signal-to-noise ratio, wearable sensors

1 Introduction

Wearable devices such as smartwatches are becoming increasingly popular, not only for fitness tracking but also for health monitoring applications, including fall detection and arrhythmia recognition. A core sensing modality in these systems is photoplethysmography (PPG), a non-invasive optical technique used to detect blood volume changes in the microvascular bed of tissue.

Despite its widespread use, the quality of PPG signals acquired from the wrist is usually lower than that of signals measured at the fingertip or earlobe, primarily due to anatomical differences, lower perfusion, and motion-related artifacts. These limitations affect the reliability of physiological parameter estimation in wearable applications.

Sensor design is known to have a significant impact on PPG signal quality. Key factors include emitter-detector spacing, geometry, and optical coupling with the skin. However, less attention has been paid to the exact placement of the sensor on the dorsal side of wrist itself.

The aim of this study is to systematically investigate how the placement of a sensor on the dorsal wrist affects PPG signal quality.

2 Related work

The performance of PPG sensors depends on several critical parameters. One of the most influential is the distance between emitter and photodetector. Shorter spacing typically leads to higher signal amplitudes and improved signal-to-noise ratios (SNR) [1], especially when combined with optimized sensor geometry and casing properties [2].

In addition to design parameters, the anatomical positioning of the sensor has a major influence on signal quality. In clinical settings, sensors are placed at fingertip or earlobe. But these positions are impractical for long-term monitoring in wearable devices. Instead, most wearables acquire PPG from the dorsal side of the wrist, which is more comfortable and aesthetically acceptable but generally provides weaker signals [3].

Previous research has demonstrated the feasibility of wrist-based PPG measurement using multi-position sensor arrays, but studies focusing on the dorsal wrist remain limited. In this context, it is essential to identify sensor placements that offer reliable signal quality.

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3 Methods

3.1 Sensor design

The sensor developed for this study consists of a circular array of eight photodiodes (PD) and multiple green light-emitting diodes (LEDs). Two photodiodes (PD1 and PD2) were positioned centrally, while the remaining six (PD3 to PD8) were evenly spaced around the periphery. The configuration is illustrated in Figure 1. This configuration enabled a structured comparison between the central and surrounding PDs. Corresponding LEDs were placed with a distance of 1.5 mm

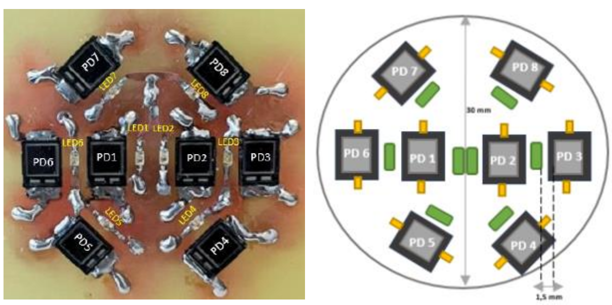

Figure 1: Sensor array for synchronous multi-channel measurements. The sensor was placed at dorsal side of the wrist, with PD6 in distal and PD3 in proximal direction.

3.2 System design

The system consists of the sensor, an analog front end (AFE) on an evaluation board, a microcontroller board (ADICUP3029) and a PC for data collection.

The ADPD4100 (Analog Devices, USA) was selected as AFE on account of its eight PD inputs and eight LED outputs. Consequently, each PD and LED was connected to a distinct input or output. For each sample, the AFE accumulates 32 LED pulses using a 14-bit analogue-to-digital converter (ADC) into a single 32-bit value. All measurements were captured at a 100 Hz sample rate, augmented by a decimation factor of two, thereby yielding an effective sample rate of 50 Hz.

3.3 Measurement configuration

During each sample period, 13 different sensor configurations where recorded, spitted in two measurement setups. In the first configuration, each PD was sampled while the neighbouring LED was active. PD1 and PD2 were sampled individually, whereas the PDs 3 to 8 were sampled concurrently with the PDs on the opposite side, as tests showed that such parallel recordings did not influence each other. Each PD was connected to an individual PD input at the AFE. In this configuration, each LED was driven with a current of 50 mA. The second configuration was chosen to compare different combinations of LEDs and PDs in the centre of the sensor. The configuration was further subdivided into five distinct sets (S1 to S5), the combinations of which are illustrated in Table 1. During S5, PD1 and PD2 were connected in parallel to the same AFE channel. To circumvent the risk of saturation at the AFE input amplifier due to elevated light levels or PD area, LED current was set to 20 mA in all five sets.

Table 1: connection table for sets in configuration 2

	S1	S2	S3	S4	S5
LED1	x		x	x	x
LED2		x	x	x	x
PD1	x		x		x
PD2		x		x	x

3.4 Study design

A total of 20 volunteers participated in the study (12 female, 8 male), with a mean age of 38.9 ± 16.0 years (range: 15–69 years). For each participant, three PPG recordings of 60 seconds duration were acquired, two at the left wrist and one at the right. All measurements were conducted under resting conditions to minimize motion artifacts. Skin type was not formally classified, and most participants had light skin tones.

To reduce variability in skin contact and pressure compared to manual fixation, the sensor array was attached to the wrist using a wristband, replicating the fit of a conventional smartwatch.

3.5 Signal processing

To quantify the quality of the photoplethysmography signals recorded from different wrist positions, a surrogate SNR_S for the signal-to-noise ratio (SNR) was calculated [4]. Signal processing was performed using Python 3 and standard scientific libraries.

Each raw PPG signal was subjected to a two-stage filtering process. First, a fourth-order high-pass Butterworth filter with a cutoff frequency of 0.5 Hz was applied in-place to remove baseline wander and slow drifts. Subsequently, a low-pass filter with a cutoff frequency of 6 Hz was applied in-place isolate the frequency band relevant for physiological pulsations.

The root mean square (RMS) value of the filtered signal in the physiological frequency band (0.5 Hz–6 Hz) was denoted as RMS_{Signal}, while RMS_{Noise} was computed from the residual high-frequency components above 6 Hz. SNR_S was then derived for each sensor position using the following expression (see eq 1).

$$SNR_S = 20\ log_{10}\left(\frac{RMS_{SIGNAL}}{RMS_{Noise}}\right) \quad (1)$$

SNR_S was calculated for the last 30 seconds of each recording. This approach provides a robust surrogate metric for signal quality, allowing for comparison across sensor configurations and subjects. An example of the signals can be seen in Figure 4.

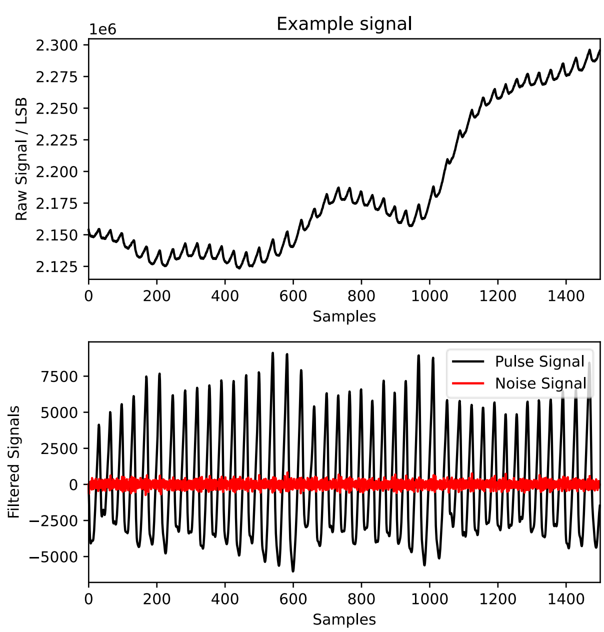

Figure 2: Raw signal in comparison to filtered signals

4 Results

Figure 3 and Figure 4 show the calculated values for SNR_S at the left and right wrist for all 20 subjects, for photo detectors PD1 to PD8. In Figure 6, the SNR_S for individual measurements on all subjects at the right wrist are shown.

Figure 5 shows the results for the sets S1 to S5 and the left and right wrist.

Among all sensor positions, PD2 (central, distal) showed the highest average SNR across both wrists, while some individuals showed better results at other positions, PD2 provided consistently strong performance across most subjects.

Configurations S3 and S4, which incorporated an additional LED, resulted in a moderate SNR increase. In contrast, configuration S5, using both photodiodes simultaneously, showed an increased signal amplitude (total and RMS_{Signal}) but did not improve the SNR compared to S3 and S4.

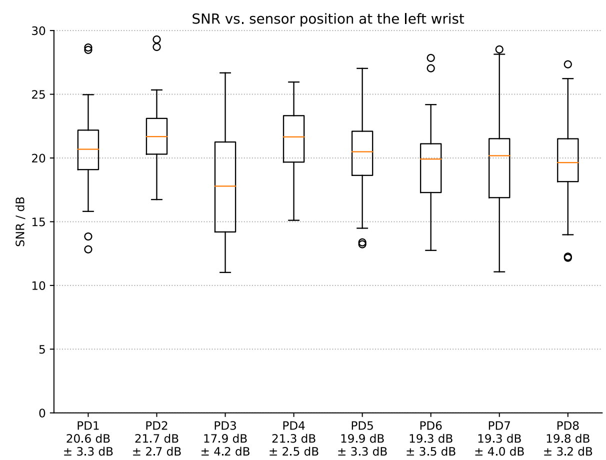

Figure 3: SNR_R at the left wrist

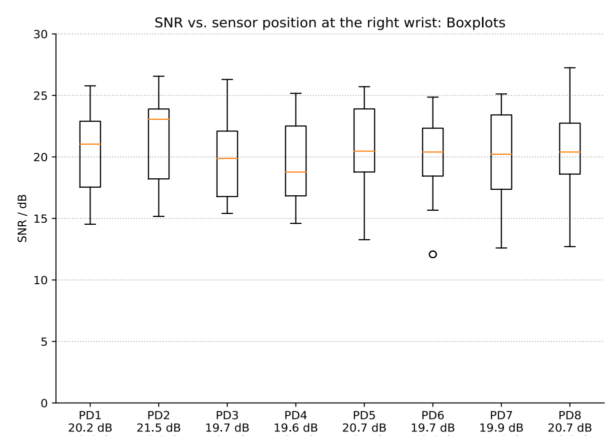

Figure 4: SNR_R at the right wrist

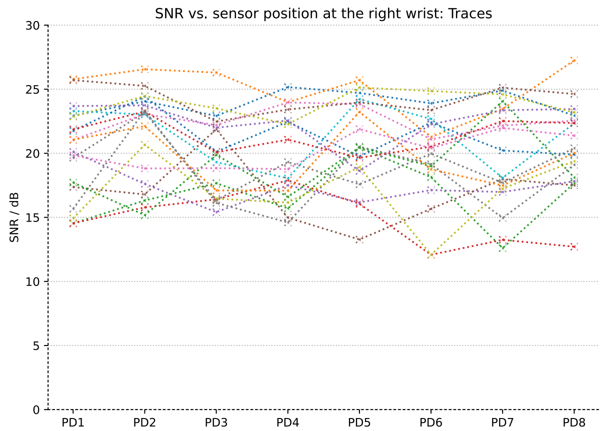

Figure 5: Individual measurements on all subjects at the right wrist

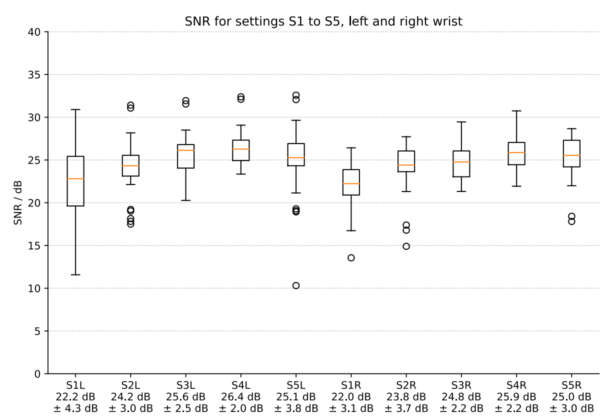

Figure 6: Results for the sets S1-S5 on the left and right wrist

5 Conclusion

SNR depends strongly on sensor placement. The PD2 position proved optimal in most cases, although individual variability suggests no superior location for all users. Central positions offer a good compromise between robustness and signal quality.

Adding a second LED improved SNR modestly, whereas using multiple photodiodes increased signal amplitude without enhancing quality. So, increasing PD area does not necessarily improve signal quality, but using multiple PD and covering different locations at the wrist simultaneously might increase the probability of getting optimal signal quality.

A limitation of this study is the use of a rigid sensor array, which may have introduced variability in skin contact. Future work should investigate flexible arrays with smaller inter-sensor distances to improve placement conformity and spatial resolution.

Author Statement

This work was funded by the German Federal Ministry of Economic Affairs and Climate Action (Project “CareWarn”). Authors state no conflict of interest. Informed consent has been obtained from all individuals included in this study. The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration and has been approved by the authors’ institutional review board.

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