Identifying the Optimum Region of the Human Sole to Extract the PPG Signal for Pulse Rate Estimation

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ABSTRACT
Photoplethysmography (PPG) can be identified as a non invasive technique which measures the blood volume changes in the blood vessels, through which key health indicators could be identified and used for abnormality detection. PPG has been integrated in numerous modern applications. This research is conducted in order to evaluate the possibility of applying PPG to the human sole and identifying the optimum regions of measurement. The research calculates the normalized cross correlation between the PPG extracted from the finger and different regions of the sole, and develops an algorithm for Pulse Rate estimation.

CCS Concepts
• **Hardware → Digital Signal Processing.**

Keywords
PPG; Pulse Rate; Bathroom Scale; k-means

1. INTRODUCTION
Photoplethysmography (PPG) can be identified as a non invasive, inexpensive, optic technique which measures the blood volume changes in blood vessels through which oxygen saturation, blood pressure, cardiac output could be measured. In recent researches it has been identified that PPG is a promising technique towards early screening of diseases as the PPG waveform possess significant information embedded within. [1] The PPG is normally extracted through the fingertips, ear lobe, and the toe of the foot. Our research focusses on extracting the PPG through the human sole and thus focus on pulse rate (PR) estimation. [2]

The augmented focus on healthcare is signified through the rapid development of devices towards health monitoring in order to ensure the perfect health conditions of humans. [3] Such devices focusses on achieving the identified objectives in the most user friendly and commercially practicable manner. The research focusses on evaluating the suitability of applying the PPG to a human sole, and on the optimum PPG sensor placement of the human sole in order to develop an IoT Smart Bathroom Scale [4][5] capable of extracting key health parameters of the user in a convenient manner.

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2. METHODOLOGY
A total of 10 male volunteers between the age group 22 – 25 were asked to relax in a sitting position for a period of 2 minutes before the commencement of measurements. The measurements were performed afterwards in the same posture under a dim lighting condition. The PPG waveform and the PR were obtained from identified regions in alphabetical order presented in the Figure 1 below. In addition, a Pulse Oximeter (Oxypal Neo OLV-3100K Nihon Kohen Corp., Tokyo, Japan) was used simultaneously to continuously measure the volunteer candidate's PR to analyze the accuracy of the proposed system.

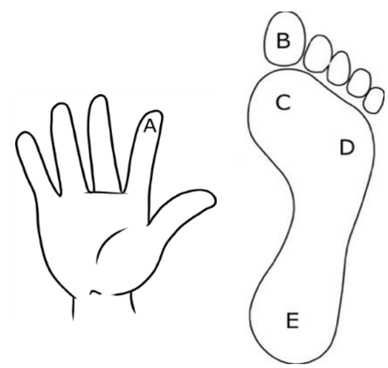

Figure 1. PPG Extraction Regions.

2.1 Experimentation Setup
A MAX30100[1] pulse oximeter & heart rate sensor from Maxim Integrated, equipped with inbuilt signal processing components and an ambient light cancellation system was used to extract the PPG waveform. The sensor comprises of an IR and a Red LED with approximate wavelengths 875nm and 660nm respectively, and an inbuilt 50/60Hz Filter. The sensor has been used in previous researches in order to measure the PR from the fingertip. [6][7]

The sensor was fixed to a wooden platform which is placed on a table to obtain the PPG from Region A (Fingertip) and is placed on the floor to obtain the readings from the identified regions of

[1] MAX30100 Datasheet can be found on: https://datasheets.maximintegrated.com/en/ds/MAX30100.pdf

the sole while the candidate is in a relaxed sitting position. The experimentation setup is depicted in Figure 2.

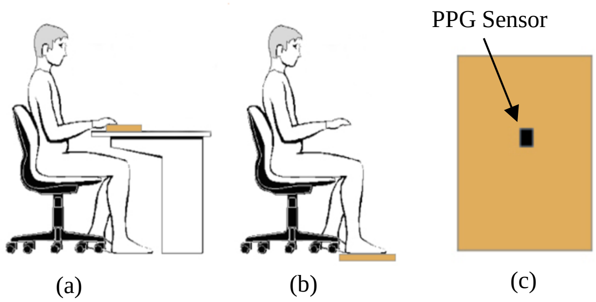

Figure 2. Experimentation Setup. (a) PPG Extraction from the Fingertip. (b) PPG Extraction from identified regions of the sole. (c) PPG Sensor fixed on wooden platform.

The DC component of the raw PPG obtained was removed in order to minimize the noise arising due to motion artifacts and the venous pressure. [8] The undesired DC components are removed to eliminate the detrimental effect on the spectral analysis in order to calculate the PR. [9]

The DC Filtered PPG (IR) waveform was applied a Mean Median filter to increase the ability to detect peaks [10], and a Butterworth Filter to remove the unwanted harmonic components present in the process of estimating the PR. The cut off frequencies of the filter were calculated at f_L = 0.83Hz and f_U = 3.66Hz assuming a PR range between 50 – 220 BPM for the volunteer candidates. A block diagram of the signal processing stages of the PPG is shown in Figure3.

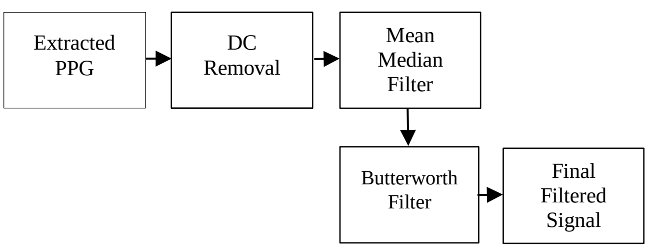

Figure 3. Signal Processing Stages of the Extracted PPG.

2.2 Pulse Rate Detection Algorithm

The PR could be calculated through the extracted PPG waveform. It has been identified that several methodologies are present to determine PR ranging from simple FFT methods obtaining the PR through frequency domain analysis, peak detection via threshold setting [11] and peak clustering based methods. [12]

Considering the final filtered PPG waveform of the human sole, an algorithm was developed to identify the peaks of the PPG and classify the peaks appropriately using k-means clustering to detect the peaks related to the PR. The PR is thus derived using the identified peaks and their number of occurrences within the given time period.

The algorithm was developed considering the comparatively low amplitudes and increased noise of the PPG waveform obtained via the human sole. It was identified that the threshold for PPG peak detection varies due to the thickness and pressure changes in the identified regions of the sole. Thus an approach to cluster the PPG peaks was used towards better results.

3. RESULTS & ANALYSIS

3.1 PPG Waveform Analysis

The PPG waveform extracted from the fingertip of the candidates is used as the reference for analysis purposes to evaluate the quality of the PPG extracted through the sole. It is assumed that the effect of the minute changes in the PR during the measurements are negligible towards the comparison of the PPG waveforms.

A qualitative analysis could be carried out through visual inspection of the extracted PPG waveforms from the fingertip and the selected region of the sole. An example set of PPG waveforms extracted from the identified regions are presented from Figure 4 - 8.

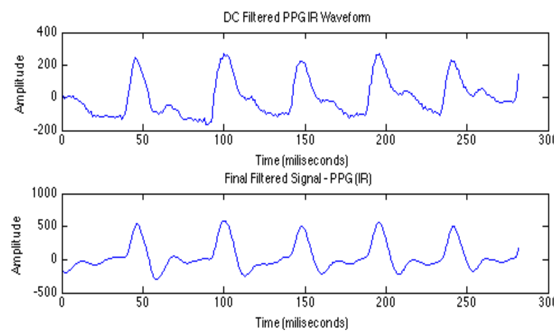

Figure 4. Extracted PPG – Region A

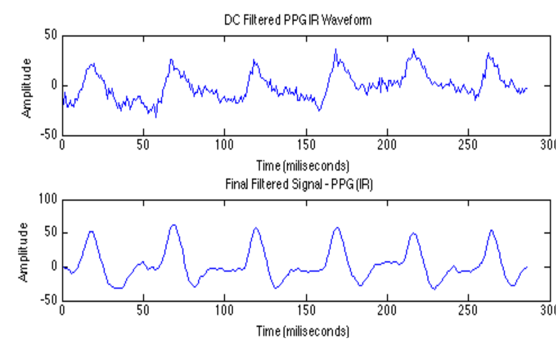

Figure 5. Extracted PPG – Region B

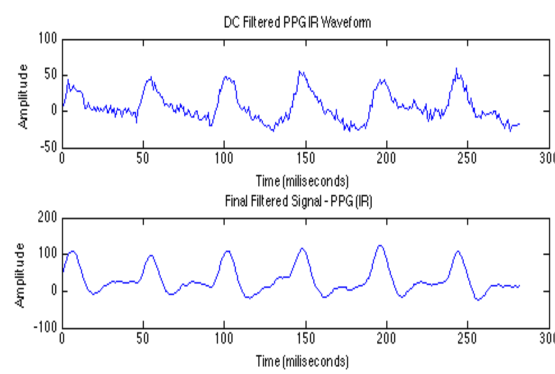

Figure 6. Extracted PPG – Region C

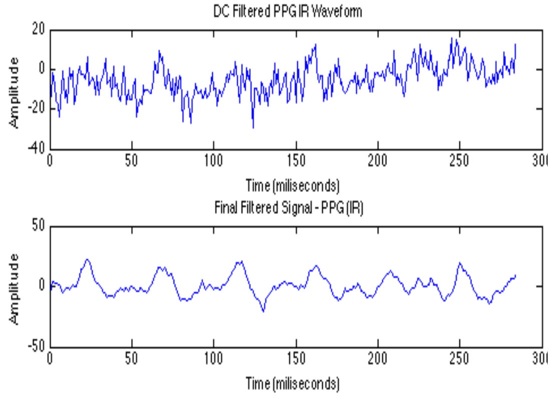

Figure 7. Extracted PPG – Region D

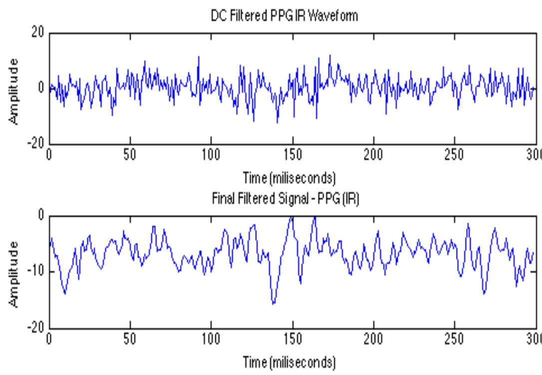

Figure 8. Extracted PPG – Region E

It is evident that the PPG waveforms of the human sole in most cases shows similar structure to the reference PPG waveform obtained by the fingertip. A significant reduction in waveform amplitudes could be seen through careful examination which is expected due to the increased thickness of the skin at the sole region and pressure variations. The amount of noise embedded within the signal has also increased due to the large number of motion artifacts and ambient light artifacts during the measurement through the sole.

In order to carry out a quantitative analysis between the reference and the PPG from the sole, a Normalized Cross Correlation (NCC) is calculated between the reference and each of the waveforms obtained from the sole. The maximum NCC value computed between the reference window and the comparison window is obtained for the analysis purposes. The equation of the NCC is presented in Equation 1. [13]

$$R_{NCC}(u,\tau) = \frac{\sum_{n=u}^{u+W-1} f(n)g(n+\tau)}{\sqrt{\sum_{n=u}^{u+W-1} f^2(n).\sum_{n=u}^{u+W-1} g^2(n+\tau)}}, (\tau_1 \leq \tau \leq \tau_2) \quad (1)$$

The calculated NCC values are presented in the Table 1. Through the analysis of the mean of the NCC, it is evident that Region E has the weakest correlation which was also clear through the inspection of the PPG waveform which contained a significant amount of noise. Through the Regions from B – D the correlation between the reference has also reduced which is due to the increase of noise from Regions B – D.

Overall, it can be identified that the ability to extract the PPG deteriorates from Region B – E.

Table 1. Mean / Standard Deviation (SD) of Normalized Cross Correlation

Region	A	B	C	D	E
Mean - NCC	1.00	0.52	0.44	0.40	0.25
SD - NCC	0.00	0.16	0.18	0.18	0.18

3.2 Pulse Rate Analysis

The PR of the candidate is calculated by applying the Pulse Rate Detection Algorithm to the extracted PPG. Thus the quality of the PPG waveform directly affects the PR calculated. The PR was also analyzed in order to validate the above results obtained through the calculated normalized cross correlation and visual inspection methods.

The obtained result is compared against the measurements obtained through the Nihon Kohen OLV-3100K Pulse Oximeter to validate the obtained measurements. The mean and the standard deviation of the PR errors are presented in Table 2. The Regions D & E were identified as highly erroneous regions to calculate the PR which is directly associated with the distorted PPG waveform obtained.

Table 2. Mean / Standard Deviation (SD) of the PR Errors on Different Regions

Region	A	B	C	D	E
Mean	1.40%	1.42%	12.45%	95.0%	299.1%
SD	0.01	0.01	0.30	0.98	1.95

The PR obtained through Region B was highly similar to the PR obtained via Region A (Fingertip) with both regions recording a mean error of 1.42% and 1.40% respectively. Although Region C identified a mean error of 12.45%. Upon careful observation of the recorded data it was identified that a couple of data points had highly deviating pulse rates. Disregarding the identified erroneous data points, the mean error was re calculated at 1.13%. It is important to note that such erroneous data is present due to the practical limitations existing during the contact of the sole and the PPG sensor where proper contact may not have been achieved.

4. DISCUSSION

The research was carried out as an initial feasibility to identify the possibility of extracting the PPG from the human sole for the possible development of an IoT Bathroom Scale embedded with the PPG technology. In modern applications, PPG probes for the fingers are used to eliminate improper contact, motion artifacts and ambient light artifacts which can be identified as root causes of a deteriorated PPG waveform.

However, in the context of this application and research, there exist many practical challenges due to the form factor limitations and biological limitations due to the thickness of the skin at the sole.

5. CONCLUSION

The research identified sole Region B & C as viable options to obtain the PPG and thus determine the PR with acceptable accuracy. However, it is important to research further on the extracted PPG of the above regions to ascertain the possibility of determining key health parameters other than the PR to explore the greater potential of PPG analysis.

Hence it is important to focus on analyzing the PPG obtained from the human sole to determine the capability of developing accurate algorithms to measure Heart Rate variability (HRV) [14], Blood Pressure (BP) [15] and Blood Oxygen Level (SpO2) [6] etc.

The feasibility of such research would justify the development of a comprehensive IoT bathroom scale possessing the ability to measure key health parameters as well as the potential to be used as a disease prediction tool.

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