Journal of Medical Engineering & Technology

ISSN: 0309-1902 (Print) 1464-522X (Online) Journal homepage: http://www.tandfonline.com/loi/ijmt20

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Maha Alafeef

To cite this article: Maha Alafeef (2017): Smartphone-based photoplethysmographic imaging for heart rate monitoring, Journal of Medical Engineering & Technology, DOI: 10.1080/03091902.2017.1299233

To link to this article: http://dx.doi.org/10.1080/03091902.2017.1299233

Published online: 16 Mar 2017.

JOURNAL OF MEDICAL ENGINEERING & TECHNOLOGY, 2017
http://dx.doi.org/10.1080/03091902.2017.1299233

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INNOVATION

Smartphone-based photoplethysmographic imaging for heart rate monitoring

Maha Alafeef

Department of Biomedical Engineering, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan

ABSTRACT
The purpose of this study is to make use of visible light reflected mode photoplethysmographic (PPG) imaging for heart rate (HR) monitoring via smartphones. The system uses the built-in camera feature in mobile phones to capture video from the subject's index fingertip. The video is processed, and then the PPG signal resulting from the video stream processing is used to calculate the subject's heart rate. Records from 19 subjects were used to evaluate the system's performance. The HR values obtained by the proposed method were compared with the actual HR. The obtained results show an accuracy of 99.7% and a maximum absolute error of 0.4 beats/min where most of the absolute errors lay in the range of 0.04–0.3 beats/min. Given the encouraging results, this type of HR measurement can be adopted with great benefit, especially in the conditions of personal use or home-based care. The proposed method represents an efficient portable solution for HR accurate detection and recording.

ARTICLE HISTORY
Received 19 December 2016
Revised 20 February 2017
Accepted 20 February 2017
Published online 16 March 2017

KEYWORDS
Heart rate; smartphone; photoplethysmography; mobile health care system

1. Introduction

In the last few years, the medical field faced massive and rapid development in several aspects, especially in the field of Mobile-Based Health (M-Health) systems. The smartphone became an essential part of our daily life, and thus, there is a great opportunity to develop mobile phone-based systems that mimic the performance of medical devices. These systems make people's lives easier and reduce the number of doctor visits for health status check. This would provide massive economic benefits to individuals by reducing doctor visits and providing them with more time to work or rest.

An important vital sign that must be regularly monitored is the heart rate. The importance of HR recording has increased because of the dramatic increase in the number of patients suffering from cardiovascular diseases. HR is an essential risk factor for cardiovascular disorders that may cause sudden death in both adult and infants [1]. HR provides an indicator of one's overall fitness. Higher resting heart rate can be an indicative of preposition to both obesity and diabetes [2]. On the other hand, a low heart rate during rest periods may indicate good health and cardiovascular efficiency [3]. In addition, measuring the heart rate after exercise is an indicator of cardiac fitness. In other words, the ability of individual's body to restore his/her resting heart rate after exercise could indicate overall heart health status [4]. Thus, there is an actual need for a portable and comfortable device for continuous HR investigation. The system should be efficient and reliable in HR estimation with minimal error, and it must be convenient, comfortable, easy-to-use, fast, and user-friendly in order to be able to track the HR in all cases continuously.

The heart rate can be successfully estimated from reflected photoplethysmography (PPG) signal. PPG signal is an important signal that can be used for the detection of many biological disorders as well as vital signs monitoring [5]. PPG signal represents the change in blood volume due to heart action [6]. It provides a non-invasive comfortable way for HR detection because of the PPG signal recording approach. This technique is first reported in the 1930s by Hertzmann and Spielman [7] based on the fact that the blood absorbs light more than the surrounding tissue and the variation in blood flow affects the light reflected from it. This change is reflected in PPG signal components recorded using a suitable probe. Clinical PPG signal applications include monitoring of cardiac output, blood pressure, haemoglobin concentration, respiratory activity and oxygen saturation. PPG signal is usually acquired by illuminating a part of the body

CONTACT Maha Alafeef mahaalafeef@gmail.com Department of Biomedical Engineering, Faculty of Engineering, Jordan University of Science and Technology, P.O.Box 3030, Irbid 22110, Jordan

extremities (mainly the index or ear lobe) by infrared or red light. The photodiode is used for light collecting and signal measurements.

This paper focuses on the benefits of the PPG imaging realised by replacing the photodetector with a camera, offering the advantages of real-time measurement of a large area and higher sensitivity. In addition, because the smartphone camera is used as a light detector, the system is cost-efficient, feasible and its portability is guaranteed. Although now there are many heart rate monitoring devices available such as wristbands or watches, the use of smartphone for heart rate monitoring is superior. It represents a personal tool for heart rate measurement and health status investigation without paying any additional cost; what you need is just your smartphone. Moreover, many people prefer smartphone-based heart rate monitoring, and also they believe that the wrist or ankle bands or flexible straps are inconvenient ways for heart rate monitoring. Furthermore, the smartphone provides an accurate method for heart rate detection. In addition, it is essential to measure your heart rate after training which indicates your overall fitness level, and it can be used for many other quantities measurements such as the heart rate variability (HRV) and blood pressure (BP).

Many efforts have been introduced in the past few years to study the use of the PPG signal in heart rate estimation and monitoring [8–12]. Kwon et al. [8] presented a method for heart rate estimation using the facial video recorded by iPhone 4. The recorded video was separated into frames using MATLAB software, then selected region of interest (ROI) was used to apply the analysis. Two methods were used for the heart rate estimation: the trace of the green signal channel and the second independent source signal (IC2). The accuracy of the HR determination method is validated using ECG-derived heart rate as a reference value. The maximum absolute errors were found to be 19.31 and 3.36 for the raw trace and IC2, respectively, which is very high. Moreover, in this work, mobile phone application for the heart rate estimation from a facial video called FACEDEAT was developed. However, the application estimated the heart rate based on 20 s facial video recorded from the subject. This process consumes significant time and also it is inconvenient for many patients. Further, a complicated algorithm (i.e. Independent Component Analysis (ICA)) is employed for HR estimation which increases the processor load and also increases the HR computational time. In the case of portable devices such as smartphones, complex algorithms which consume significant energy must be avoided for efficient use of the battery. Chen et al. [9] introduced a method for blood pressure monitoring and heart rate estimation using PPG signal. NI DAQ is used as an acquisition unit for PPG signal recording. Labview-based algorithm was developed for PPG signal processed and peak detection for heart rate estimation. The maximum absolute error was found to be 2 beats/min which could be improved. Further, the use of NI DAQ acquisition unit for PPG signal recording reduces the system portability and cost-efficiency. Li et al. [10] presented a method for breath rate and heart rate detection from the PPG signal obtained from a wearable sensor. This paper introduces a new approach in the PPG signal processing based on the finite Gaussian basis. The obtained PPG was decomposed by the application of *n* set of Gaussian basis to approximate the original signal. The heart rate was estimated, and the results were compared with reference data obtained from ECG. The maximum error was found to be 7 beats/min, which is very high. Furthermore, the sensor used for PPG signal extraction reduces the system portability and also the system cost-efficiency. Siddiqui et al. [11] presented a method of PPG signal recording using smartphone. The video recorded from the subject was decomposed into individual frames then the pixel intensities over the frame that is higher than a predefined threshold are combined. The system has been tested on several volunteers and shows a maximum error of 3 beats/min, which is significant in clinical practice. Although the employed algorithm is simple, it requires a user input (Threshold value) that may differ among individuals. Thus, reduces the system efficiency versatility and its capability to be used with different persons. Finally, Bal [12] proposed a method for the detection of heart rate from video recordings of the human face. Dual tree complex wavelet transform-based denoising algorithm was used to reduce the artefacts results from artificial lighting, movement, etc. In addition, in this study, experiments to estimate oxygen saturation was conducted. The non-contact HR estimation error of several volunteer's classes was computed and also the relationship between the haemoglobin and the HR estimation error also studied. The maximum absolute error of HR estimation of healthy subjects was found to be 6.85 beats/min, which is very high.

In this paper, a solution for accurate continuous heart rate recording is introduced. The proposed method employs the smartphone camera for PPG imaging recording. Simple processing was used for heart rate estimation to reduce the computational load on the processor and save the phone battery. Because of the technological advances in field of smartphone production, present day mobile phones have a camera that supports a high frame rate suitable for real-time imaging. Thus, it represents an efficient method for PPG signal extraction to be used in heart rate monitoring. This system has an active need because it helps save the patient life by the continuous tracking of HR, providing an early alarm of any cardiovascular problem. The proposed system has many attractive virtues included low-cost, portability, easy to use, patient comfortable, accurate and robustly. Thus, the proposed system is convenient for continues monitoring of heart rate and early detection of cardiovascular disorders.

2. Material and methods

2.1. Data recording system

The proposed system was based on a video recording from a subject's fingertip using built-in smartphone camera. The video was recorded from the subject index fingertip using Samsung Galaxy smartphone with 30.30 frames per second, RGB24, 1280 × 720 Pixel resolutions with the flashlight on. The finger must cover both the flashlight and the camera to obtain accurate results. Simultaneously, the plethysmography signal was recorded using a plethysmography sensor attached to the IWX214 unit. This sensor is a strain gage type that detects the pulsation action at the subject fingertip. The plethysmography signal waveform is displayed using Labscribe software. The plethysmography waveform obtained from subject's fingertip was compared with the PPG signal obtained from the smartphone. Moreover, the subject heart rate is recorded manually using a stopwatch for error calculation purposes. Strain gage sensor is used in this study because of its sensitivity to the changes occur due to cardiac action, and its ability to detect a similar signal to the PPG. It represents a standardised technique for plethysmography waveform recording [13,14]. Thus, the plethysmography waveform was compared with the obtained smartphone-based PPG signal to ensure that the proposed method able to detect the actual blood flow waveform without any missed peak.

2.2. PPG signal extraction

The recorded video **(**mp4 format**)** was transferred from smartphone to the core i5 laptop via the Bluetooth™ connection for further processing. The recorded video has been processed using MATLAB 2014a software (Mathwork Inc., Natick, MA). A Matlab code for computing the mean intensity of different channels has been carried out. Red, blue and green average intensities are all extracted from the individual video frames. The obtained intensity values are plotted as a function of time providing PPG time series signals as shown in Figure 1.

Three channels PPG signal are obtained from the video processing, but not all of them can give a clear PPG waveform. Thus, to investigate which channel provides the clearest PPG signal for HR estimation, all channels are extracted as illustrated in Figure 1. It is clearly shown that the red channel gives the clearest PPG waveform without any additional processing or even filtration. Because of the clarity of the PPG

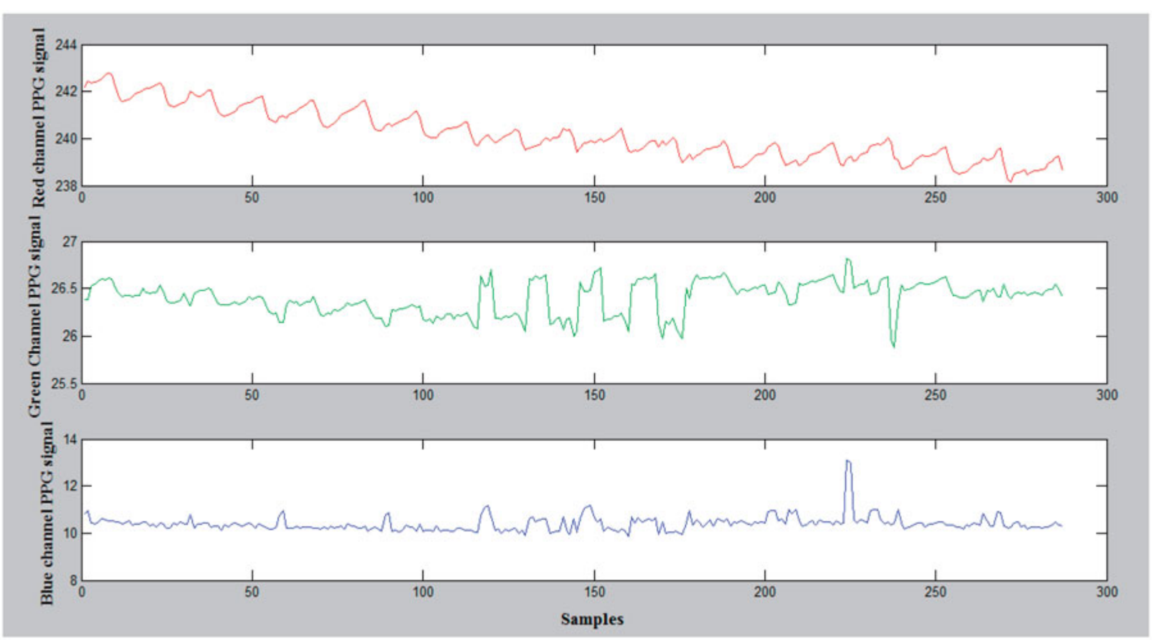

Figure 1. Red, green, and blue PPG signal extracted from fingertip video stream.

waveform obtained from the red intensity, the red channel will be used for the estimation of heart rate. The PPG signal obtained from both the green and blue channel, however, look unclear and require complex additional processing to obtain the desired information. The intensity of each colour channel (red, blue and green) of all pixels presented in each video frame is averaged. In this way, the effect of spatial variation is eliminating, and each frame gives a single value which represents the PPG signal amplitude of each channel at the moment at which the frame has been captured. The same hold true on the entire video frames. When the average intensity of each channel are computed for all video frames, the PPG waveform is produced by plotting the channel signal intensity of all frames as a function of the frame number (samples) or versus time (calculated using Equation (1)). Figure 2 illustrates the red channel PPG signal extracted from a selected video stream.

$$\text{Time} = \frac{\text{Frame number of each intensity value (frame)}}{\text{Frame rate (frame/sec)}} \tag{1}$$

Figure 3 shows the flowchart of the proposed system for heart rate monitoring.

The PPG signal extraction algorithm consists of the following steps:

1. Video decomposition into individual frames in which each frame represents an RGB image.
2. Take the average value of the red pixel intensity of each frame giving one value for each frame.
3. Calculate the time associated with each frame based on Equation (1).
4. Plot the average intensities of each frame as a function of time which providing the PPG time series.

2.3. Heart rate estimation algorithm

Red channel PPG signal is used for heart rate estimation because of the above reason. Because of the clarity of PPG waveform in the red channel, a simple algorithm has been used for heart rate calculation. The PPG signal peaks were localised using a peak detection algorithm applied on the extracted PPG data

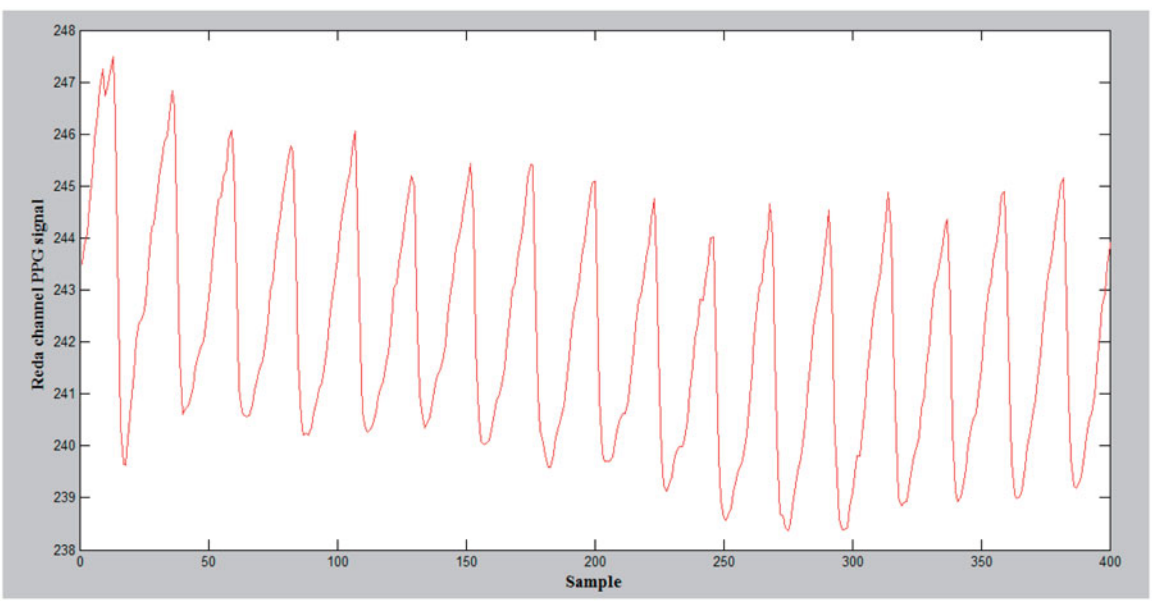

Figure 2. The red channel PPG signal obtained from the video stream collected from one subject fingertip.

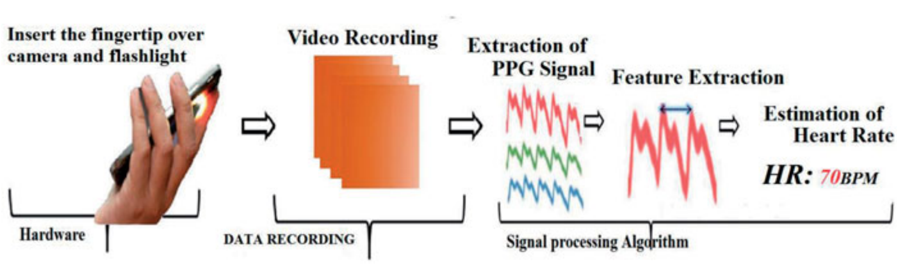

Figure 3. Flowchart of heart rate estimation using smartphone built-in camera.

using MATLAB 2014a software. After that, the time between each consecutive peaks has been calculated which represents the time of one successive cardiac cycle. The time is taken to complete one cardiac cycle is calculated from the number of frames between two consecutive maxima divided by the frame rate as in Equation (2)

$$\text{Time of onecycle} = \frac{\text{number of frames (frame)}}{\text{frame rate (frame/sec)}}\ \text{sec/onecycle} \quad (2)$$

After the computing of the time of all successive cardiac cycle in the subject PPG signal, the average value of the cycles time was used for heart rate

Table 1. Specifications table of the volunteers.

Specifications	Age (y)	Heart rate (bpm)
Average	25.8	87.6
Standard deviation	9.1	31.8

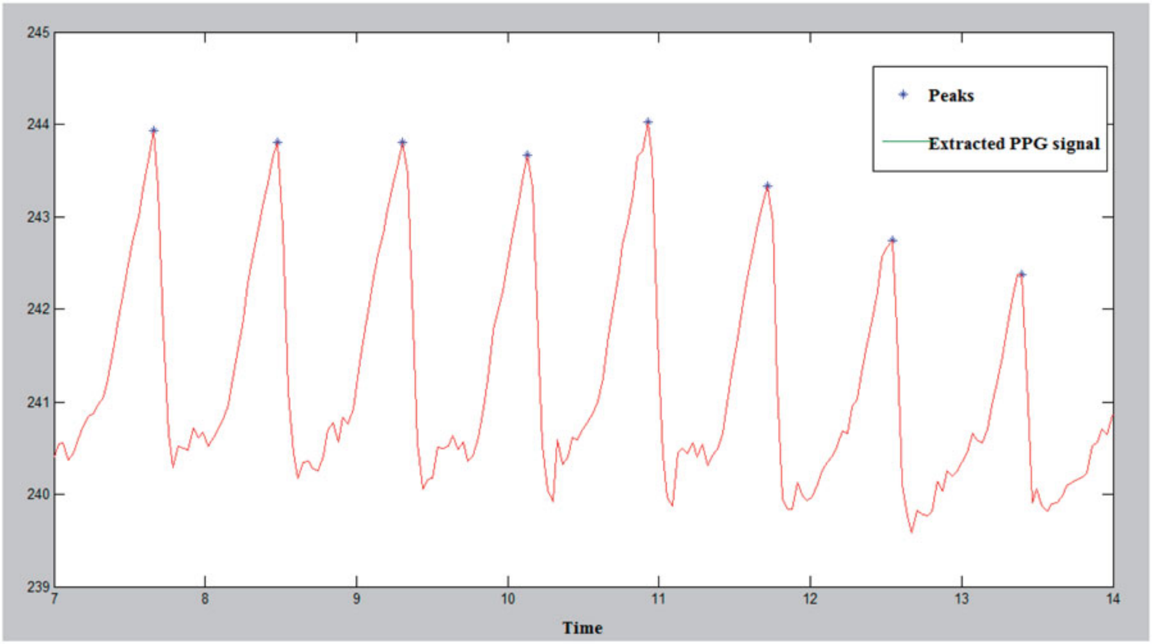

Figure 4. PPG signal extracted from video stream after peak detection algorithm implantation. The blue stars represent the peaks result from the application the proposed algorithm.

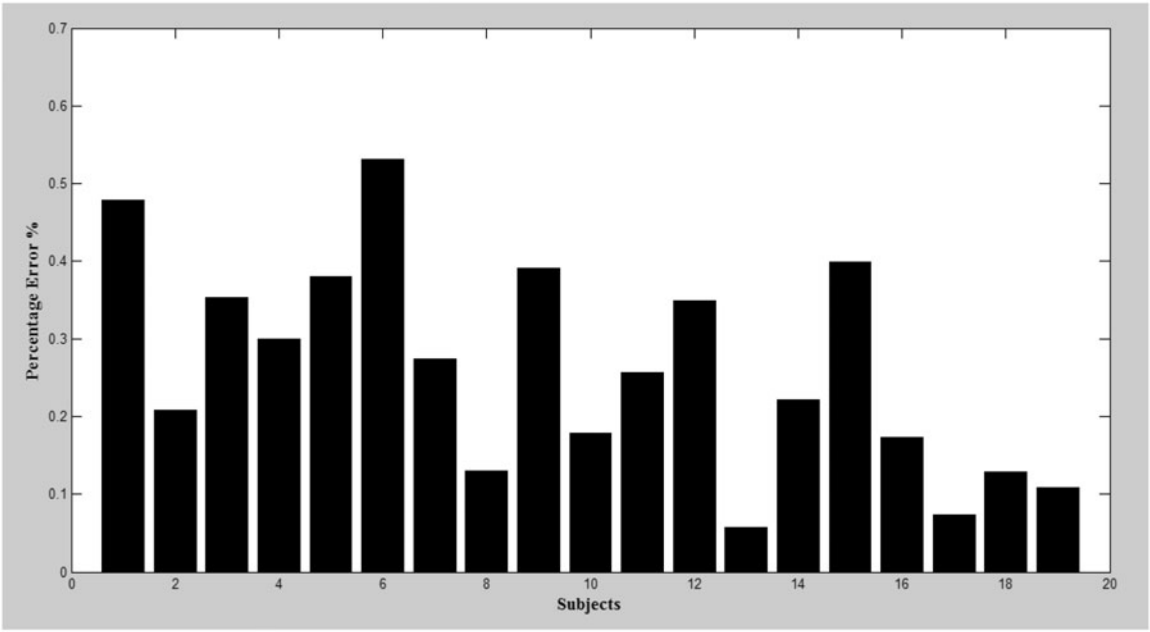

Figure 5. The percentage errors result from the proposed system applied on 19 subjects.

estimation as shown in Equation (3).

$$\text{Heart rate} = \frac{60}{\text{Average [Time of onecycle]}} \text{ beats/minute} \quad (3)$$

In this study short video was collected from each volunteer. The video is few seconds in length. The average heart rate was computed for each short duration video. These short videos have been used for heart rate estimation to mimic the continuous heart rate estimation process.

Table 2. Comparison between the PPG-derived heart rate and the actual heart rate in beats per minute (bpm).

Subject	Actual heart rate (bpm)	PPG-based heart rate (bpm)	Absolute error (bpm)
1	77.1	77.5	0.4
2	76.8	77	0.2
3	72.5	72.2	0.3
4	78.3	78.5	0.2
5	79	79.3	0.3
6	65	64.7	0.3
7	69.4	69.2	0.2
8	142.3	142.1	0.2
9	73.3	73	0.3
10	70.1	70	0.1
11	68.5	68.7	0.2
12	116.7	117.1	0.4
13	71.3	71.3	0.0
14	70.3	70.1	0.2
15	64.8	64.5	0.3
16	170.3	170	0.3
17	59.9	59.9	0.0
18	93.2	93.3	0.1
19	145.2	145.4	0.2

2.4. Volunteers

We evaluated the performance of our method by measuring the heart rate of 19 subjects during both rest and after exercise. The age of the volunteers ranged from 19 to 52 years and the estimated heart rate lies in the range of 59.9–170.3 beats/min. None of them had a chronic disease. The heart rate of each subject was recorded manually, and a plethysmography signal was collected using the IWX214 unit in synchronising with the video recording in order to compare the extracted PPG signal with the actual waveform. The average and the standard deviation of the volunteer's age and the measured heart rate are shown in Table 1.

3. Results

The proposed system has been tested, and the accuracy of the introduced method was evaluated by comparing the estimated heart rate from red PPG signal with the actual heart rate measured directly from the subject. The maximum absolute error was observed to be 0.4beats/minute. Figure 4 shows the PPG signal extracted from the video stream of one subject after the application of peak detection algorithm (peaks marked as blue stars).

The experiment was performed on 19 subjects. The volunteer's information is shown in Table 1. The average percentage error and the percentage accuracy of the proposed method were found to be 99.7% and

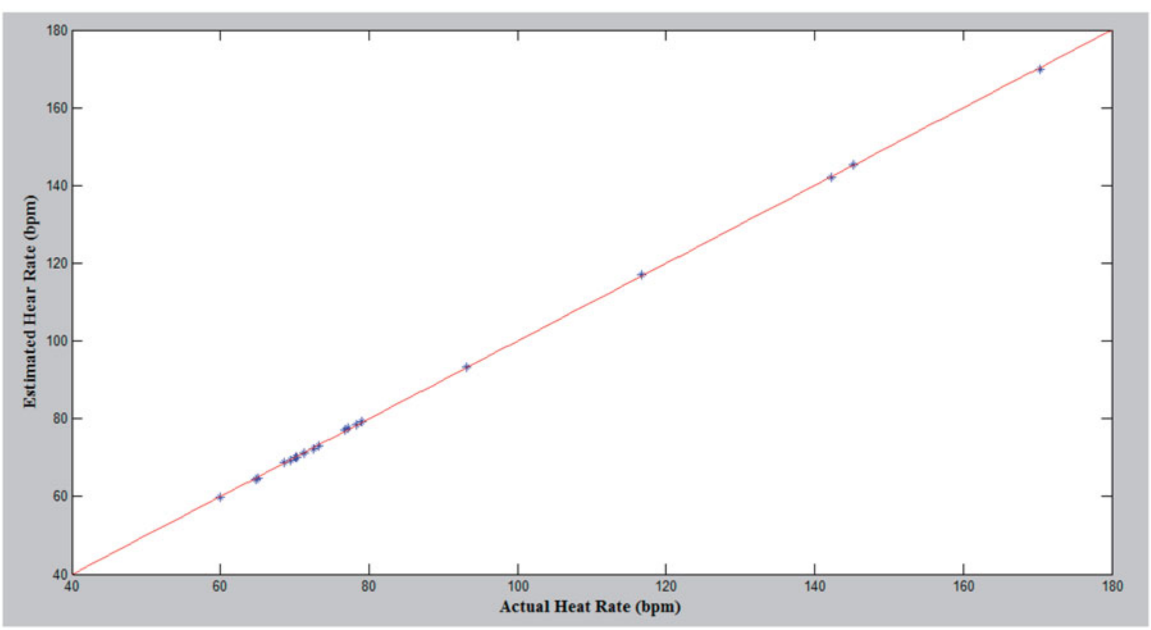

Figure 6. Results obtained from the introduced method. Each point represents the estimated heart rate and its actual corresponding heart rate. The measurements were done both at rest and after exercise. As it can be seen the points very close to the diagonal line and the error very close to zero.

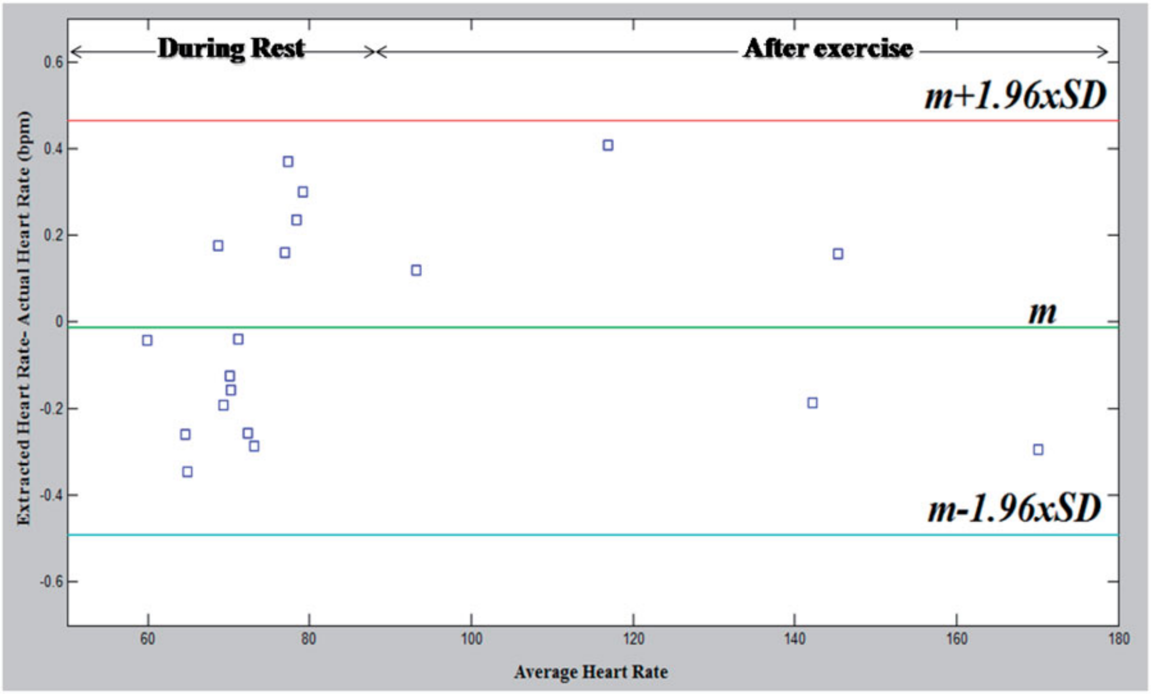

Figure 7. Bland–Altman plot of the results obtained from the proposed system that is contained in Table 2, the horizontal lines represent the mean bias level and the 1.96 standard deviation from the bias mean.

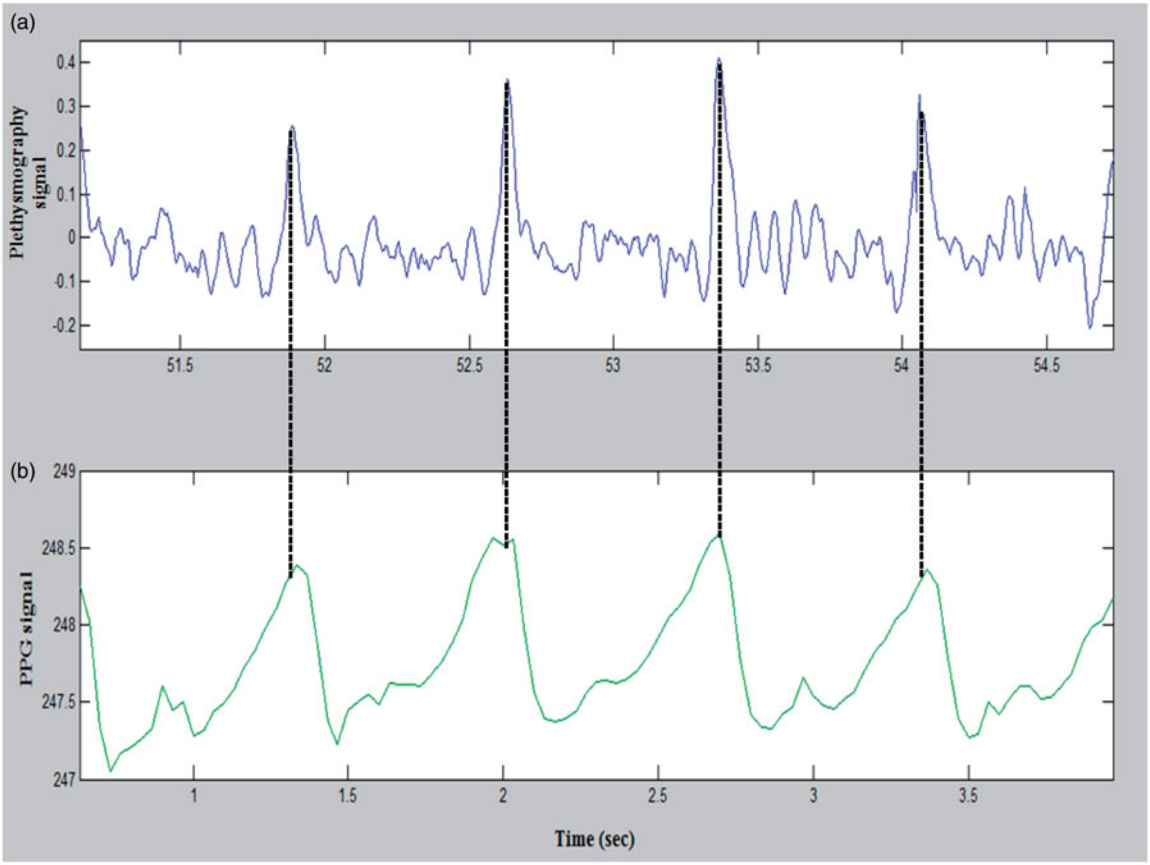

Figure 8. (a) Plethysmography signal obtained from a subject fingertip using pressure sensor, (b) The PPG signal extracted from the video collected simultaneously with the signal in (a).

0.3%, respectively, and the standard deviation of the percentage error and accuracy was found to be 0.14%. Figure 5 shows the percentage error of the 19 subjects, as it can be seen that the obtained percentage error is ranging from 0.05% to 0.53%. The maximum observed absolute error was found to be 0.4 beats/min, but most of the errors lie within the range of 0.04–0.3 beats/min. Table 2 shows the results of the full analysis. The PPG-derived and the actual heart rate are illustrated, with the difference between them less than half beats per minute and the average error is very small (0.26 beats/min). Figure 6 shows the results obtained using the proposed method. Each point represents the estimated heart rate and its corresponding actual heart rate. The closest the point to the diagonal line has the least error and vice versa. Figure 7 shows the Bland–Altman plot that is used to evaluate the agreement between the estimated heart rate and the actual one. The graph shows that there is slight mean system bias value that was found to be 0.0135 beats/min between the actual heart rate and the PPG-derived heart rate. Different values are tightly arranged around the mean bias with all points located within the $1.96 \times SD$ marked on the graph. Furthermore, it can be concluded from the plot that there is no rate-dependent error. Figure 8 illustrates a comparison between the PPG signal recorded using strain gage sensor and the extracted PPG signal from the video stream. It can be seen that the extracted PPG signal from red channel similar to the original PPG recorded from the pressure sensor without any missed peaks which indicate the sensitivity and the ability of the smartphone in accurate detection of blood pulsatile action caused by the cardiac activities.

Table 3. Comparison between the maximum absolute errors in heart rate estimation obtained from different methods.

Work	Maximum absolute error (bpm)
[8]	3.36 (raw) 19.31 (IC2)
[9]	2
[10]	7
[11]	3
[12]	6.85
The proposed method	0.4

4. Discussion

This article introduces a novel method for heart rate estimation using the smartphone. This approach provides a convenient and easy way for heart rate recording anytime and everywhere without any prior experience in medicine. The video was collected from the subject's fingertip, processed to extract a time series PPG signal. PPG signal was used for heart rate estimation using a simple computing formula. The obtained results indicate that the use of mobile phone camera can provide the sensory information needed to estimate the heart rate. The set-up was successfully able to predict the heart rate with an accuracy of

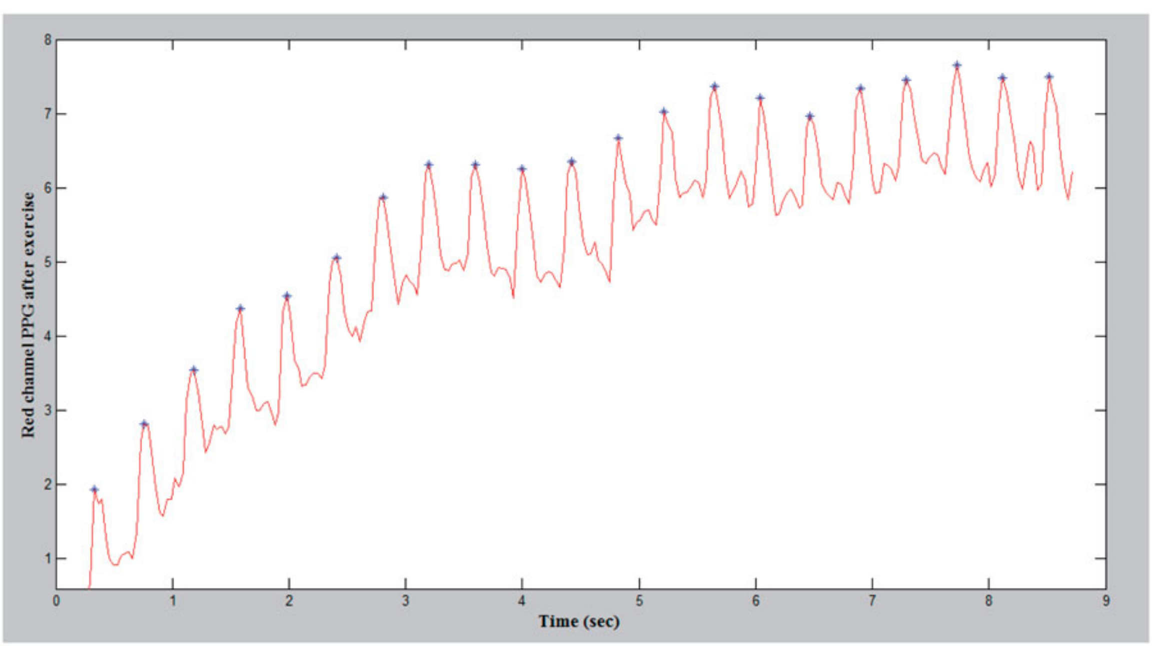

Figure 9. PPG signal extracted from video stream from a subject after exercise. The peak detection algorithm is applied on the PPG signal and the peaks marked as red stars.

99.7%. Table 3 introduces a comparison between the absolute error obtained from the previous work and our proposed method. As it can be seen, the errors obtained in the previous literatures are higher than the ones obtained in this work. In addition, the presented method provides an inexpensive, user-friendly, convenient, and ease-to-use system to measure patient heart rate. Also, the proposed system was able to measure the high heart rate (after exercise) with a slight error (0.2 bpm). Figure 9 shows the PPG signal extracted from a subject after exercise. Thus, our system allows users to check their heart fitness and cardiovascular health status by measuring the heart rate value after exercise. Moreover, the system provides us the ability to measure how much time requires the heart to restore the resting heart beat represents an important indication of human health [4].

5. Conclusions

This article discusses the use of smartphone technology in the medical area. A Mobile phone camera has been used for PPG signal extraction for heart rate monitoring. This method provides a convenient way for heart rate monitoring anytime and everywhere because there is no need for any additional external devices, only your personal smartphone. Moreover, the application of smartphone in heart rate detection will save time, reduce the test expenses and guarantee the privacy. Further, the smartphone-based HR estimation can provide an indication of the cardiovascular system status, and thus, it can save the patient life. Measurement of heart rate at rest and after exercise were recorded. The maximum absolute error found to be 0.4 beats/min, and the average percentage accuracy is 99.7%. Therefore, mobile phones represent an efficient tool for heart rate recording and examination.

Disclosure statement

The author reports no conflicts of interest. The author alone is responsible for the content and writing of this paper.

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