EXTRACTING HEART RATE AND RESPIRATION RATE USING A CELL PHONE CAMERA

Luis Felipe Jimenez
Department of Computer Science
Kean University
Union, NJ 07083
jimluis@kean.edu

Avinash Parnandi
Department of Computer Science
and Engineering
Texas A&M University
College Station, TX 29634
avinashparnandi@gmail.com

Dr. Ricardo Gutierrez-Osuna
Department of Computer Science
and Engineering
Texas A&M University
Clemson, SC 29634
rgutier@cse.tamu.edu

ABSTRACT

The rapid growth of smartphone technology and onboard sensors has enabled non-invasive physiological measurements, which can simplify self and remote assessments. This holds tremendous potential in efficient delivery of health care. This study investigates the feasibility of extracting heart rate (HR) and breathing rate (BR) using a cell phone camera in a non-invasive way, without the need of external sensors and it is independent of ambient lighting condition. The method works by placing the index finger over the cell phone camera and computing the amount of light absorbed by the finger tissue. The phone thus acquires the Photoplethysmographic (PPG) signal. From this HR is estimated by using a peak detection algorithm in order to find the local maxima of the PPG signal and computing the time difference between peaks. We compared the accuracy of HR estimated by our method with a commercial sensor over three different controlled experimental conditions. Here the subject was asked to breath at rate of 6, 10, 12 breaths per minutes (bpm). The results showed a mean error of 0.06, 1.07 and 2.39 bpm under the three settings respectively. We then computed BR from the fast Fourier transform (FFT) of the estimated HR signal. The FFT plots showed a clear harmonic peak at the frequencies, which corresponded to the respective breathing. This study demonstrated an innovative and a simple approach of physiological measurement specifically HR and BR under controlled settings. A mobile application is being developed in order to measure HR and BR. The implementation and results are presented in this study.

1. INTRODUCTION

Current physiological sensing (measuring heart rate, breathing rate and heart rate variability) is commonly done using contact sensors such as chest straps, electrodes or finger clips. However, these sensors are uncomfortable (e.g. finger clip sensors cannot be used while walking and can also restrict activities such as grasping) and introduce additional costs to the users. In addition, users tend to be very concerned with the way sensors affects their appearance or habits; thus, the use of external sensors poses additional usability concerns.

There are some mobile applications in the market that measures heart rate and respiration rate without needing an external sensor. As examples: *cardio buddy, What's my heart rate*, *Vital Signs Camera*. These applications use the front camera to measure the micro color changes of the face produced by every heartbeat to estimate HR and analyze the motion of the chest to compute respiration rate [1,2] These applications require certain amount of light to work properly, under poor lighting conditions they do not work effectively. In order to deal with the issue of variation in ambient lighting, applications such *What's my heart rate,* or *cardio buddy* use as an option the back camera to measure the heart rate using the fingertip over the cellphone's camera and the flash turned on. However, these apps do not measure respiration rate.
BR measurement is important because it could help subjects to achieve a calm state and to detect and prevent abnormal respiratory rates that may lead to cardiac arrest, stroke and chronic obstructive pulmonary diseases. This study presents an innovative and simple methodology of estimating HR and BR even under poor lighting conditions. The study is based on the effects of respiratory sinus arrhythmia (RSA). That refers to the variation in heart rate when breathing. During inspiration the HR accelerates and during expiration the HR slows down [3]. As well, the principles of PPG. Figure 1 illustrates the effects of RSA using the PPG signal (not filtered) collected from a cellphone's camera recordings. The peaks under the red line correspond to the heartbeats, and the peaks shaped by the red line are the respiration rate traced by the heart rate over time. The PPG signal was recorded for four minutes at a breathing rate of 6 breaths per minute. The graph clearly shows twenty-four peaks that correspond to the breathing rate. Finally, the results determined the feasibility of extracting HR and BR using a cell phone camera by comparing the measurements acquired using a commercial sensor.

This investigation is divided in two phases. In the first phase, studies were conducted in order to create a proof of concept of the feasibility of extracting HR and BR using an iPhone 4 to record the light absorbance of the finger tissue. The HR is extracted from the PPG signal obtained from the video recordings. Respectively, BR is computed by applying the FFT to the HR data. The data gathered was analyzed using Matlab offline. The second phase, which is still in progress, consist in the implementation of the method on a smartphone application, that can estimate HR and BR in real-time. The method proposed is explained in section 3.3.

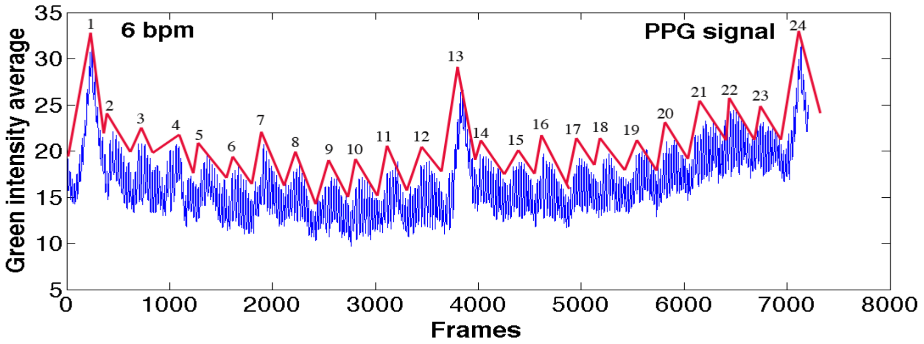

Figure 1. Photoplethysmographic signal and Respiratory sinus arrhythmia

The rest of the paper is organized as follows. Section 2 provides a brief overview of PPG, RSA and summarizes related work on HR and BR extraction using a cell phone camera. Section 3 describes the approach implemented for extraction of HR and BR. Section 4 presents data analysis and results. The paper then concludes with a discussion in Section 5 and directions for future work in Section 6.

2. RELATED WORK

Photoplethysmography is a non-invasive technique for measuring blood volume changes in the blood vessels close to the skin. PPG has become a popular non-invasive method for extracting physiological measurements such us heart rate and oxygen saturation [4]. In order to extract BR from the PPG, the effect of respiratory sinus arrhythmia on the PPG signal is analyzed. This is because respiration rate modulates both amplitude and frequency of the signal [19]. This phenomenon refers to the periodic fluctuations in heart rate that are linked to breathing by which the R-R interval on an ECG is shortened during inhalation and prolonged during exhalation. [6,7]

Previous studies [8, 9, 12] have demonstrated the feasibility of measuring heart rate using a built-in cellphone camera without any additional hardware. By placing the index finger over the cellphone camera with its flash turned on, the camera records the light absorbed by the finger tissue. Then, from the video, each frame is processed by splitting every pixel into red, green and blue (RGB) components. This way, the cell phone camera acquires the PPG signal. Denis Laure et al. [10] and Mayur Lunawat et al. [11], used the red values from the RGB components in order to extract the PPG signal from the cell phone camera and compute HR. Unlike these studies, in this research, the clearness of the cardiac pulse peaks in the red component was weak compared to the clearness of these peaks using the green components. Furthermore, in this study only the green components were used. This is because there is high absorption by hemoglobin in the green range. As well, the green component has stronger PPG signal that the red and blue components [13]. Also, Maeda et al. [14], E. Jonathan et al. [9] and G. Scully et al. used the green values to acquire the PPG signal in order to extract HR. In order to extract breathing rate from the PPG signal G. Scully et al. detected respiratory rate by applying the variable frequency complex demodulation (VFCDM) method to the green signal. However, for this study the fast Fourier transform is applied instead.

3. METHOD

The specific objective of this work was to determine the feasibility of extracting HR and BR from a cell phone camera. Figure 2. explains the entire process. In order to extract heart rate and respiration rate a similar procedure proposed in previous studies [9, 8, 16, 17] was used for this research. The method started with a subject placing his finger over the cell phone camera without pressing down any additional force and the smartphone camera's flash turned on. The subject was instructed to breath at a controlled breathing rate of 6, 10, 12 breathes per minutes (bpm), which corresponded to 0.1, 0.16 and 0.2 Hz. by providing a breathing tone, the subject was guided to inhale and exhale at appropriate times to maintain the desired breathing frequency. Also, Three sets of uncontrolled data were also recorded from the same subject, as follows: breathing under regular pace, sit-ups and walking.

For the first phase of this experiment, a smartphone (iPhone 4 by Apple Inc.) was used to record a video of the light absorbed by the index tissue. The length of the videos was four minutes for each data setting. The videos were recording at a sampling rate of 29.97 fps with an image pixel density of 1280 x 720. After the videos were recorded, Matlab was used to analyze the data gathered. First, the VideoReading tool offered in Matlab was used to extract frames from the recoded video. Next, the RGB components were extracted from every frame. However, for this study the only the green values were used to compute the average of light absorbed by the finger tissue in every frame. Thus, the PPG signal is acquired and used to extract HR and BR.

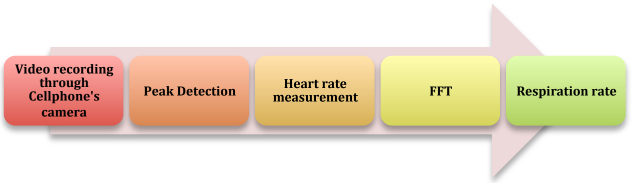

Figure 2. Overview of the method.

3.1 HEART RATE DETECTION

The heart rate is being obtained as follows; During the cardiac cycle, when the heartbeats, it creates a wave of blood that reaches the capillarity at the tip of the finger, when the capillarity is full of blood, it will block the amount of light that can pass through. When the blood retracts, more light can pass through the tissue. If these changes are recorded over time, a waveform is going to be created that correspond to the pulsatile changes in the arterial blood in that tissue. These changes in the arterial blood volume correspond to the heart rate. This process is known as PPG. Using the method described above we try to detect the cardiac waveform and from that the heart rate.

The heart rate extraction was validated using a commercial sensor (Zephyr Bioharness) [18], which provides the ECG signals at the sampling rate of 250Hz. It also provides other physiological parameters such as heart rate, breathing rate, skin temperature, and activity information. For validation, the Bioharness sensor was attached around subject's chest to monitor heart rate and respiration rate while simultaneously recording PPG/cardiac information from the index finger using the cell phone camera.

From the recorded video, the green values from every frame were extracted in order to acquire the PPG signal (figure 1). The green intensity average in the PPG signal formed peaks that correspond to cardiac pulse. A peak detection algorithm was used in order to find all the cardiac peaks in the signal. Once a peak was found, the time difference between consecutive peaks was computed. This time difference is known as R-R interval (RRI). From the RRI values the HR was estimated using the formula given below.

$$HR = \frac{60}{RR}$$

Equation 1. Heart rate equation

After the data collection, the signals from the two modalities (cellphone and bioharness) were synchronized and resampled to maintain a uniform sampling rate. After estimating HR from the cell phone camera, a high correlation of HR was found compared to the measurements from the commercial sensor.

3.2 RESPIRATION RATE DETECTION

After acquiring HR from the PPG signal, the next step was extracting BR from the HR in the spectrum domain. This is possible because respiration rate modulates amplitude and frequency of a signal. Before spectral analysis, the HR signal was interpolated in order to address the issue of irregular sampling from the cellphone and because R-wave are not equidistantly timed events. After this, the fast Fourier transform (FFT) of the HR was computed. We observed that the FFT plots showed a clear harmonic peak at the frequencies, which corresponded to the respective breathing rate. Figure 5 shows the FFT of the HR signal.

3.3. HR & BR ESTIMATOR APP PROTOTYPE

Based on the method explained in section 3 a prototype of HR & BR estimator is being developed on the Android platform. The results obtained from the HR & BR estimator app are presented with the purpose of showing the progress and status of the prototype. The results from the HR & BR application were again compared with a commercial sensor for validation purposes.

The smartphone used for the app development was an HTC Nexus One with a 5 MP camera at a sampling rate of 24 fps with an image pixel density of 2560 x1920. The smartphones runs the Android OS 2.3.6 version. The HR & BR Estimator works by processing and acquiring the timestamp for every frame. The pixel values are encoded in YCbCr pixel format, which needs to be converted to RGB values to obtain the green values. Equation 2. Illustrates the integer operation of the international telecommunication union-radio communication sector (ITU-R) standard for YCbCr (8 bits per channel) to RGB888 [15]. Formula implemented in the applications.

Cr = Cr - 128;
Cb = Cb – 128;
R = Y + Cr + (Cr >> 2) + (Cr >> 3) + (Cr >> 5);
G = Y – ((Cb >> 2) + (Cb >> 4) + (Cb >> 5)) – ((Cr >> 1) + (Cr >> 3) + (Cr >> 4) + (Cr >> 5));
B = Y + Cb + (Cb >> 1) + (Cb >> 2) + (Cb >> 6);

Equation 2. YCbCr to RGB conversion formula

After performing the conversion, the green values are extracted and averaged for every frame. A peak detection algorithm is implemented in order to detect every cardiac pulse peak from the PPG signal. A peak is defined as the highest average of green values in a fixed window size. We empirically chose a window size of 0.7 seconds because it led to least number of false peaks. Once a peak is found, its timestamp is used in order to find the time difference between adjacent peaks, which gives us the RRI. We compute the HR from RRI using the formula presented above (equation 1). After the HR is acquired from the application, the HR is interpolated following which the FFT will be applied in order to find the breathing frequency of the subject. Figure 3. illustrates the procedure.

4. RESULTS

In order to quantify the accuracy of the heart rate obtained from the cell phone camera (with offline processing on Matlab) and the real-time HR & BR Estimator app, the absolute mean error (ME), standard deviation of the error (STDE), root mean square error (RMSE) and correlation coefficients were estimated. Three sets of controlled and uncontrolled data were recorded using a cell phone camera and a commercial sensor (BioHarness). The controlled data was recorded at three different frequencies 0.1, 0.2 and 0.16 Hz., which corresponds to 6, 12 and 10, breathes per minute. After the data was obtained the heart rate was validated using the BioHarness sensor measurements. Table 1. illustrates the results obtained

The HR derived from offline processing shows a strong correlation with the measurements from the commercial sensor for the three sets of data (figure 4). A delay was observed between the signal collected using the cellphone and the bioharness signal. This is because there is a delay in delivering blood to the capillarity at the tip of the finger due to the distance between the finger and the heart. On the other hand, the commercial sensor belt is around the thoracic cavity, which makes closer to the heart and therefore can detect the pulse earlier.

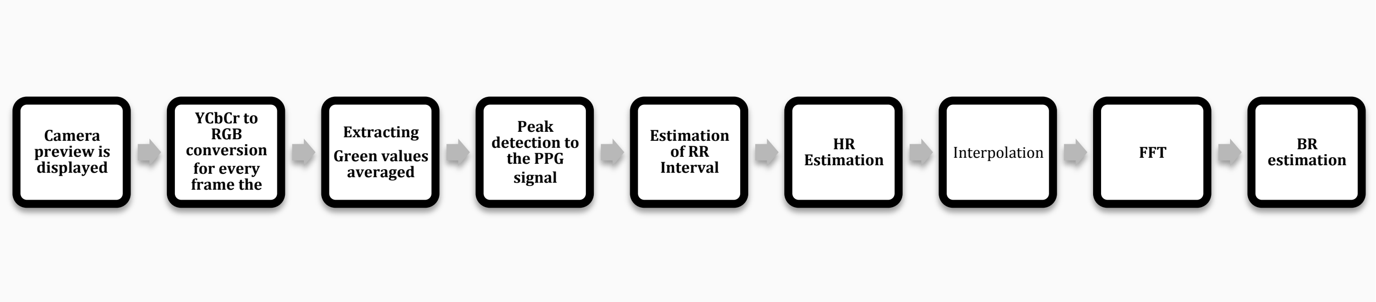

Figure 3. HR & BR Estimator app BR and HR acquisition process

Statistics	Heart rate estimation							
	Offline processing						HR & BR Estimator app	
	Controlled settings			Uncontrolled settings				
	6 bpm	10 bpm	12 bpm	Regular pace	Sit-ups	Walking	6 bpm	10 bpm
RMSE	10.98	5.45	74.50	14.23	129.56	88.48	8.71	5.35
ME	0.05	0.07	74.36	-1.63	38.72	14.37	2.39	0.68
STDE	11.00	5.45	4.70	14.17	123.90	87.49	8.40	5.33
Correlation coefficients	0.92	0.96	0.51	0.39	0.01	-0.03	0.02	0.32

Table 1. Summary of error correlation.

The respiration rate was validated by applying the fast Fourier transform using Matlab. The respiration frequencies were obtained in the same frequency that they were taken (figure 5).

From the three sets of uncontrolled settings, the heart rate results from breathing under regular pace were similar to that obtained from the commercial sensor. However, for the sit-ups and walking, the heart rate data was not closely correlated with the data obtained from the commercial sensor. After applying the FFT to the three data sets, the respiration rate was not clearly found in any frequency. There was not a strong peak in the HR spectrum, which corresponded to the breathing rate. These results were expected. This might be due to the abrupt movements between the finger and camera while the subject was performing the tasks (sit-ups and walking). These movements could be the cause of interference, which makes a signal noisy. Therefore, while looking for a specific frequency signal in the spectral domain, it is hard to pick a frequency component that correspond respiration rate.

Using HR & BR estimator app along with the commercial sensor, two sets of controlled experimental conditions were recorder at 6 and 10 breaths per minute for a period of two minutes. The application creates logs files with the HR data. This data was analyzed and compared with the data collected from the commercial sensor using Matlab. Figure 6. represents the correlation between the commercial sensor and the HR & BR estimator application at the two different respiration frequencies. The signals were normalized in order to find correlation between both measurements. We note that the signals are not strongly correlated. There could be many factors that influenced the low correlation results from the HR & BR Estimator application. One of them might be due to the inconsistent frame rate from the camera in the window size of 0.7 seconds that is being used. This is a factor that makes difficult to detect cardiac peaks; furthermore, the peak detection algorithm might not be detecting every peak from the PPG signal.

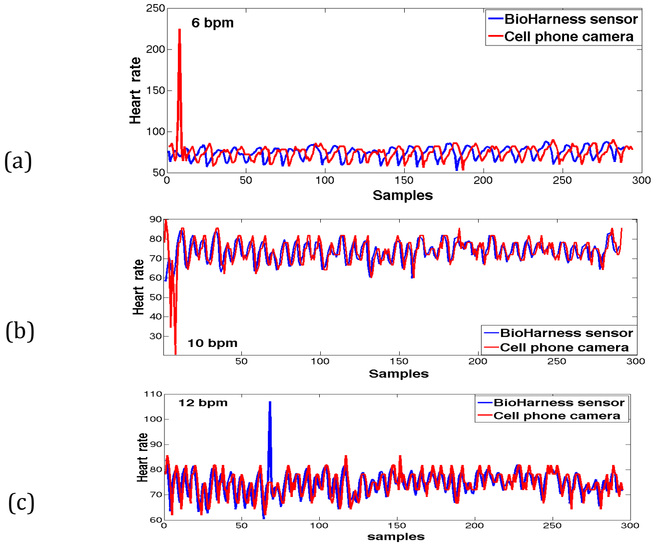

Figure 4. Represents heart rate correlation between the commercial sensor measurements and the HR estimation from the iPhone camera recordings at (a) 6, (b) 10 and (c) 12 bpm.

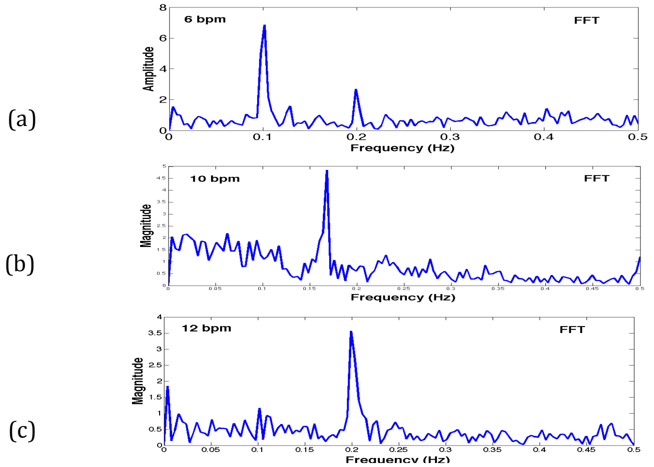

Figure 5. Represents the fast Fourier transform plots. Each harmonic peak corresponded to the respective breathing frequency, in which the samples were collected. (a) Breathing frequency of 0.1hz corresponds to 6bpm, (b) 0.16 corresponds to 10bpm and (c) 0.2Hz corresponds to 12bpm.

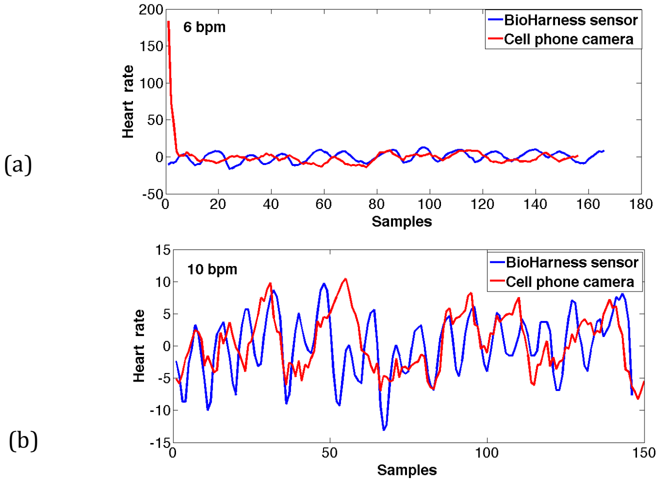

Figure 6. HR correlation between the commercial sensor and the HR & BR estimator application at two different respiration frequencies. (a) 6 bpm and (b) 10 bpm.

5. DISCUSSION

The purpose of this study is to demonstrate a proof of concept of the feasibility of obtaining HR and BR in real time using a cell phone camera and no other sensors. By extracting the PPG signal and identifying the cardiac pulse peaks in the PPG signal, the peak-to-peak intervals are obtained from which the HR is estimated.

Next, the FFT is being applied to the HR data and the BR is acquired. Then, by comparing the measurements with a commercial sensor, the results of the study have demonstrated an effective method of physiological measurements under controlled settings. The method is being implemented on an Android phone. The statistical measurements from the cellphone recordings, which were processed offline showed a stronger correlation when comparing with the data from the commercial sensor, whereas the results from the HR & BR estimator were not as strong. This is because the HR & BR application is still in the development phase, the results showed are just part of the test that are being performed on the prototype in order to improve the algorithm of the application. However, The results are promising considering that the HR & BR application is still in development.

Implementing a smartphone application to monitor HR and BR that do not require external sensors is a cheap and accessible solution for self-assessment health care. This application can potentially benefit many people as source of estimation for possible breathing or heart conditions over time. Monitoring respiration rate is important because it could help subjects to achieve a calm state and to detect and prevent abnormal respiratory rates that may lead to cardiac arrest, stroke and chronic obstructive pulmonary diseases. Also, Changes in the cardiac cycle or a weak pulse can be a red flag for a cardiac disease. The application aims to be a remote self-assessment for delivering health care.

During the study, some limitations were found. First, according to the results of the uncontrolled settings from the cellphone camera, the camera does not properly estimate HR and BR if the subject is moving. This is because when the subject moves, it creates motion artifacts introducing noise that can affect the accuracy of the estimation. This situation is planning to be tackled in the implementation of the HR & BR application by creating filter algorithms. Second, the low sampling rate and the frame rate variation every second makes hard to compute the peak-to-peak distance; furthermore, the HR estimation accuracy can be affected. Third, The application might have problems with some cell phones and operating system. As an example, the EVO HTC has the flash LED light separated from the camera lens, thus, the camera lens acquires less light when estimating HR.

The proposed study is part of a long-term project that seeks to integrate HR and BR measurements with mobile games in order to perform game biofeedback. Due to the duration of the REU program (ten weeks), I was not able to integrate my work with the mobile game currently being developed by other students in the PSI lab.

6. FUTURE WORK

The HR & BR estimator application will be finished and tested for HR and BR measurements. The final goal of this project is to be incorporated with an android game application that is going to be developed further in the PSI laboratory. The purpose of the game is that in order to make progress, the user needs to breath clearly and deeply. If the user's respiration signal is erratic while playing, which means that the player is not breathing properly, the dynamic of the game will be modified and a warning message will be displayed to the player. This way, the player will maintain a constant and clear breathing during the game.

By incorporating the HR & BR estimator application to the game, the issues previously mentioned will be potentially solved. By controlling the player's breathing during the game, a specific frequency signal in the spectral domain will be obtained, which correspond to the breathing rate. As well, For the noise issue caused by motion between camera and the index finger most likely in real world scenario people won't be moving abruptly while playing a cell phone game.

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