Estimation of Heart Rate During Exercise Using Photopletyhsmoraphy

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Heart rate monitoring during exercise is becoming very popular due to high risk of heart attacks involved in intensive exercise. Photoplethysmography (PPG) is one such technique which is non-invasive, non- complex, and has higher usability and portability than electrocardiogram (ECG) technique. PPG signals are captured by a photodetector which records small variations in the intensity of light sent by a light emitting diode (LED). These intensity variations correspond to the changes in the volume of blood vessels.

The PPG signals obtained from the device are corrupted by noise, which is generically known as artifact. The artifacts which occur due to motion make analysis of PPG signals increasingly difficult, hence the most important task in PPG signal analysis is to suppress the motion artifacts (MA). There are many approaches to motion artifact suppression which employ time-domain filters. In our study, we chose wavelets to cancel out the motion artifacts. Through extensive experimentation, we found out that the 'db4' filter yields the best results. In this paper, an algorithm is proposed to monitor heart rate effectively.

PPG data used for analysis was available under IEEE SP Cup 2015. Each data set comprised of six signals- one ECG signal, two PPG signals, and three accelerometer signals in x, y and z directions. The signals were recorded when the subjects aged between 18 and 35 ran at different speeds for particular time intervals. The goal is to estimate the heart rate in a time-window of 8 seconds, with consecutive windows overlapping by 6 seconds. Since the motion artifacts occur is in the same band as the frequency band of interest (1-3 Hz) of PPG signal, suppression methods relying on the frequency of PPG signal and frequency of MA would be ineffective, hence wavelets are employed. In this way, partial suppression of MA can be achieved. To suppress noise, we employ a bandpass filter in a band of 1-3 Hz. Next, a new power spectrum *D(f)* is computed after deducting the power spectra of accelerometer signals from the power spectrum of the PPG signal. This new power spectrum is the power spectrum of pure PPG signal. It is given as:

$$D(f) = \frac{X(f)}{\max(X(f))} - \frac{X\prime(f)}{\max(X'(f))} \qquad (1)$$

Since the PPG signal is periodic in nature, the frequency corresponding to maximum magnitude is the heart rate. This process is repeated for the entire signal, and then for the entire data set of 5 signals. This results in an array of estimated heart rates and is compared with the ground-truth heart rates. Post-processing procedures like smoothening is required to yield better results. If the heart rate falls below 60 BPM and exceeds 180 BPM, the heart rate of previous index is assigned to the current index. The performance of our algorithm is then evaluated by calculating average error (μ) and standard deviation (SD) as, $\mu = \frac{1}{N}\sum_{t=1}^{N}[BPM_{est}(i) - BPM_{true}(i)]$, and $SD = \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\left|BPM_{est}(i) - BPM_{true}(i)\right| - \mu\right)^2}$. The standard deviation (SD) obtained is in the range of 1-5 BPM (Beats per minute). This highlights the accuracy of our method. These results can be enhanced further by employing an improved method to suppress the motion artifacts. Fig. 1 shows the comparison between the true BPMs and estimated BPMs before post-processing, while fig 2 depicts the same comparison, but after post-processing. The calculated values of μ and SD for DATA01 are shown in Table I.

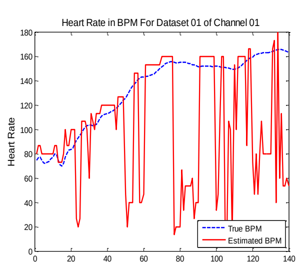

Fig 1. Comparison between true BPM and estimated BPM before post-processing

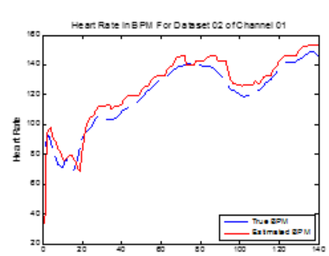

Fig 2. Comparison between true BPM and estimated BPM after post-processing.

TABLE I: μ and SD for DATA01

	State	BPM_{est}	BPM_{tru}	μ	SD
DATA 01	Rest	82.14	75.33	6.80	2.27
	8 km/h	100.49	95.69	4.8	2.7
	15 km/h	138.55	136.59	1.96	2.68
	8 km/h	159.52	153.21	6.31	1.58
	15 km/h	161.84	156.55	5.29	2.88
	Rest	173.58	164.94	8.64	1.89

ESTIMATION OF HEART RATE DURING EXERCISE USING PHOTOPLETHYSMOGRAPHY

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Abstract

- Photoplethysmography (PPG) is gaining prominence for diagnosis of cardiovascular diseases because of its greater usability and portability.
- The presence of motion artifacts complicates the analysis of PPG signals since both the desired PPG signal and the motion artifacts share the same frequency band.
- In this project, we aim to suppress the motion artifacts by using wavelets. Subsequently, we propose an algorithm to estimate heart rate in the frequency domain.
- The heart rate is to be calculated for a time-window of 8 seconds with two consecutive windows overlapping by 6 seconds.
- The estimated heart rates are compared with available true BPM (Beats per Minute) values.
- Average absolute error and standard deviation is calculated and results are tabulated. Standard deviations in the range of 1-6 BPM were obtained.

Introduction

- Monitoring heart rate during exercise is vital to prevent heart-related accidents.
- Previously, electro-cardiogram (ECG) was used extensively for this purpose, but due to its low usability while exercising, PPG replaced it.
- Heart-rate monitoring using PPG signals is very convenient with respect to its usability and portability.
- PPG acquisition system comprises of an emanation LED which illuminates the blood vessels. A photodetector records small variations that occur in intensity of light. These changes in intensity form the PPG signal.
- Device proposed in [1] can be used to acquire PPG signal.
- In this work, we employ a method based on 1-D wavelets to suppress the motion artifacts. Then, we propose an algorithm to estimate the heart rate from the de-noised signal in frequency domain.
- Parameters like average absolute error and standard deviation are calculated to evaluate the performance of our algorithm.
- The recorded standard deviations were in the range of 1-6 BPM (Beats per Minute).

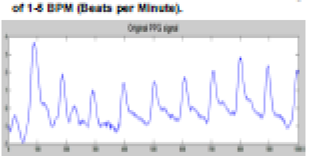

Fig 1. PPG Signal recorded from the device.

Artifacts in PPG Signal

- PPG signals are corrupted by noise which are known as artifacts.
- Various aberrations in PPG signal are described as. low-frequency noise, powerline interference, pre-ventricular contractions (PVCs) and motion artifacts.
- It is to be noted that only motion artifacts significantly influence the experimental results in PPG signal analysis.
- This is so because motion artifacts manifest themselves in the band of 1-3 Hz, which is also the band of interest in PPG signal analysis.
- Several methods like use of Kalman filters , and use of RLS filters to suppress motion artifacts available, but these methods are not useful in our study as these methods require a desired signal.
- Hence we employ wavelets to suppress motion artifacts.

Signal Data

- The data is acquired from two pulse oximeters, a three-direction accelerometer and an ECG sensor. The data was provided by IEEE [2].
- Each data set contains two PPG signals, one ECG signal and three accelerometer signals.
- Data is recorded for subjects aged between 18 and 35, running at varying speeds.

De-Noising of PPG signal

- In the noise affected PPG signal, high frequency component represents noise while the low frequency component contains pure PPG signal.
- Hence, the PPG signal is decomposed into high-frequency and low-frequency components.
- By extensive experimentation, it was found that the 'db4' wavelets suppress noise effectively.

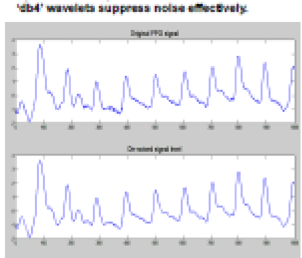

Fig 2. Original and de-noised PPG signal

- Fig 2 shows the original PPG signal, along with its de-noised version. The abnormalities in the original signals are now absent in de-noised version.

Heart Rate Calculation

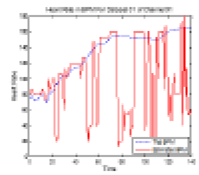

Fig 3. Comparison of true BPM and estimated BPM before post-processing.

- A time-domain method based on peaks in the signal is described to estimate the heart rate. But, this method is indeterminate when it comes to identifying a peak to be a systole or a diachrotic notch.
- Hence, we adopted a method based on frequency domain analysis of PPG signals.
- Power spectrum is calculated as:

$$P(f) = \frac{X(f)}{\max(X(f'))} - \frac{X'(f)}{(\max(X'(f')))} \quad (1)$$

X(f) is the power spectrum of PPG signal, and X'(f) is the combined power spectrum of accelerometer signals.

- Since PPG is a periodic signal, the frequency corresponding to the maximum magnitude of power spectrum is the heart rate. The estimated heart rates are to be compared with the ground truth values.

Post- Processing

- Fig 3 shows the comparison between the true BPMs and the estimated BPM. The non-uniformities visible can be attributed to partial removal of motion artifacts.
- Post-processing is a two-step procedure. In the first step, thresholding is done, and then smoothening is performed.
- Thresholding comprises of retaining the BPM values between 60-180 BPM. If at a particular instant, BPM value falls below 60 and exceeds 180, then BPM at previous instant is assigned to the current index.
- The smoothening process is a moving average filter which removes any remaining abnormalities.

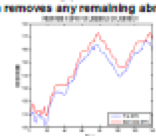

Fig 4. Comparison of true BPM and estimated BPM after post-processing.

Experimental Results

- The algorithm described previously was applied to each of the 5 signals, in a span of 8 second windows.
- For each signal, true and estimated BPMs were compared as shown in fig 4. Fig 4 shows how closely the estimated BPM traces the true BPM value.
- To evaluate the performance of our algorithm, we calculated average absolute error μ and standard deviation SD as given below :

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left|BPM_{est}(i) - BPM_{true}(i)\right| \quad (2)$$

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\left|BPM_{est}(i) - BPM_{true}(i)\right| - \mu\right)^2} \quad (3)$$

- μ and SD were calculated for all the five signals. Table I shows the calculated μ and SD for one signal.

TABLE I : Calculated μ and SD for DATA01

	State	BPM_{est}	BPM_{true}	μ	SD
DATA 01	Rest	82.14	75.33	6.80	2.27
	8km/h	108.49	95.69	4.8	2.7
	15 km/h	138.55	136.59	1.96	2.68
	8km/h	159.52	153.21	6.31	1.58
	15 km/h	160.84	158.55	5.29	2.88
	Rest	173.58	164.94	8.64	1.89

Conclusions

- The results of this experiment are encouraging as the values of μ and SD are low as compared to those in [3].
- Hence our algorithm provides a reasonable estimate of hear rate during exercise.
- It is to be noted that the results of this algorithm depend on the degree to which the artifacts have been suppressed. Hence an effective motion cancellation algorithm will enhance the results further.

References

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