# A Novel Method for Pulse Onset Detection on Photoplethysmogram Using Changes of Waveform Trend

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*Abstract*— **Photoplethysmogram (PPG) is an important physiological signal for evaluating the status of arterial wall, such as calculating markers like pulse wave velocity and pulse arrival time to reflect arterial stiffness. Detecting the onset points is an important prerequisite for analyses of PPG. In this paper, we proposed a novel algorithm using trend change of PPG waveform to detect its pulse onset points. This idea raised from the physiological phenomenon that due to the arrival of arterial pulse, the trend of PPG waveform changes sharply on both sides of PPG onset points from a decreasing trend in the previous end-diastolic phase to a sharp rising trend in the coming early systolic phase. In our algorithm, a published method was adopted to detect the peaks of 1st derivative wave of PPG. And then, in the neighborhood of each 1st derivative PPG peak point, the waveform trend changes between two sides of each point in this neighborhood was calculated, and the onset point was defined as the one with biggest positive trend change. The trend on one side of a target point was calculated from the arc tangent angles between the target point and its nearby points on this side. To evaluate the performance of the proposed algorithm, data collected on 15 healthy elderly subjects in a previous exercise study was analyzed. The results showed that the proposed algorithm achieved at a sensitivity of 99.69%, a positive predictivity of 99.24% and a failed detection rate of 1.07%. Our results demonstrated that the proposed method was robust to noises during exercise and was able to detect PPG onset points of these subjects at a satisfactory accuracy. Since the algorithm is also low in computing cost, it is promising to be used real time in ambulatory/wearable systems in the future.**

*Keywords*— **photoplethysmogram, onset detection, waveform trend, real-time.**

## I. INTRODUCTION

In recent years, the non-invasive photoplethysmogram (PPG) is used in a wide variety of cardiovascular and hemodynamic analysis. One of the most important application of PPG is to calculate the markers such as pulse wave velocity (PWV) or its reciprocal pulse transit time (PTT) to evaluate the arterial stiffness. Detection of PPG onset points is a necessary prerequisite for correct calculation of these markers; however, a lot of factors may influence the detection of PPG onset point, such as baseline drift induced by respirations and motion artifacts.

Many efforts have been made to develop a reliable and fast PPG onset point detection algorithm. Some authors proposed methods based on wavelets transform. Though it is often accurate to detect the peaks and the onsets using wavelet transforms, these algorithms are hard to be implemented in real time. What's more, due to ease of measurement, PPG is an optimal signal for unobtrusive and wearable devices. And wavelet transform is too complicated to be implemented in small scale, low cost, ubiquitous devices.

In 2010, Farooq et al [1] proposed a time-domain algorithm to detect the onset and peaks of PPG with a small computing cost. The core concept of this algorithm is to obtain a transformed PPG waveform which changes the systolic rise of PPG to be a significant peak and thus makes the peaks and onsets of original PPG more robust to detect.

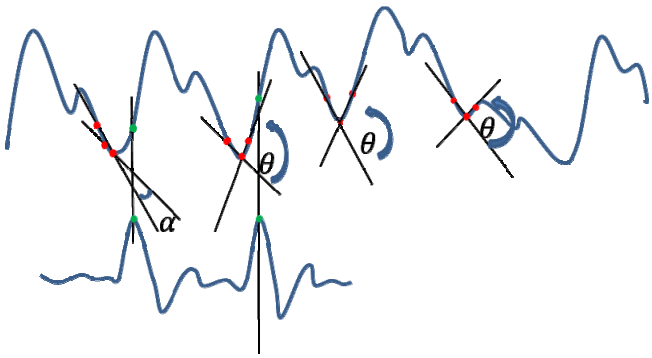


Fig. 1: Onset detection.

α: subtract angle in the same side
θ: subtrat angle on the two sides

The waveform on the top is the PPG waveform and the waveform beneath is the derivate waveform. From the picture we can see that the derivate peak is near the PPG wave's onset point. And the trend has been changed apparently on the two sides of the onset point.

In this paper, we purpose a new algorithm to detect the onset points of PPG by using the waveform trend changes. This idea is based on the fundamental physiological

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phenomenon that at the arrival of arterial pulse, the local blood volume sharply increase, which changed the trend of PPG waveform: PPG waveform changes from a decreasing trend (in the previous end-diastolic phase) to a sharp rising trend (in the coming early systolic phase). Since the onset point indicates the arrival time of arterial pulse, the change of waveform trend on both sides of PPG onset point would be the very significant, as shown in Fig. 1. In this paper, we make use of this phenomenon to indicate the PPG onset points.

## II. MATERIALS

In this study, the PPG data of 15 healthy elderly subjects collected in our previous exercise study [2] was used to evaluate the performance of the proposed algorithm. The exercise study was approved by the Clinical Research Ethics Committee. All subjects were asked to sign the authorization forms before participating in the study. The baseline physical information of these subjects are listed as follows: 1) gender (11 males); 2) age (55±9 years); 3) BMI (23.52±3.23 kg $m^{-2}$); 4) heart rate (73±12 beats $min^{-1}$); 5) systolic blood pressure (141±18 mmHg); 6) diastolic blood pressure (91±7 mmHg); 7) cardiac output (5.5±1.2 L $min^{-1}$).

The protocol of the exercise study was introduced in detail in [2] and it was summarized as follows. Upon arrival, the subject was asked to rest on the bicycle ergometer (Lode, Groningen, Netherland). Then BP was measured on the right arm by a registered nurse using a mercury BP meter (Riester, Germany). After a calibration phase of an impedance cardiographic device (Physio Flow PF-05, Macheren, France), continuous signals including PPG were recorded thereafter, until the end of the experiment. After a signal recording of 40 seconds was collected on the subject at rest with a simultaneous BP measurement, the subject started to ride the bicycle. The riding load was increased from a starting level of 25 W by 25W every two minutes until it reached the tolerant limit of the testing subject, and it then kept constant until the testing subject reached his/her target heart rate ($85\% \times (220 - Age)$). After a BP measurement was taken at the subject's target heart rate, the subject was asked to stop the exercise and lie on the bicycle for recovery for no later than 15 min (a blood test should be taken within 15 min after exercise). In the exercise phase, BP was first measured one minute after the start of exercise and then measured every two minutes later, until the end of exercise. n the recovery phase, BP was firstly measured immediately after the stop of exercise and then every two minutes later, until the end of the experiment. We then split the total length of PPG data into trials of 40 s using BP measurement as markers, with trials cut from the onset of each BP measurement and from in between of two sequent BP measurements.

PPG was acquired by an in-house designed acquisition device (MPAS, JCBME lab, CUHK, Hong Kong) on the left index finger of the subject. The PPG acquisition device was a finger clip with reflection mode LED emitter (850 nm, SFH-4250Z, Osram) and detector (850-880 nm, SFH-319 FA-3/4, Osram) embedded. It was connected to a small portable procession unit, where the PPG were filtered (band-pass filter: 0.35-16 Hz) and amplified (19× dc gain). Then, the analog output of PPG and other signals were connected to an analog to digital converter (Dataq D1-719, USA), converted to digital signals, sampled at 1000 Hz, and then stored in a desktop for offline analysis.

## III. METHODS

The proposed method detected the onsets in PPG waveform in three steps: A) PPG transformation, include filtering, 1st derivative calculation, moving window summation and rectification. B) peak detections on transformed PPG and corresponding 1st derivative PPG wave; C) Onsets identification: in the neighborhood of each 1st derivative PPG peak point, the waveform trend changes between two sides of each point in this neighborhood was calculated, and the onset point was defined as the one with biggest positive trend change. Steps A) and B) are following the procedures in Farooqs' algorithm. All procedures above were implemented using software MATLAB 7.0.

Next, we conducted statistical analysis to evaluate the accuracy of our method. In order to show the onset point detecting performance of the proposed method, a comparison between the detection results of our method and Farooq's method was made.

### *A. PPG Transformation*

The concept, procedures and formulas for PPG waveform transformation was introduced in detailed in [1]. And we summarized here as follows. First, PPG signals were filtered using a band-pass filter to reduce the high-frequency noises and low-frequency baseline shift. Next, the 1st derivative PPG was calculated using equation (1), and then a moving window summation (with a window size of 128 ms) was conducted on 1st PPG wave using equation (2). These two steps make the PPG signal become more prominent and the peaks become easier to be detected. Finally, rectification was applied on the transform wave.

$$diff = \text{PPG(2:n)-PPG (1:n-1)} \quad (1)$$

$$\text{mwsum}=\sum diff \quad (2)$$

### B. Transform Wave's Peak Detection

As introduced in [1], the peaks on the transformed PPG using an adaptive double-threshold method. An initial threshold (threshold 1) was set empirically at the beginning of detection to judge the peaks, and then adaptively updated by values of latest detected transformed PPG peaks. If the threshold 1 was not able to detect a new peak in an adequate long time period, a threshold 2 (which was half of threshold 1) was utilized as a new judging criterion to detect the new peak. Here we set the initial learning phase to be 1.5s and use the 0.6 times of max point in the learning phase to set threshold 1. The no. of most recent peaks used to update the value of threshold 1 was set to be 8. After peaks of transformed PPG was successfully detected, according to the relationship introduced in [1], the peaks of 1st derivation is the max point in the very nearby neighborhood around peaks of transformed PPG.

### C. Onsets Identification

Here we defined the waveform trend on either side of each target point using the arc tangent angles between the target point and its nearby points on that side. Since the onset of PPG was induced by sharp changes of PPG waveform trend, we identify the onset points of PPG waveform in a neighborhood of PPG 1st derivative peak using the following criteria:

1) if we calculate the arc tangent angles between the onset point and all of its nearby N points (N=40) on one side (either diastolic phase or systolic phase), the differences between neighbor arc tangent angles should be less than 5 degree (the same trend);

2) the sum of angle differences between pairs of mirror points (a pair of mirror points is two points on different sides respectively but with the same distance away from the target point) should be max at the onset point within the neighborhood of the 1st derivative PPG peak.

### D. Evaluation

After we find onset point by the proposed algorithm, we also annotated the PPG onset points by Farooq's algorithm. And then we compare the performances of the two different methods by using statistical analysis.

Two experts manually annotated the onset points of all PPG trails and used as reference to evaluate the results of automatic algorithms. The trails where the annotation results from two experts differed were removed from the later analysis. Statistical parameters such as Sensitivity(SE), Positive predictivity(+P), and Failed detection rate(FDR) were calculated and their formulas are listed below.

$$\text{Sensitivity (SE)} = \frac{True\ positive}{True\ positie + \text{False}\ negative} \quad (3)$$

$$\text{Positive predictivity (+p)} = \frac{True\ positive}{True\ positive + False\ positive} \quad (4)$$

$$\text{Failed detection rate (FDR)} = \frac{Failed\ detection}{Number\ of\ peaks} \quad (5)$$

## IV. RESULTS

462 trials were collected from 15 subjects in the exercise experiment. 37 trials were removed due to disagreement on the manual annotations of two experts, and 10 trials were removed due to poor signal quality. As a result, 415 trials were left for further analysis.

Fig. 2 shows PPG waveforms of three typical subjects during exercise and the onset points detection results by the proposed algorithm.

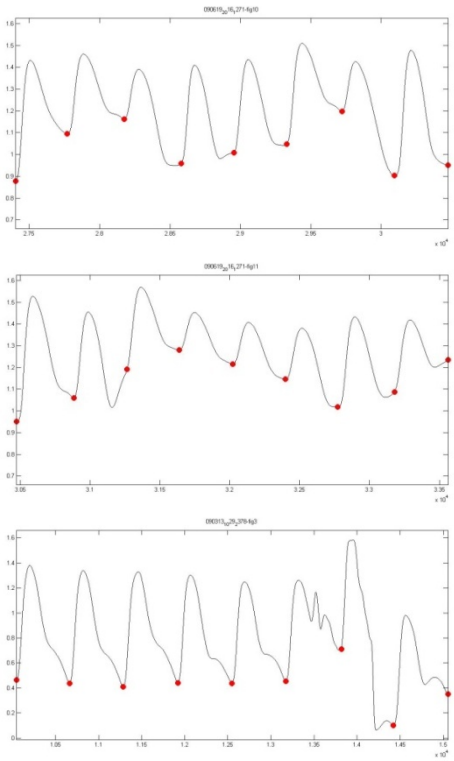

Fig. 2: An example of PPG signal conditioning, and onset detection result by our novel method.

Table 1 shows the comparison of statistical analysis results on the onset point detections by the proposed methods and those by Farooq's method.

Table 1: Comparison on algorithm performances of proposed and Farooq's methods.

| Parameter | Proposed Method | Park's method |
|---|---|---|
| Total No. of onset points | 29017 | 29017 |
| True Positive | 28707 | 27693 |
| False Positive | 221 | 1235 |
| False negative | 89 | 89 |
| Sensitivity(%) | 99.69 | 99.68 |
| Positive Predictivity(%) | 99.24 | 95.73 |
| Failed detection rate(%) | 1.07 | 4.56 |

## V. DISCUSSION

It has been a long-time need and also a challenge task to detect the characteristic points of a physiological signal accurately, automatic and in real time. In 1985, Pan et al [3] proposed their famous time-domain method using adaptive-double thresholds detect the ECG R peak in real time. In Pan's algorithm, a series of procedures, including 1st derivative calculation, squaring and wave integration, were implemented to augment the amplitude of the QRS complex as well as to reduce the influence of T wave. In 2000, Farooq et al [1] successfully adopted this idea to the peak and onset point detection of PPG waveform, where similar procedures were utilized to change the systolic rising edge of PPG waveform to a pulse shape signal and other features, e.g. reflective wave were removed. Farooq's algorithm made the PPG signal more robust and the peak more prominent to detect.

In this paper, we focused on the detection of PPG onset point, due to the reason that the detection of onset point of critically important in many clinical and research applications such as calculating the pulse transit time. The assumption made by us is that the PPG onset point is the sharpest waveform trend changing point in its neighborhood.

The results on 15 elderly healthy subjects proved the effectiveness of the proposed method. It achieved a high sensitivity of 99.69%, high positive predictivity of 99.24% and a low failed detection rate of 0.92%. Compared with Farooq's algorithm, the proposed algorithm showed a comparable sensitivity but a much lower failed detection rated. This indicated that the waveform trend change may be a reliable feature to mark the PPG onset points.

Fig. 2 shows the robustness of the proposed algorithm to motion artifact and baseline shifting of PPG waveform during exercise. It is clearly that the proposed algorithm could track the PPG onset points even if the PPG waveform has greatly deformed due to noises and motions during exercise.

## VI. CONCLUSIONS

To conclude, in this paper we proposed a novel algorithm to detect the PPG onset points using the feature of waveform trend changes. The results on healthy elderly patients in a previous exercise study showed the accuracy of the proposed method as well as its robustness to noises and motion artifacts. In the future study, we will try to further reduce the computational cost of the algorithm and implement this algorithm in a real time detection application. Further, this method also needs to be tested on more subject populations to prove its validity.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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