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A Combined Heartbeat Detector based on Individual BCG and IPG Heartbeat Detectors

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***Abstract*— This paper presents a preliminary approach for heartbeat detection on a weighing scale, using a combined heartbeat detector and an ensemble method. First, two independent sub-detectors are implemented based on the BCG (*Ballistocardiogram*) and lower-body IPG (*Impedance Plethysmogram*) signals. Then, the results of these sub-detectors are combined using a higher level decision maker. The BCG, which describes the reaction of the body to cardiac ejection of blood, was measured using the strain gauges in a modified commercial weighing scale. For the lower-body IPG, a small amount of current was injected into the subject through the electrodes under the subject's toes, and the resulting differential voltage across the heels was measured. We tested our method on the first 30 seconds of the BCG and IPG signals collected from 8 subjects. The results show the combination significantly improved over individual detector, with a resulting interval accuracy of 97%.**

I. Introduction

Heartbeat detection is a fundamental component of monitoring a person's cardiovascular (CV) health. Additionally, accurate detection of heartbeat locations enables ensemble averaging of cardiovascular signals to improve signal-to-noise ratio (SNR) and extraction of other diagnostically-relevant features. The most common tool used for heartbeat detection is generally the electrocardiogram (ECG). However, there are many cases when measuring an ECG is not convenient, such as in home monitoring, or some continuous monitoring applications.

One alternate cardiovascular signal that may be better-suited for these applications is the ballistocardiogram [1], which in recent studies has been shown to be effective in measuring important parameters of cardiovascular health [2]. Several research groups have designed heartbeat detectors for the BCG signal, e.g., using auto-correlation functions [3], [4], [5], template matching [6], and pattern recognition [7]. However, if the BCG signal is corrupted by motion artifacts, floor vibrations, or other disturbances, these algorithms will inevitably be prone to making errors. To mitigate these problems, we recently designed a BCG acquisition system with an auxiliary cardiovascular signal—the lower-body impedance plethysmogram (IPG)—such that even in the instance of artifacts corrupting the BCG, the IPG signal could be used to supplement the information lost in the BCG [9], [10].

Here, we have designed a novel heartbeat detector by combining imperfect sub-detectors based on the BCG and IPG signals. This method first uses two sub-detectors, each of which detects heartbeats from the BCG and IPG independently, then employs a higher-level detector which uses the information from these two sub-detectors to make the ultimate decision of whether or not a heartbeat has occurred.

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II. Signal Acquisition

In this study, signals were collected by the CV home monitoring system based on a modified bathroom scale described in [9], [10]. The BCG signal was measured using a sensing unit in the scale that consists of four stain gauges configured in a Wheatstone bridge [2]. The sensing unit measures mechanical pressure applied to the barefoot soles of the subject while the subject is standing on the scale. The lower-body IPG signal was measured using the electrodes and supporting electrical circuits. The circuit injects a small amount of current to the subject through the subject's toes, and simultaneously measures the voltage difference between the heals [11]. The measured instantaneous voltage equivalently represents the instantaneous lower-body impedance of the subject. The BCG and IPG signals were digitized and sampled at 1 kHz. For more information on signal acquisition methods, and subject demographics, the reader is referred to [10].

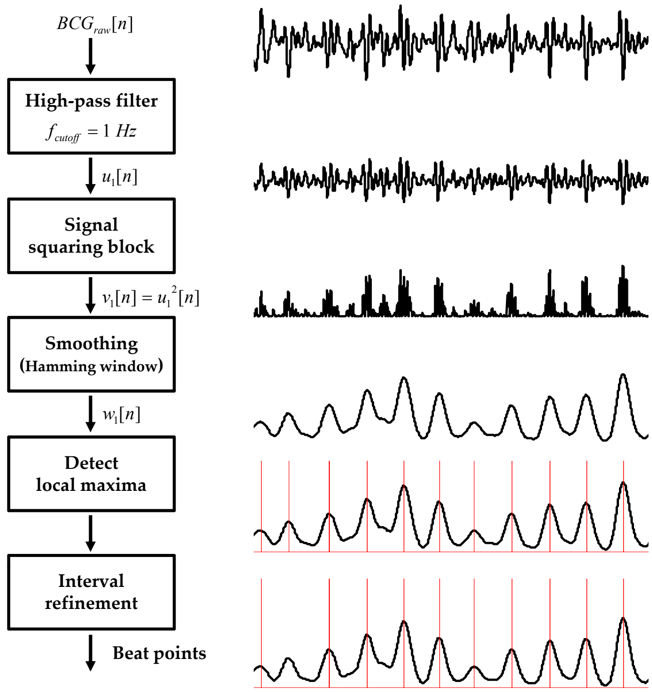
III. The Combined Heartbeat Detector using The BCG and IPG Heartbeat Sub-Detectors

The basic idea of the 'Combined Heartbeat Detector (CHD)' is to design a higher-level heartbeat detector using two independent sub-detectors, based on either the BCG or IPG. In this section, we will first describe the design of the two independent sub-detectors, the BCG heartbeat detector (BHD) and the IPG heartbeat detector (IHD). Then, based on these two sub-detectors, we will describe the details of the combined heartbeat detector (CHD).

A. The BCG Heartbeat Detector (BHD)

Figure 1 illustrates the signal processing procedure in the proposed BCG heartbeat detector (BHD).

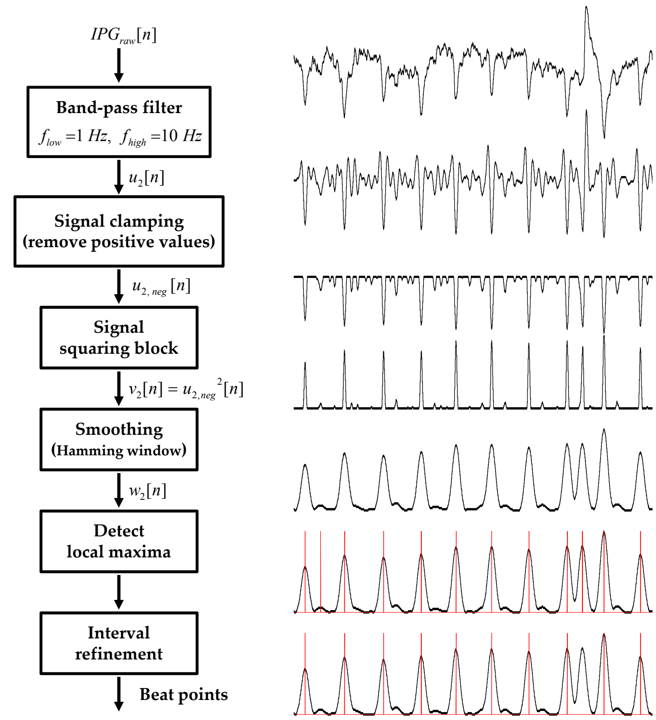
The BCG signal acquired from the bathroom scale [9], [10] is high-pass filtered to remove low frequency components including respiration, with a cutoff frequency of 1 Hz. After the high-pass filtering, the most eminent characteristics of the filtered BCG signal is a variation in its signal envelope. The envelope width alternates between a local maximum



(a) Signal processing procedure of the BCG heartbeat detector.

(b) The BCG signal and the corresponding signals to each of the processing steps.

Fig. 1: Signal processing procedure of the BCG heartbeat detector and example signals.



(a) Signal processing procedure of the IPG heartbeat detector.

(b) The IPG signal and the corresponding signals to each of the processing steps.

Fig. 2: Signal processing procedure of the IPG heartbeat detector and example signals.

and a local minimum quasi-periodically, and the maximum-to-maximum interval is a good measure of the beat-to-beat interval of the CV activity. To estimate a local maximum of the signal's envelop, a smoothed instantaneous signal power is used. The instantaneous signal power, $v_1[n]$, is the instantaneous square of the high-pass filtered signal, $u_1[n]$. The smoothing process is done by a Hamming window. Based on the smoothed signal, $w_1[n]$, by extracting local maxima, we can detect heartbeats. However, the local maxima may contain false positive points. Thus, we apply an 'interval refinement process' to the local maxima.

Basically, the interval refinement process checks interval lengths between two consecutive local maxima and removes the false positive points which resulted in exceptionally short intervals. The decision is based on the latest valid beat-to-beat interval, L_{valid} and predefined percent allowance, γ in interval variation. The latest valid beat-to-beat interval is continuously updated and the absolute allowance, $\gamma \cdot L_{valid}$, is adaptive. If new interval length is longer than $(1+\gamma) \cdot L_{valid}$ or shorter than $(1-\gamma) \cdot L_{valid}$, the corresponding new beat point is regarded as a false positive and discarded. At the beginning of the process, the interval refinement needs an initial valid interval. To calculate the initial interval, first, calculate the average of all un-refined intervals. Let us call the average L_{init}. Then select the intervals whose length is longer than $(1+\gamma) \cdot L_{init}$ or less than $(1-\gamma) \cdot L_{init}$. Then exclude those intervals and re-calculate the average, L_{init}, based on the remaining intervals. Repeat this process until L_{init} converges. Then, the converged L_{init} will be the initial interval value for the refinement process. In this work, γ was chosen to be 0.2.

Figure 1b shows an example set of signals corresponding to the each signal processing step.

B. The IPG Heartbeat Detector (IHD)

Figure 2 illustrates the signal processing procedure in the proposed IPG heartbeat detector (IHD).

The IPG signal acquired from the bathroom scale [9], [10] is band-pass filtered (1-10 Hz) to remove low- and high-frequency components. After the band-pass filtering, the most eminent characteristics of the filtered IPG signal are a long negative tail which is repeated over time. To extract this feature from the filtered IPG, $u_2[n]$, the positive parts of the signal are removed and replaced with zero (signal clamping). The clamped signal, $u_{2,neg}[n]$, is passed through the signal squaring block and, then smoothed by a Hamming window. The maxima of the smoothed signal, $w_2[n]$, correspond to the heart beat points. Since the local maxima also may contain false positive points, we need to apply the interval refinement process described in Section III-A to the maxima of $w_2[n]$. Figure 2b shows an example set of signals corresponding to the each signal processing step.

C. The Combined Heartbeat Detector (CHD)

The combined heartbeat detector (CHD) is based on the established BHD and IHD. The two detectors independently

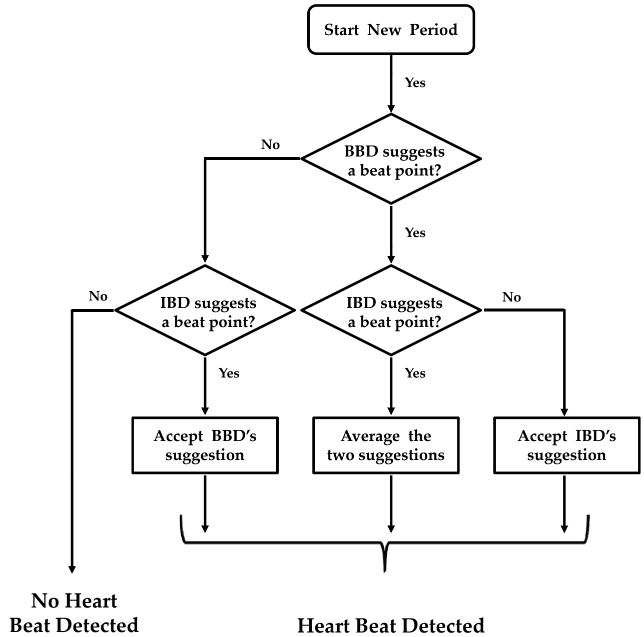


Fig. 3: Decision flow chart of the Combined Heartbeat Detector (CHD). Please note that this flow chart shows only the basic idea of the EHD and the same interval refinement process of Section III-A is also applied here to avoid simple additions of possible false positives.

recognize the beat points based on the BCG and IPG respectively. Subsequently, the CHD determines the heart beat points of the subject. As mentioned in Section I, the CHD behaves more like a decision maker based on the suggested beat points by the individual sub-detectors, the BHD and IHD. This is the motivation of the CHD and by constructing a collaboration/compensating mechanism between the BHD and IHD, we can design a more robust heartbeat detector.

Figure 3 shows the decision flow chart used in this study. If both detectors, the BHD and IHD, suggest beat points falling in the interval, then the CHD takes the two results and averages them to determine the heartbeat point in the interval. If only one of the two detectors suggests a beat point falling in the interval, i.e. the other fails, the CHD just takes that beat point as the beat point of the interval. In these two cases, the CHD still can detect correct heartbeat points. If none of the two suggests a beat point, the CHD asserts 'No heart beat point found.' The last situation can happen if the subject's CV system fails or the two acquisition systems, one for the BCG and the other for the IPG, fail together.

IV. Experiments and Results

We tested our detectors over first 30 seconds parts of each subject's signals collected by the CV monitoring system [9], [10]. Heartbeat points determined using the ECG signal recorded simultaneously from the same monitoring system were used as the reference heartbeat points.

The performance of the CHD was evaluated by comparing the estimated heartbeat points and beat-to-beat interval lengths with the reference points/values of the ECG. We defined the heartbeat points as positive responses, and false positives and negatives were defined with respect to the ECG heartbeats. For example, if an actual heartbeat point was not detected by a detector, the detector made a 'false negative' at the beat point.

Table I shows results of our experiments. The BHD had 2 false positives and 17 false negatives over 315 heart beats of 8 subjects. The IHD had 11 false negatives over the 315 beats. The CHD had no false positives and negatives. This is because even though each individual detector made some mistakes, those errors did not happen at the same time and the combined detector selectively chose the right beat points all the time. In terms of interval length estimations, the CHD achieved 97.2% of accuracy in average with 2.6% standard deviation over 315 beats. Even though the interval lengths estimation accuracy of the CHD in Table I was slightly lower than that of the IHD, we must interpret these numbers with 'Sensitivity' and 'Positive predictive value' [6] of each detector. The accuracy of interval estimation was calculated based only on correctly detected heartbeat points. Effectively, to get a fair comparison between two detectors, we need to compare the values of *(Sensitivity)·(Interval Accuracy)*. By this comparison metric, the CHD has 97.2% and still outperforms the IHD (95.6%) in terms of the effective interval estimation accuracy.

V. Limitations and Future Directions

One limitation of this approach is that sometimes motion artifact can corrupt both signals simultaneously. In this case, both sub-detectors would make errors and the combined detector would not improve performance. Nevertheless, in many cases, only one of the signal will be corrupted at a given time: For example, when a subject's foot loses contact even slightly with one of the electrodes, the IPG signal will show major artifact although the BCG signal will not. Alternately, if the subject talks during the measurement, the BCG signal will be corrupted but the IPG signal will not. For both of these cases, the algorithm described here will show major improvement over using only one signal individually.

Another limitation is in the interval refinement procedure: as we have designed this procedure here, arrhythmias will be lost in the process of beat detection. This precludes the use of the beat detector in its current state for arrhythmia detection from the BCG. However, the detection algorithm described here *would* be adept in its current state for detecting heartbeat fiduciary points that could be used to direct ensemble averaging algorithms. This would lead to an improvement in the signal-to-noise ratio of non-arrhythmic beats, and would allow more accurate extraction of important features: IJ amplitude, BCG rms power, etc. Furthermore, in future work, the interval refinement algorithm can be paired with morphological analysis to determine if a detected extra-systole with an unusually short heartbeat interval is due to measurement error, or an arrhythmia.

Finally, the performance of the algorithm must be verified on more challenging recordings—in particular, recordings including arrhythmias, motion artifacts, and other disturbances.

TABLE I: SUMMARY OF RESULTS

Subject Number		1	2	3	4	5	6	7	8	Summary
Total number of heartbeats (0∼30 sec)		32	54	37	31	45	38	40	37	315
BCG heartbeat detector(BHD)	# of false positives	0	0	0	0	2	0	0	0	2
	# of false negatives	1	4	0	0	10	0	0	0	17
	Sensitivity(%)	96.9	92.6	100	100	78.3	100	100	94.6	94.6
	Positive predictive value(%)	100	100	100	100	94.74	100	100	100	99.33
	intervals accuracy(mean, %)	95.6	93.1	97.6	95.8	89.1	98.3	97.2	95.7	95.3
	intervals accuracy(std, %)	3.4	5.1	1.9	3.6	8.5	1.5	1.8	3.3	3.6
IPG heartbeat detector(IHD)	# of false positives	0	0	0	0	0	0	0	0	0
	# of false negatives	0	4	1	1	1	0	4	0	11
	Sensitivity(%)	100	92.6	97.3	96.8	97.8	100	90.0	100	96.5
	Positive predictive value(%)	100	100	100	100	100	100	100	100	100
	intervals accuracy(mean, %)	99.5	98.3	98.8	99.6	99.4	99.4	98.5	99.3	99.1
	intervals accuracy(std, %)	0.5	1.3	1.5	0.3	0.5	0.5	1.8	0.5	0.9
Combined heartbeat detector(CHD)	# of false positives	0	0	0	0	0	0	0	0	0
	# of false negatives	0	0	0	0	0	0	0	0	0
	Sensitivity(%)	100	100	100	100	100	100	100	100	100
	Positive predictive value(%)	100	100	100	100	100	100	100	100	100
	intervals accuracy(mean, %)	97.8	96.2	98.7	97.6	93.3	99.0	98.1	97.9	97.3
	intervals accuracy(std, %)	1.7	3.0	1.0	2.0	5.6	0.9	1.5	1.4	2.2

The performance will be evaluated for these recordings based on both the interval detection accuracy (as described here), as well as any possible improvement in BCG feature extraction enabled by ensemble averaging methods.

VI. CONCLUSION

This preliminary study demonstrated that by combining two independent BCG and IPG heartbeat detectors, heartbeat detection can be improve compared to using each signal independently. Even though each sub-detector which uses only one signal had a possibility of temporal detection failure, the CHD overcame a sub-detector's temporal failure by selectively using the beat points information provided by its sub-detectors, the BHD and IHD. For over 8 subjects and 315 test heart beats, the CHD achieved 97.2% accuracy in beat-to-beat interval length estimation.

Future work will improve the beat detection algorithms of the BHD and IHD, and the decision algorithm of the CHD. Then the CHD will be evaluated under more various test situations, e.g. recordings with motion artifacts or from patients with CV diseases.

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