Heart Rate Algorithm Verification

Whitepaper by OMsignal
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***Abstract*—The OMsignal heart rate measurement algorithms were demonstrated to be accurate within 5 beats per minute during running and jogging. This accuracy was verified for 95% of the recording time with 95% statistical certainty. The overall heart rate accuracy was measured to be 4 bpm (CI+ 4.71 bpm). The average sensitivity and PPV of the algorithm were measured to be 90.95% and 99.6% Data for the verification was taken from 20 recordings by women and men wearing the OMsignal bio-sensing garments.**

Keywords*—*Heart Rate, Electrocardiogram, Bio-sensing Textile.

I. Purpose and Scope

The verification was designed to quantitatively assess the performance of the OMsignal heart rate measurement algorithm. The scope of the verification encompassed heart rate measurements while running and jogging with the latest version of the OMbra and OMshirt as of the date of writing.

II. Methodology

A. Data Selection

The verification data was selected to closely resemble the data recorded by customers wearing the OMsignal garments.

Ten recordings with the OMbra were selected among a data-set of 40 recordings used to ensure the quality of the OMbra during the garment's development. The verification data-set was selected to have a median duration and signal quality similar to all of the quality assurance recordings. Furthermore, 2 recordings with ill-fitted bras were included in the data-set to represent the incidence of ill-fitted garments expected to take place with customers. Ten recordings with the OMshirt were selected randomly from a data-set of male OMsignal employees completing 5 kilometer runs outdoors.

Rules were predefined to exclude segments in the recording when it was not appropriate for the algorithm to measure a heart rate (Section II-B). Roughly 20% of the remaining recording was labelled by manually assigning time-stamps to visually discernible heart beats in the electrocardiogram (ECG). The algorithm heart rate measurement was compared against the heart rate derived from the manual annotations. Table I presents the recording lengths, total exclusion and total labelled time.

TABLE I. Verification Data Summary

File ID	Total (min)	Included (min)	Excluded (min)	Labelled (min)	Labelled (%)
W01	13.5	13.5	0	5.8	42.8
W02	10.1	9.7	0.4	4	41
W03	13.7	13.7	0	7	51.3
W04	9.4	9.3	0.1	3.3	35.7
W05	14.3	14.3	0	3.6	25.5
W06	15.5	15.5	0	5.3	33.8
W07	14.5	14.4	0.1	3.3	23.1
W08	11.9	10.4	1.5	5.5	53.1
W09	9.4	9.4	0	3.6	38.2
W10	13.2	13.2	0	6.7	50.7
M01	59.5	41.2	18.3	8.9	21.6
M02	84.7	39.3	45.5	8.6	22
M03	55	32.7	22.3	10.1	31
M04	84.7	37.9	46.8	7.8	20.6
M05	84.7	38.6	46.1	6.6	17.1
M06	33.6	32.2	1.4	6.3	19.6
M07	84.7	40	44.8	7.9	19.9
M08	84.7	35.4	49.3	7.4	20.9
M09	84.7	50	34.7	8.9	17.8
M10	84.7	36.8	48	6.9	18.6

B. Exclusion Criteria

Sections of the recordings were excluded based on these rules:

1. Segments when the OMsignal box was disconnected were excluded. These segments were easy to identify because the ECG became a flat-line. (Figure 1a).

2. Segments when skin-electrode conductivity was very poor could not be labelled because noise overwhelmed the heart beat signal (Figure 1b).

C. Manual Labelling Process

The heart beats in the electrocardiogram (ECG) recordings were manually labeled by an engineer following these steps:

1. A representative 20% of each file was selected for labelling in order to reduce time spent on the manually intensive labelling process.

2. A heart beat was identified by the presence of a QRS complex in the ECG (Figure 2a). The label was placed on the maximum ECG value of the QRS complex, which corresponded to the R peak [1].

3. In some cases, the presence of noise made it necessary to estimate the time of the R peak based on the sequence of previous R-R intervals (Figure 2b).

4. Median and 5-15 Hz band pass filters were selectively applied to the ECG to aid in the identification of heart beats in the presence of noise. Also, the breathing signal was observed alongside the ECG to facilitate heart beat identification.

5. The labels were manually assigned by an engineer using a graphical user interface (GUI). The GUI automatically placed points chosen by the engineer on the nearest local ECG

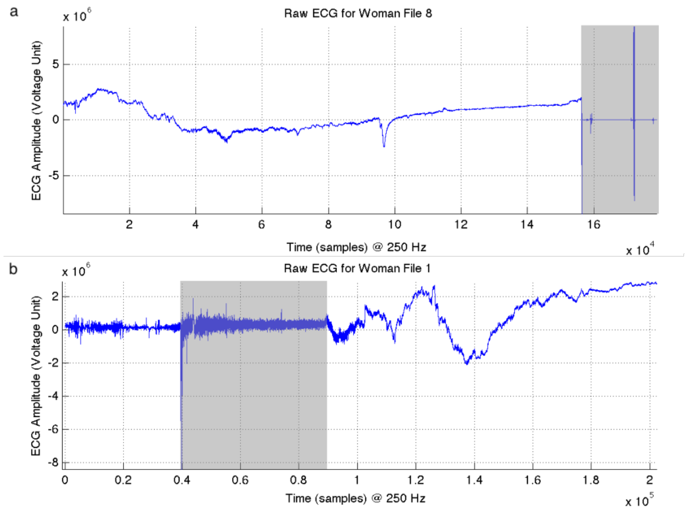

Fig. 1. (a) Excluded segment due to OMsignal box disconnection marked in grey. (b) Excluded noisy segment due to poor skin-electrode conductivity marked in grey.

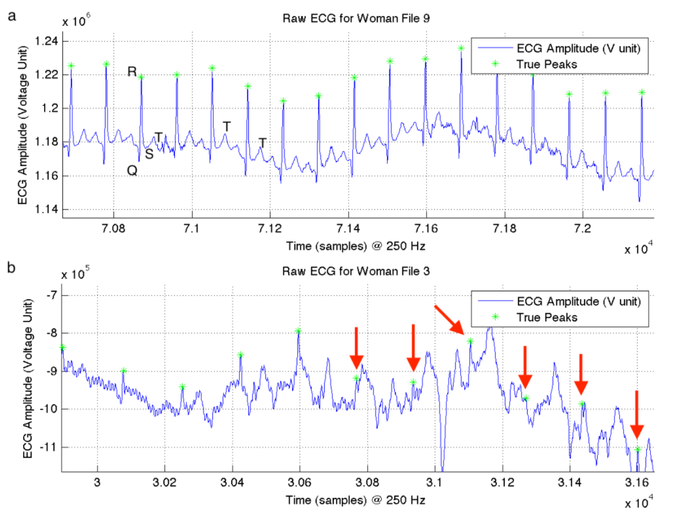

Fig. 2. (a) Labelling QRS complexes in the ECG. (b) Estimating subsequent R peaks based on R-R interval sequence.

maximum to ensure the label time-stamps closely matched R peak occurrences.

D. Results Process

The steps to arrive to the final result were as follows:

1. The labelled heart rate was computed from the difference of consecutive labelled R peaks. The formula used for computing heart rate from an R time series was: $HR_k = 60/(R_k - R_{k-1})$, where HR_k denotes the heart rate in beats per minute (bpm) and R denotes the time-stamp in seconds of the R peak label for the k^{th} R-R interval in the sequence.

TABLE II. 95$^{\text{TH}}$ PERCENTILE HEART RATE ACCURACY, SENSITIVITY AND PPV FOR INDIVIDUAL FILES

File ID	HR95 (bpm)	Sensitivity (%)	PPV (%)
W01	3.99	90.12	99.47
W02	2.92	93.39	100
W03	8.62	81.13	98.95
W04	2.73	99.26	100
W05	10.8	78.49	99.76
W06	2.06	99.1	100
W07	1.7	100	100
W08	7.79	75.18	98.23
W09	2.02	100	100
W10	1.8	100	100
M01	4.69	75.19	98.2
M02	4.82	79.35	98.68
M03	4	88.76	99.92
M04	2.25	99.6	100
M05	1.74	99.56	100
M06	2.61	98.27	100
M07	4.69	99.84	100
M08	5.42	98.42	100
M09	4.8	99.21	100
M10	5.66	63.95	98.81

2. The algorithm heart rate was computed using the OMsignal C production firmware.

3. The accuracy was computed as the 95$^{\text{th}}$ percentile absolute difference between the labelled and algorithm heart rate signals.

4. Heart rate signals were concatenated in order to compute the overall, OMbra and OMshirt heart rate accuracy.

5. The 95% confidence interval on the accuracy was computed using a bootstrap confidence interval [2].

6. Sensitivity and positive predictive value (PPV) were computed using formulas (1) and (2). TP denotes true positives detected by the algorithm in agreement with the annotations. FP denotes false positives detected by the algorithm without agreement by the annotations. FN denotes manual annotations that were not confirmed by the algorithm.

$$sensitivity = TP/(TP + FN) \quad (1)$$

$$PPV = TP/(TP + FP) \quad (2)$$

III. Results

A. Performance Metrics and Success Criteria

The verification set-out to determine the 95$^{\text{th}}$ percentile accuracy of the heart rate measurement algorithms with a 95% statistical significance. The algorithm achieved the success criteria of 5 beats per minute heart rate accuracy within the predefined requirements. As a secondary requirement, the verification measured the sensitivity and positive predictive value of the algorithm. These metrics were used to assess the underlying explanation for algorithm performance.

B. Results - Individual Files

The 95$^{\text{th}}$ percentile heart rate accuracy, sensitivity and PPV for the individual files are presented in table II. Characterization of the major causes of algorithm inaccuracy are discussed in section III-D.

TABLE III. 95TH PERCENTILE HEART RATE ACCURACY BY BREAKDOWN PRESENTED WITH 95% CONFIDENCE UPPER BOUND, SENSITIVITY AND PPV

Breakdown	HR95 (bpm)	CI+ (bpm)	Sen. (%)	PPV (%)
Overall	4	4.71	90.95	99.6
Women	2.86	4.89	91.67	99.64
Men	4.32	4.95	90.22	99.56

C. Overall Results and Breakdown

The overall, OMbra and OMshirt 95th percentile heart rate accuracy are presented with the 95% confidence upper bound, sensitivity and PPV in table III. The upper bound of the 95% confidence interval on the heart rate accuracy was within 5 beats per minute for all breakdowns. Sensitivity and PPV were above 90%, which indicated a good agreement between the manual labels and algorithm. The PPV was generally higher than the sensitivity; this result can be explained because the algorithm was designed to favour heart rate precision over sensitivity.

D. Error Characterization

This section deals with the characterization of the algorithm performance:

1. The algorithm applied a threshold to the confidence of its heart rate estimate. For segments when the confidence was below the algorithm threshold, the algorithm released a message stating it could not compute a heart rate. Table IV documents the algorithm heart rate coverage for individual files. To clarify, coverage measured the time when the algorithm was able to compute a heart rate relative to the time of the entire recording. Figure 3a presents an example when skin-electrode conductivity was strong enough to enable labelling of the ECG, but the algorithm was unable to compute a heart rate.

2. In cases of very poor ECG signal quality during changing heart rate, the algorithm could persist an incorrect heart rate measurement. Figure 3b presents an example when the algorithm persisted a heart rate value that was incorrect.

3. The algorithm lagged behind the labelled heart rate when heart rate variability was high. Figure 3c presents an example where the algorithm lagged behind the labelled heart rate. The total error due to algorithm lag did not exceed 1 beat per minute.

IV. CONCLUSION

The algorithm achieved the success criteria set out for the verification: The algorithm heart rate measurement was within 5 bpm of the heart rate labelled by an engineer for 95% of the time and with 95% statistical certainty. The accuracy of the OMsignal heart rate algorithm was measured to be 4 bpm with an upper 95% confidence bound of 4.71 bpm. Furthermore, average sensitivity and PPV were measured to be 90.95% and 99.6%. These secondary metrics suggested a strong agreement between the algorithm and the labelled heart rate.

TABLE IV. HEART RATE ALGORITHM COVERAGE

File ID	Record Time (min)	Coverage (min)	Coverage (%)
M01	41.24	35.82	86.9
M02	39.28	36.07	91.8
M03	32.73	30.89	94.4
M04	37.93	37.48	98.8
M05	38.61	32.26	83.6
M06	32.21	31.88	99
M07	39.95	39.69	99.3
M08	35.39	34.9	98.6
M09	50	44.58	89.2
M10	36.76	29.33	79.8
W01	13.53	6.8	50.3
W02	9.71	9.64	99.3
W03	13.68	12.68	92.7
W04	9.28	9.23	99.5
W05	14.29	10.67	74.7
W06	15.55	15.5	99.7
W07	14.41	14.34	99.5
W08	10.41	9.34	89.7
W09	9.43	9.38	99.5
W10	13.23	13.18	99.6

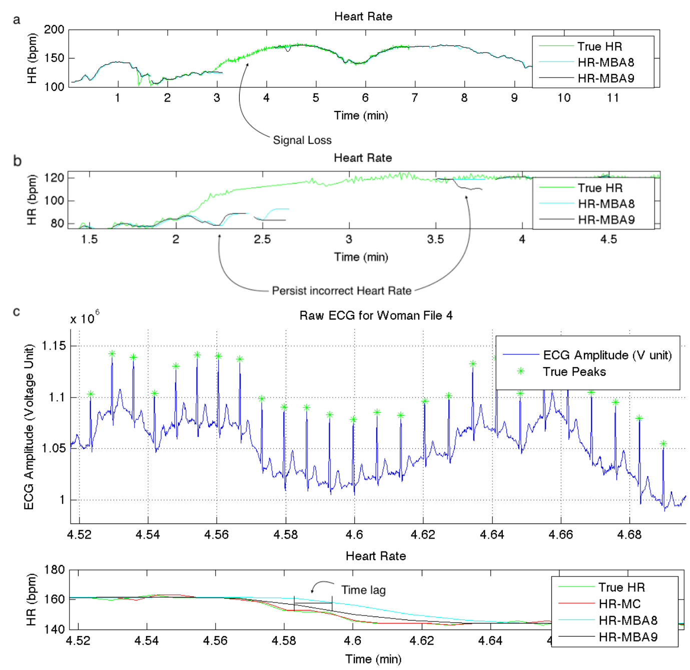

Fig. 3. (a) Algorithm unable to compute heart rate for section of poor skin-electrode conductivity. (b) Algorithm persisted an incorrect value in cases where the ECG signal quality was very poor during a changing heart rate. (c) Algorithm lagged behind the labelled heart rate. Total error due to lag did not exceed 1 bpm. True HR denotes the labelled heart rate and HR-MBA9 denotes the algorithm heart rate.

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