Matched Pairs T-Test Analysis Of Regression Model For Enhancement Of Measurement Accuracy Of Microcontroller-Based Heartbeat Measurement Device

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***Abstract*— In this paper, matched pairs t-test analysis of regression model for enhancement of measurement accuracy of microcontroller-based heartbeat measuring (MCHBM) device is presented. The heartbeat device measurement accuracy was done with respect to Pulse Oximeter CE012 IPx2 heart beat measuring device used in many hospitals. The procedure requires development of the calibration regression model which is then programed in the microcontroller, such that for every heart beat data captured using the MCHBM device, the microcontroller will automatically adjust the value based on the programed model so as to reflect the heart beat value that would have been obtained if the heart beat measurement was conducted using the Pulse Oximeter CE012 IPx2 heart beat measuring device. The algorithm used to develop the model is presented along with the flow diagram of how the real-time calibration of the MCHBM device measured heart beat data is performed. Furthermore, matched pairs t-test is conducted on the empirically measured heart beat dataset to ascertain how accurate the MCHBM device measured values were with respect to the measurements conducted using the Pulse Oximeter CE012 IPx2 heart beat measuring device. A quadratic regression model was also developed to enhance the measurements accuracy of the MCHBM device measured and the matched pairs t-test is conducted on the model enhance heart beat measured values. The matched pairs t-test analysis results show that the mean error in the measurement datasets was 0.039285714 before the model optimization and 0.036488095 after the optimization model was applied. Also, the standard deviation decreased from 1.144978936 before the optimization to 1.132810159 after the optimization model was applied. Similarly, the RMSE decreased from 1.190119124 to 1.166072703. Similar results were obtained when a validation dataset was used on the model. In all, the results show that the regression model was effective in the improvement of the measurement accuracy of the microcontroller-based heartbeat measurement device.**

Keywords*— *Heartbeat Measuring Device, Calibration, Matched Pairs t-Test, Microcontroller-Based System, Correlated t-test, Pulse Oximeter CE012 IPx2

1. Introduction

The synergy of electronic, wired networks, fiber optics networks and wireless communication technologies have given rise to the Internet and the uncountable applications and solutions [1,2, 3, 4, 5,6, 7, 8,9, 10,11, 12,13, 14, 15, 16, 17,18, 19,20, 21,22, 23,24, 25, 26, 27, 28]. Today, wireless sensor networks, Internet of Things, smart systems, web and mobile applications, intelligent software solutions, and various forms of embedded systems are just some notable applications of the electronic, software and communication technologies [29,30,31, 32, 33, 34, 35, 36,37, 38,39,40, 41,42,43,44,45, 46,47,48,49,50,51, 52, 53,54, 55,56,57, 58, 59,60, 61,62, 63,64]. Furthermore, the use of web application to interface with embedded firmware program output has also made it possible to facilitate remote storage, processing and control of embedded systems [65,66,67]. In this paper, the application of electronic and wireless communication technologies, as well as web application to a microcontroller-based heartbeat measurement device presented is presented [68,69,70,71,72].

Notably, the microcontroller-based heartbeat measurement device presented in this paper is designed for capturing and transmitting heartbeat measurements for storage on an online database. It is equipped with suitable sensor, microcontroller, and connectivity to the Internet via wireless network access module. It has the relevant embedded firmware and online hosted web application for remote storage of the heartbeat measurements.

However, the essence of this paper is to improve the measurement accuracy of the heartbeat measurement device by using a model to tune or calibrate the actual measurements of the device to reflect the heartbeat measurements that would have been obtained if the measurements were conducted using a a standard reference heartbeat measurement device. In this case, the Pulse Oximeter CE012 IPx2 heart beat measuring device is used as the reference heartbeat device [73,74]. Empirical measurements were conducted with the reference device and the microcontroller-based heartbeat measuring (MCHBM) device and a regression model was fitted of the data plot which can enable the MCHBM device measured values to be tuned automatically to be as close as possible to the measurement done with the Pulse Oximeter CE012 IPx2 device. The regression model is coded in the microcontroller firmware so as to automate the tuning or calibration process in real-time. The algorithm and flow diagram pertaining to the model development and automatic implementation of the measurement calibration in real-time are presented.

Finally, the heartbeat measurement calibration regression model effectiveness is evaluated using matched pairs t-test analysis [75,76,77,78,79]. In the implementation approach adopted in this paper, the original MCHBM device measured heartbeat value and the corresponding model calibrated value are uploaded to the remote online wed app via the wireless internet connection module incorporated in the microcontroller-based heartbeat measurement device.

2. Methodology

The focus of this paper is to present an approach that can be used to enhance the measurement accuracy of heartbeat data captured with a microcontroller-based heart beat measuring (MCHBM) device. The heartbeat device measurement accuracy was done with respect to Pulse Oximeter CE012 IPx2 heart beat measuring device used in many hospitals. The procedure requires development of the calibration model which is then programed in the microcontroller, such that for every heart beat data captured using the MCHBM device, the microcontroller will automatically adjust the value based on the programed model so as to reflect the heart beat value that would have been obtained if the heart beat measurement was conducted using the Pulse Oximeter CE012 IPx2 heart beat measuring device.

The algorithm used to develop the model is presented in ***Procedure 1*** while the flow diagram in Figure 1 shows how the real-time calibration of MCHBM device measured heart beat data is performed. Specifically, ***Procedure 1*** shows that a set of paired heart beat measurements are conducted using the MCHBM device and Pulse Oximeter CE012 IPx2 heart beat measuring device. Then, the error performance between the MCHBM device measured dataset and Pulse Oximeter CE012 IPx2 device measured dataset is performed using mean error (ME) and root mean square error (RMSE). Furthermore, **matched pairs t-test** is conducted on the paired dataset to ascertain how close the mean of the two datasets are.

Next, the graph of the MCHBM device measured dataset versus Pulse Oximeter CE012 IPx2 device measured dataset is plotted in Microsoft excel and the trend line tool in MS Excel is used to fit is appropriate quadratic regression model for estimating the Pulse Oximeter CE012 IPx2 device measured dataset from the MCHBM device measured dataset. Again, error performance between the model predicted dataset and the Pulse Oximeter CE012 IPx2 device measured dataset is performed using mean error (ME) and root mean square error (RMSE). Furthermore, **matched pairs t-test** is conducted on the paired dataset (that is, the predicted dataset and the Pulse Oximeter CE012 IPx2 device measured dataset) to ascertain how close are the mean of the two datasets.

The MCHBM device is designed such that it can store its measured dataset, it can display the calibrated data in real-time and it can transmit the raw data and the calibrated data to an online data storage server. Hence, after the model is developed, it is programed into the firmware of the microcontroller such that whenever new heart beat data is captured, the system follows the flow diagram of Figure 1 to automatically calibrate and display the calibrated heart beat value.

Procedure 1: **The Algorithm for generating the regression model using empirically paired heartbeat data measurements**

Step 1: Start

Step 2: Set the target number, n of paired heartbeat data capture for the model development

Step 3: Take the paired heartbeat RM(x) measurement, first with the MCHBM device and second HM(x) with the Pulse Oximeter for data record count x = 1, 2, 3, …, n

Step 4: Compute $Mean\ Error = \left(\frac{1}{n}\right)\left[\sum_{x=1}^{n}\left(\mathrm{RM(x)} - \mathrm{HM(x)}\right)\right]$

Step 5: Compute $RMSE = \sqrt[2]{\left(\frac{1}{n}\right)\left[\sum_{x=1}^{n}(RM(x) - HM(x))^2\right]}$

Step 6: Compute $\mathrm{dRH(x)} = \mathrm{RM(x)} - \mathrm{HM(x)}$ for x = 1, 2, 3, …, n

Step 7: Conduct matched pairs t-test on dRH(x) at 95% confidence level

Step 8: Plot the graph of HM(x) verssus RM(x)

Step 9: Use trend line tool in Microsoft Excel to fit in a quadratic regression model on the graph plot for predicting HM(x) from the values of RM(x)

Step 10: Generate predicted value of $PHM(x)$ for every given RM(x) for data record count x = 1, 2, 3, …, n

Step 11: Compute $Mean\ Error = \left(\frac{1}{n}\right)\left[\sum_{x=1}^{n}\left(\mathrm{RPHM(x)} - \mathrm{HM(x)}\right)\right]$

Step 12: Compute $RMSE = \sqrt[2]{\left(\frac{1}{n}\right)\left[\sum_{x=1}^{n}(PHM(x) - HM(x))^2\right]}$

Step 13: Compute $\mathrm{dPH(x)} = \mathrm{PHM(x)} - \mathrm{HM(x)}$ for x = 1, 2, 3, …, n

Step 14: Conduct matched pairs t-test on dPH(x) at 95% confidence level

Step 15: Stop

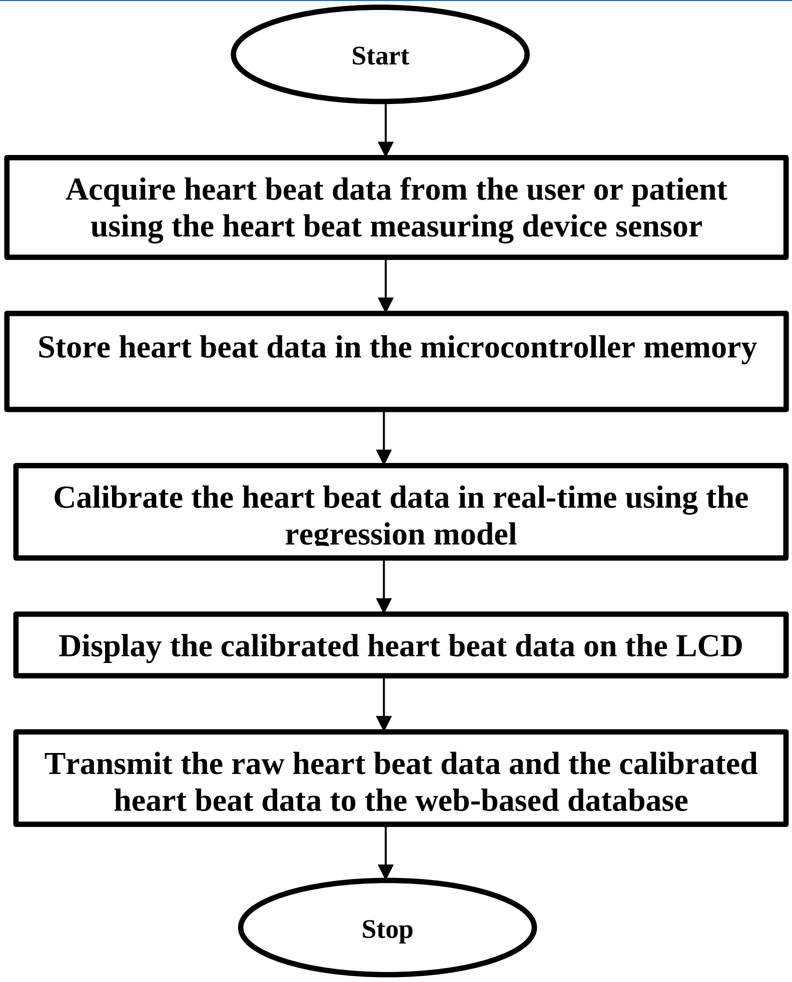

Figure 1 The flow diagram for the real-time calibration of the heart beat data captured using the microcontroller-based heart beat measuring (MCHBM) device

3. Results and Discussion

The field measured 104 heart beat data records captured using the MCHBM device (denoted as RM(x) Heartbeat (Bpm)) and Pulse Oximeter CE012 IPx2 heart beat measuring device (denoted as HM(x) Heartbeat (Bpm)) are presented in Table 1 and Figure 2. The matched pairs t-test analysis was conducted on the 104 data pairs of heart beat data records and the summary of the results are presented in Figure 3 and Table 2. Again, the quadratic regression model (Equation 1) was developed for estimating the expected Pulse Oximeter CE012 IPx2 heart beat measuring device reading (denoted as y in Equation 1) for a given MCHBM device measured heart beat value (denoted as x in Equation 1).

$$y = -0.001212x^2 + 1.190169x - 7.110458 \quad (1)$$

The quadratic regression model (Equation 1) was used to predict each of the field measured 104 heart beat data records captured using the Pulse Oximeter CE012 IPx2 heart beat measuring device based on the corresponding MCHBM device measured values and the results are presented in Figure 4 while the matched pairs t-test analysis results are presented Figure 5.

The matched pairs t-test analysis results show that the mean error in the measurement datasets was 0.039285714 before the model optimization and 0.036488095 after the optimization model was applied. Also, the standard deviation decreased from 1.144978936 before the optimization to 1.132810159 after the optimization model was applied. Similarly, the RMSE decreased from 1.190119124 to 1.166072703.

Table 1 The field measured 104 heart beat data records captured using the MCHBM device and Pulse Oximeter CE012 IPx2 heart beat measuring device

RM(x) Heartbeat (Bpm)	HM(x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	HM(x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	HM(x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	HM(x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	HM(x) Heartbeat (Bpm)
55.0	56.3	72.3	73.3	79.9	81.9	87.4	87.0	93.3	91.0
55.6	55.6	72.9	71.0	79.9	78.0	88.9	89.0	93.9	90.0
60.0	61.3	73.4	73.2	80.6	80.0	89.0	89.2	94.0	94.0

62.4	62.0	74.3	74.0	80.9	82.0	89.4	89.9	94.7	95.0
63.7	63.6	74.4	74.5	81.0	81.1	89.6	90.0	94.7	96.0
64.3	65.0	74.7	76.0	82.2	82.0	89.7	90.8	94.9	95.0
64.7	64.0	75.2	75.0	82.7	82.0	89.9	90.7	95.3	96.0
64.8	65.3	76.6	78.0	83.5	82.9	90.0	90.6	95.5	97.8
66.1	67.5	76.9	76.0	83.6	83.7	90.8	91.4	96.0	98.0
67.4	68.0	77.1	76.0	84.0	84.9	91.0	91.8	96.4	97.0
67.5	68.5	77.9	78.3	84.1	86.0	91.4	92.0	96.9	95.0
68.1	68.8	78.6	79.0	84.4	84.8	91.5	92.0	97.2	95.0
68.5	70.0	78.7	82.0	84.6	86.5	91.9	92.0	97.7	99.0
69.4	68.5	78.8	79.0	85.1	85.0	92.0	92.0	98.6	99.0
69.9	70.0	79.7	79.0	85.5	86.0	92.5	91.8	98.8	97.0
71.4	72.0	79.7	77.0	85.7	86.0	93.0	92.5	99.2	101.0
71.6	73.0	79.9	81.9	86.9	87.0	93.1	92.0	99.5	100.0

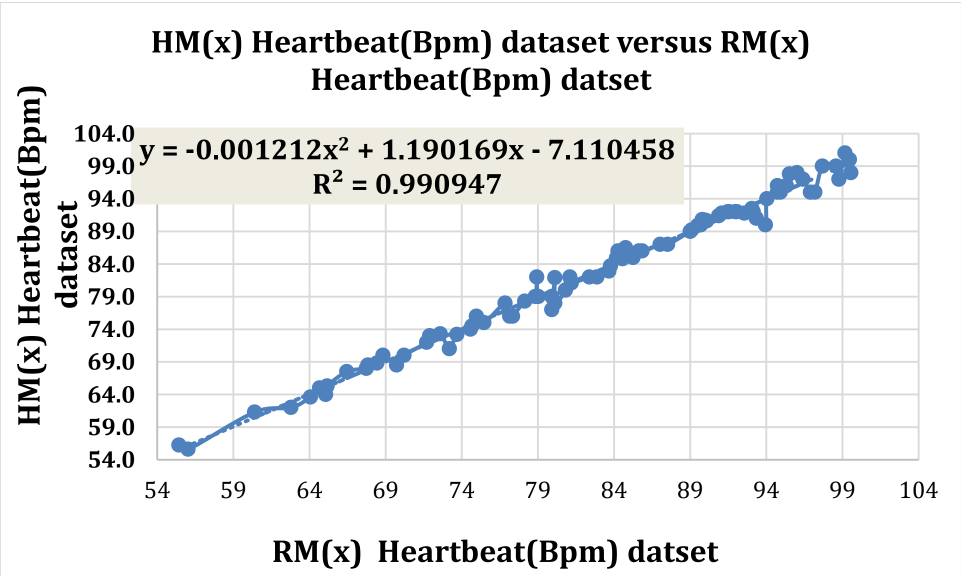

Figure 2 The graph of the field measured 104 heart beat data records captured using the Pulse Oximeter CE012 IPx2 heart beat measuring device versus the heart beat data records captured using the MCHBM device

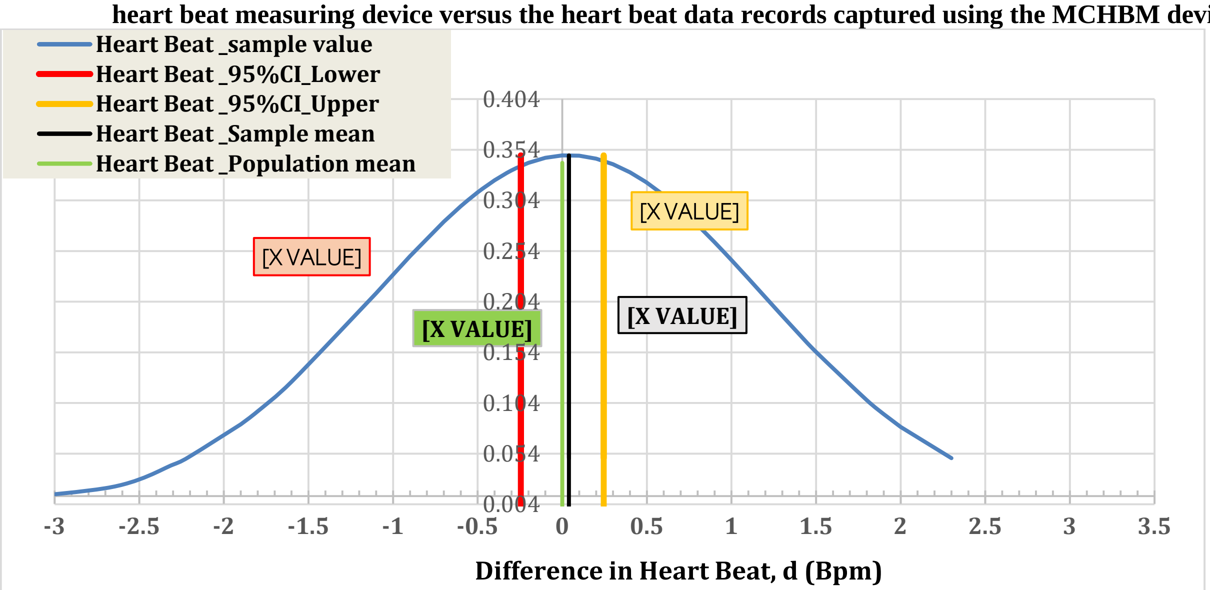

Figure 3 The matched pairs t-test analysis results for the 104 data pairs of heart beat data records without model optimization

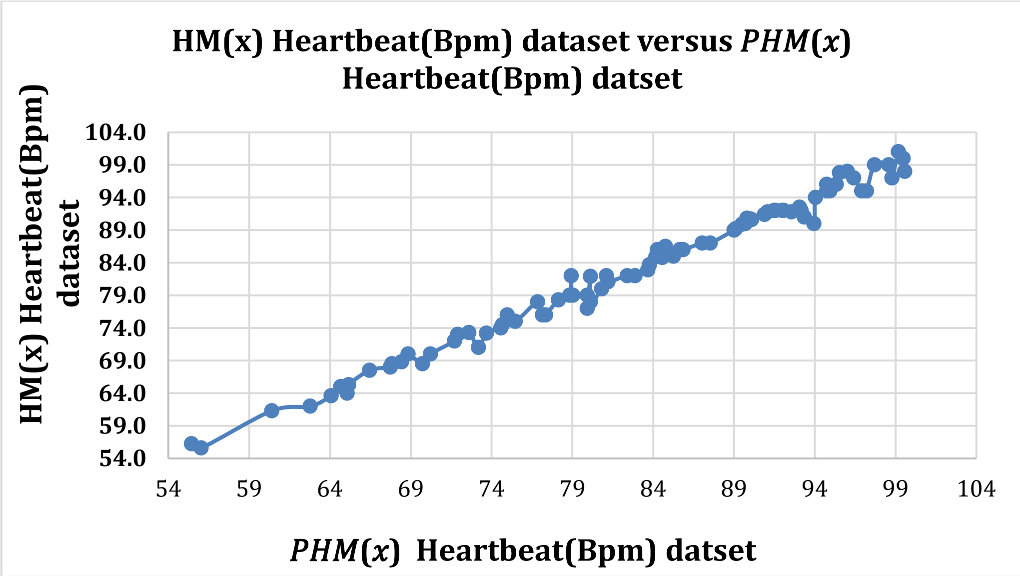

Figure 4 The graph of the field measured 104 heart beat data records ($HM(x)$) captured using the Pulse Oximeter CE012 IPx2 heart beat measuring device versus the optimization model predicted values ($PHM(x)$) based on the corresponding MCHBM device measured values

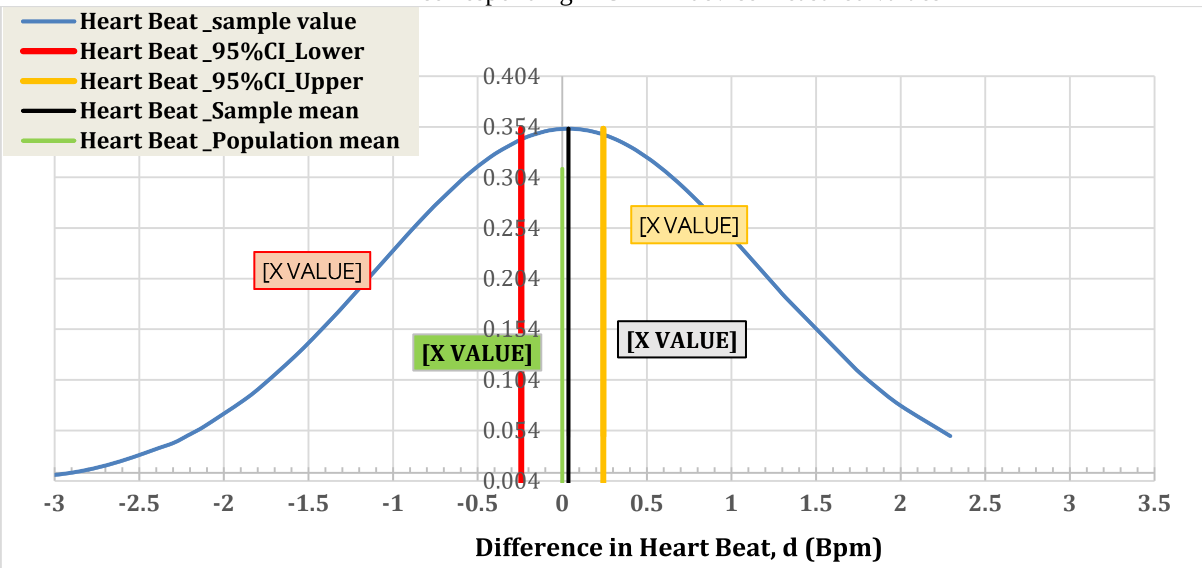

Figure 5 The matched pairs t-test analysis results for the 104 data pairs of heart beat data records obtained with optimization model

Table 2 The matched pairs t-test analysis results for the 104 data pairs of heart beat data records without model optimization and with the model optimization

1	RMSE	1.190119124	1.166072703
	Matched pairs t-test results		
2	Statistical parameter	Statistical value	Statistical value
3	Sample Mean	0.039285714	0.036488095
4	Sample Standard Deviation	1.144978936	1.132810159
5	Population Mean of difference	0	0
6	95% confidence interval; acceptable lower limit for sample mean	-0.245107645	-0.242502654
7	95% confidence interval; acceptable upper limit for sample mean	0.245107645	0.242502654

After the model was developed and evaluated , about 63 validation heart beat data records were captured using the MCHBM device (denoted as RM (x)) and Pulse Oximeter CE012 IPx2 heart beat measuring device (denoted as HM (x)) and also predicted using the optimization model (denoted as PHM (x)). The 63 data records were also subjected to the matched pairs t-test analysis and the results in Table 3 show that the mean error for the validation dataset without the prediction model was -0.030412 but with the optimization model the mean error deuced to -0.028253 after the optimization model was applied. In all, the optimization model has effectively reduced the mean error and improved on the measurement accuracy of the evaluated microcontroller-based heartbeat measurement device.

Table 3 The measured and predicted 63 validation heart beat data records captured using the MCHBM device (denoted as **RM (x)**) and Pulse Oximeter CE012 IPx2 heart beat measuring device (denoted as **HM (x)**) and also predicted using the optimization model (denoted as P**HM (x)**)

S/N	HM (x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	PHM(x) Heartbeat (Bpm)	S/N	HM (x) Heartbeat (Bpm)	RM(x) Heartbeat (Bpm)	PHM(x) Heartbeat (Bpm)
1	58.8	59	59.5	32	86.5	86.3	86.43
2	62.8	63.05	63.5	33	88	87.9	88.01
3	63.8	64.2	64.63	34	89.1	88.95	89.05
4	64.65	64.75	65.17	35	89.6	89.3	89.39
5	66.65	66.1	66.51	36	90.4	89.65	89.74
6	68.25	67.45	67.84	37	90.7	89.85	89.93
7	68.25	68	68.38	38	91	90.4	90.48
8	69.25	68.95	69.32	39	91.7	91.1	91.17
9	70.25	70.4	70.75	40	92	91.45	91.51
10	72.5	71.5	71.83	41	92	91.75	91.81
11	72	72.25	72.57	42	91.9	92.25	92.3
12	72.1	73.15	73.46	43	91.9	92.8	92.84
13	73.85	73.9	74.2	44	91.5	93.2	93.24
14	75.25	74.55	74.84	45	92.5	93.65	93.68
15	77	76.65	76.91	46	94.5	94.35	94.37
16	77	76.75	77.01	47	95	94.8	94.82
17	77.15	77.4	77.65	48	95.5	95.1	95.11
18	78.65	78.25	78.49	49	97	95.65	95.66
19	79	78.7	78.93	50	97.5	96.2	96.2
20	79	79.25	79.48	51	96	96.8	96.79
21	80.45	79.8	80.02	52	97	97.45	97.43
22	79.95	79.9	80.12	53	98	98.25	98.22
23	80	80.4	80.61	54	99	99	98.96
24	81.55	80.95	81.15	55	99.5	99.4	99.35
25	81.55	81.85	82.04	56	77.13	77.3	77.55
26	82.45	83.1	83.28	57	58.78	57.5	58.02
27	83.9	83.75	83.92	58	63.15	62.15	62.61
28	85.45	84.05	84.21	59	66.25	65.2	65.62
29	86.25	85.35	85.49	60	68.15	67.1	67.49
30	85.75	84.85	85	61	69.4	69	69.37
31	85.5	85.4	85.54	62	71.65	71.1	71.44
32	86.5	86.3	86.43	63	98	99.6	99.55
					Mean Error (Bpm)	-0.030412	-0.028253
					RMSE (Bpm)	1.1743673	1.1525473
					Sample Standard Deviation (Bpm)	1.2032144	1.090273

3. Conclusion

The measurement accuracy of a microcontroller-based heartbeat measurement device is evaluated and a regression model was developed to enhance the measurement accuracy of the measuring device. The measurement accuracy of the heartbeat measuring device was examined in respect of Pulse Oximeter CE012 IPx2 heart beat measuring device used in many hospitals.. The matched pairs t-test approach was used for the statistical evaluation of the field measured and predicted empirical heartbeat datasets. In all, the results show that the regression model was effective in the improvement of the measurement accuracy of the microcontroller-based heartbeat measurement device. Notably, the mean error, the root mean square error and the standard deviation were all reduced by the use of the regression model.

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