ARTICLE / INVESTIGACIÓN

Heart Rate Detection using a Piezoelectric Ceramic Sensor: Preliminary results

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Abstract: Real-time vital signs monitoring, particularly heart rate, is essential in today's medical practice and research. Heart rate detection allows the doctor to monitor the patient's health status to provide immediate action against possible cardiovascular diseases. We present a possible alternative to traditional heart rate signal monitoring systems, a cardiac pulse system using low-cost piezoelectric signal identification. This system could benefit health care and develop continuous pulse waveform monitoring systems. This paper introduces a heartbeat per minute (BPM) cardiac pulse detection system based on a low-cost piezoelectric ceramic sensor (PCS). The PCS is placed under the wrist and adjusted with a silicone wristband to measure the pressure exerted by the radial artery on the sensor and thus obtain the patient's BPM. We propose a signal conditioning stage to reduce the sensor's noise when acquiring the data and make it suitable for real-time BPM visualization. As a comparison, we performed a statistical test to compare the low-cost PCS with types of traditional sensors, along with the help of 21 volunteers. Experimental results show that the data collected by the PCS, when used for heart rate detection, is highly accurate and close to traditional sensor measurements. Therefore, we conclude that the system efficiently monitors the cardiac pulse signal in BPM.

Key words: Heart rate, Piezoelectric, BPM, Pulse Detection.

Introduction

Heart rate detection is critical for health care and plays a crucial role in preventing cardiovascular disease. In recent years, the number of people with cardiovascular problems has raised[1]. By studying these signals, diseases and physiological changes in the human body can be detected using sensors connected to a computer or heart rate system[2]. The radial pulse contains rich information about the human cardiovascular system[3]. Heart rate monitoring is of great importance in preventing disease. Increasing medical costs due to increased patients with noncommunicable diseases (NCD) have become a critical problem worldwide[4]. One of the main NCDs is cardiovascular disease.

Portable devices are convenient for monitoring biosignals and physical activities in daily life. Monitoring biosignals using portable devices can contribute to early disease detection[5]. Electrocardiography (ECG) is the established method to record the human heart rate[6]. Although several biomedical devices detect heart rate, a portable heart rate system based on piezoelectric identification could be a possible alternative to traditional sensors. In this paper, we propose a cardiac pulse system using PCS; this sensor is widely used in recent studies and fast processes. The PCS is used in studying pulsed disturbances of condensed media[7] due to its high sensitivity, high robustness, and low cost[8]. In the last two decades, interest in developing new technologies with the use of piezoelectric sensors has expanded[9]. The need for a low-cost sensor is due to the high demand and low supply of these devices in cardiovascular disease prevention.

In the past, heart rate alteration was not considered one of the risk factors for cardiovascular disease, but now every doctor must have access to a heart rate measuring device to monitor the patient, as heart rate is the main factor influencing the effectiveness of heart disease treatment[10]. To ensure that the proposed system provides reliable results, we compared it with an XD-58C pulse sensor[11] and an Innovo oximeter[12], testing 21 volunteers between 19 and 22 years of age.

Materials and methods

The section details the materials used in developing the cardiac pulse system. The device detects the signal by piezoelectric identification, reduces signal noise, and amplifies the signal to observe the individual's BPM on LCD screen. Our main contribution to this paper is using a PCS for cardiac pulse measurement. The energy passing through the PCS is generated from slight body movements[13].

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Piezoelectric sensors have already been used to measure a specific body part[14]. Figure 1 displays a block diagram of the procedure.

Subsection

Figure 2 displays the prototype design and its components: PCS, Arduino one, LCD screen, pass-band filter, and signal amplification. Figure 2 also shows the hardware connection: the incoming communication between the PCS and the Arduino (red arrow), and the outgoing communication between the Arduino and the LCD (yellow arrow)[15]. Table 1 describes the electronic item used[16]. Finally, Figure 3 shows the system developed in Proteus[17].

Signal conditioning

We designed a bandpass filter and a signal amplifier to correct heart rate measurement and reduce the noise produced by the PCS. The bandpass filter consists of a low and high pass filter. Filter pass-through information limiters are used to limit the passage of specific frequencies located within a given bandwidth and to attenuate those outside this width[22,23]. Thus, we get a signal with less noise and an optimal appreciation for BPM calculation and measurement.

BPM measurement

According to (8), when the PCS undergoes slight deformation, electrical charges are generated in the sensor's flat area, and in this way, pressure changes in the sensor can be captured. When a person uses the PCS under the wrist, the sensor will suffer a slight deformation due to the movements generated by blood circulation in the radial artery. Once we obtain this pressure data through the PCS, this information has to be analyzed to measure the BPM of the person[24]. The BPM is calculated by obtaining the maximum points per minute of the filtered and amplified heart pulse wave from the PCS reading [Figure 2]. As shown in Figure 4, the radial artery originates along with the ulnar artery; this artery can be divided into three segments: the proximal segment in the forearm, the middle segment, and the distal segment that passes from the wrist to the dorsal side of the hand[25]. For the sensor to have optimal functionality, it must be placed over the radial artery in the distal part of the forearm, and the patient must be at rest so that sudden movements do not affect the signal obtained by the PCS.

Results Display

The cardiac pulse analysis is performed on an Arduino

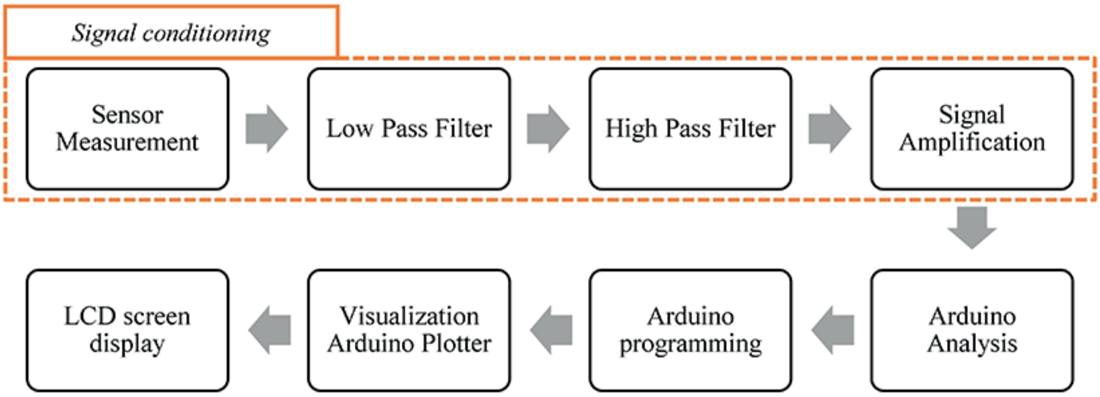

Figure 1. Block diagram representing the methodology. The pulse system design consists of four main stages: (a) electronic device design, (b) signal conditioning, (c) BPM evaluation, (d) results in visualization.

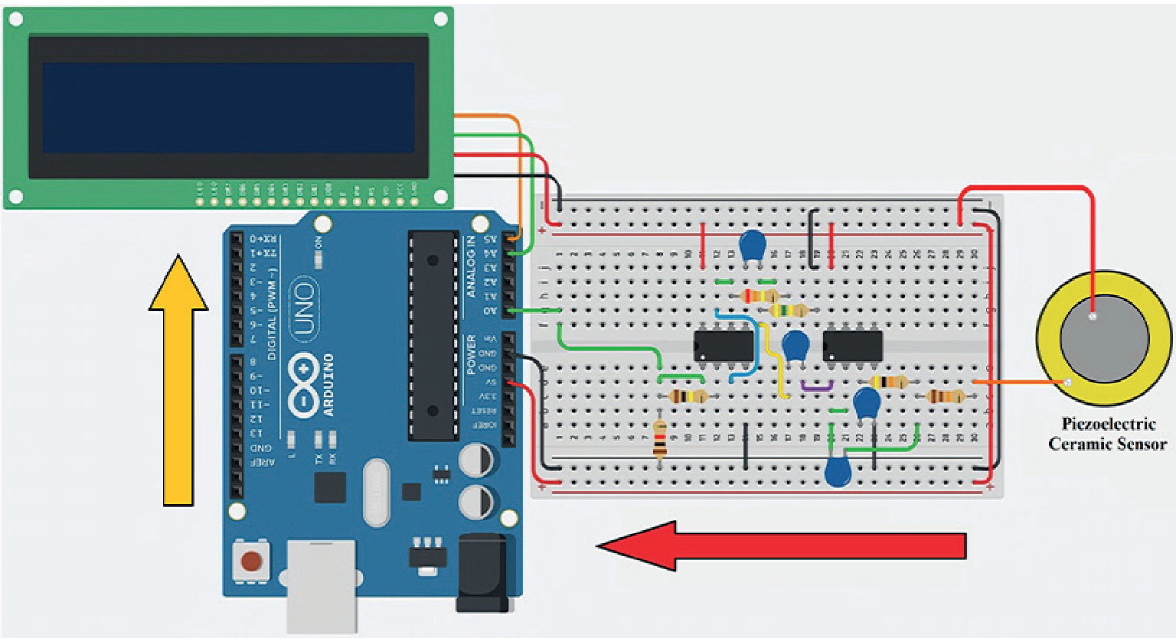

Figure 2. Pulse system hardware using piezoelectric signal identification. The red arrow reflects the incoming communication to the Arduino, and the yellow arrow reflects the outgoing communication from the Arduino to the LCD.

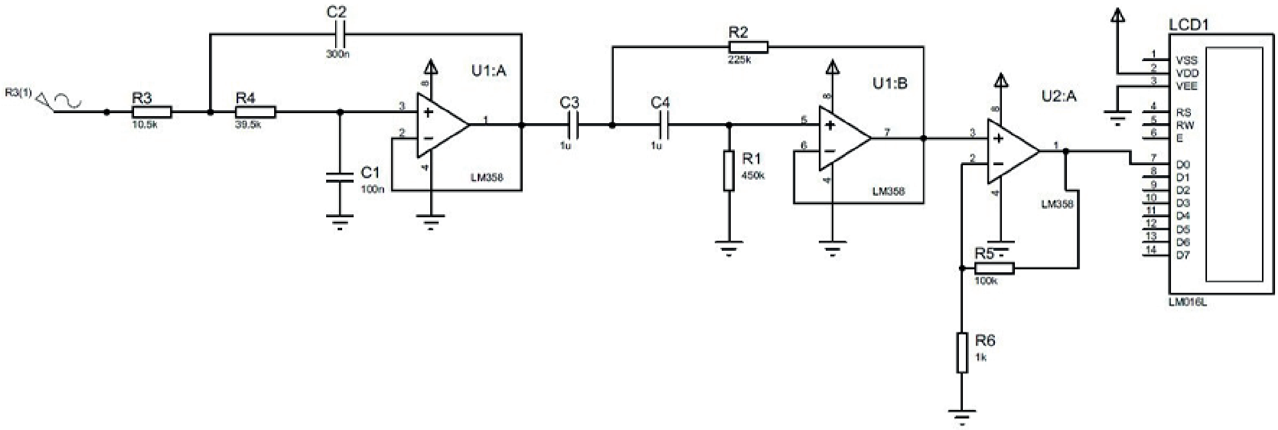

Figure 3. The pulse system's technical design, which includes the sensor signal input, resistors, capacitors, logic gates, and LCD display, was created in proteus software.

Element	Description
Arduino[18]	The Arduino one is a large, complete, friendly board that receives the sensor's data.
Piezoelectric Ceramic Sensor[19]	Piezoelectric elements help detect vibration by scanning the output voltage. For example, the BPM from the radial artery
Display LCD[20]	Primary LCD 16x2 (16 characters per 2 lines). Black text on a green background. Helpful in displaying BPM.
PIC LM311[21]	The microcontroller used in the filter passes signals within a certain range for signal conditioning.

Table 1. Description of the electronic components of the pulse system.

board, which allows us to add an LCD screen, and, together with our programming, shows the patient's BPM on the screen. Arduino Serial Plotter[26], with the help of a computer, shows the heart rate wave in real-time. As shown in Figure 5-a, the heart rate wave without signal conditioning is difficult to analyze for measuring the BPM. Figure 5-b shows the heart pulse wave with signal conditioning that allows the BPM to be calculated. Figure 4 shows the correct PCS position to obtain the necessary information to measure the heart pulse.

Experimental Framework

The data collected from volunteers between 19 and 22 years of age. It was chosen to employ a sample of healthy persons, in a defined age range, without preexisting diseases, decreasing the variability between age groups to study the reaction of the sensor versus commercial analogs. The PCS was placed on the radial artery with a flexible and comfortable silicone echo bracelet. The patient was seated and stayed comfortable while the heart rate measure was taken.

The patient does not move during the heart rate measurement because of the important relationship between the movement or the external manipulation of the sensor and the person under study. We compared each patient's heart rate using a table with the results from the PCS, the XD-58d heart pulse sensor, and the Innovo oximeter. We assess the quality of the measure using the Repeated Measures Analysis of Variance (rANOVA) statistical approach, which evaluates the differences between several variables' values[27]. It allows us to analyze the data and shows whether the PCS is statistically acceptable compared to traditional cardiac pulse measurement sensors.

Results

Data collection, BPM visualization, and statistical visualization

We assessed the heart rate of 21 participants between 19 and 22 years of age, who exhibited a positive evaluation of the data. Figure 6 displays the suggested pulse system and demonstrates that it successfully estimates the volunteer's BPM. The signal acquired by the piezoelectric behavior sensor estimates the pressure exerted by the blood circulating through the radial artery, so if this signal has a variation known as cardiac pulse, this signal has noise due to what passes through the band pass filter and ends up in the Arduino, which is in charge of displaying the individual's BPM on the LCD display. Table 2 presents the data received from participants at BPM.

Software is used to represent the results of sample data more optimally. Figure 7 shows a histogram of the patient's BPM. We infer that the data follow a normal distribution. Most of the recorded values are within the 70 to 80 BPM range.

The measure of comparison and quality

We check the quality of the measurements using the repeated measures ANOVA (rANOVA) statistical method that validates the quality of the results. We compare the resulting F-value with the F-value from the distribution table. This comparison provides us with rich information about whether or not there is a good relationship between the measurements from the three types of sensors. Our null hypothesis proposes a relationship between the data from the

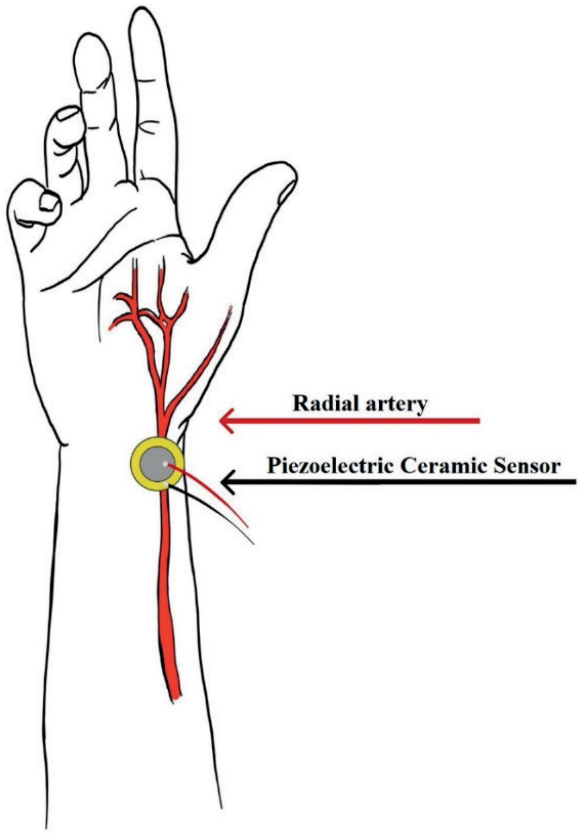

Figure 4. Proper placement of the piezoelectric sensor.

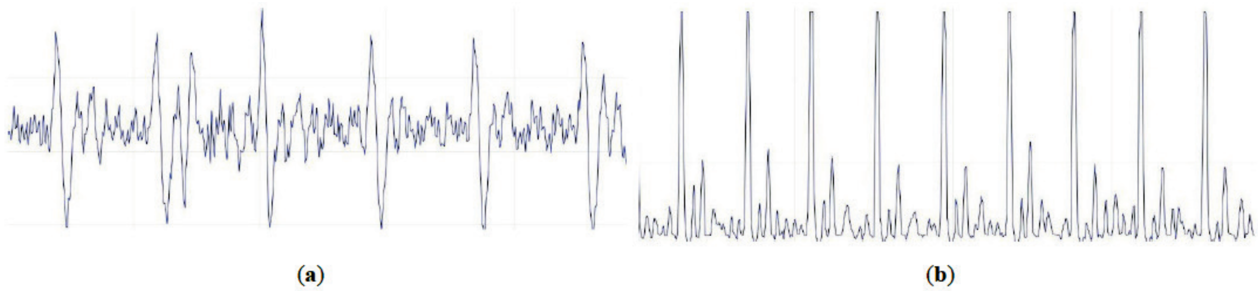

Figure 5. This figure shows the behavior of the signal, which changes due to the proper use of the bandpass filter to reduce noise efficiently. (a) Heart pulse wave without signal conditioning and (b) Heart pulse wave with signal conditioning plotted on Arduino serial plotter.

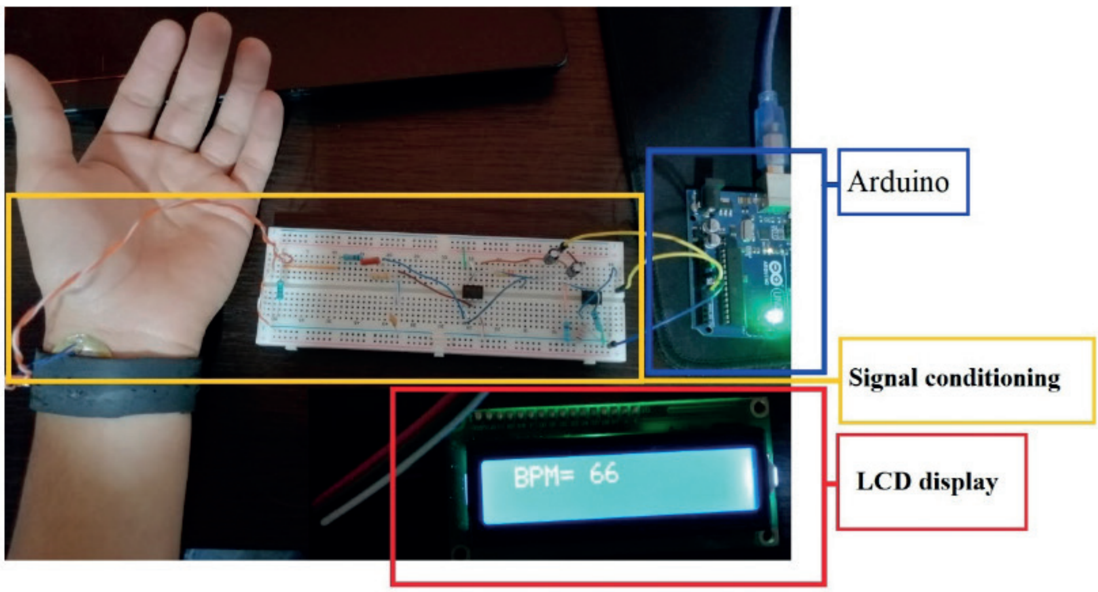

Figure 6. Location of the piezoelectric ceramic sensor attached to the silicone bracelet on the wrist. Signal conditioning stage, Arduino, and LCD screen displaying the BPM.

Data	Age	PCS	XD-58C	Oximeter
1	19	73	71	72
2	19	70	71	71
3	19	66	64	65
4	19	74	73	72
5	19	70	74	72
6	19	74	78	75
7	19	83	81	82
8	19	67	63	66
9	20	85	84	82
10	20	67	67	68

Table 2. BPM from patients between 19 and 22 years of age, measured with piezoelectric analysis, XD-58C pulse sensor, and Innovo oximeter.

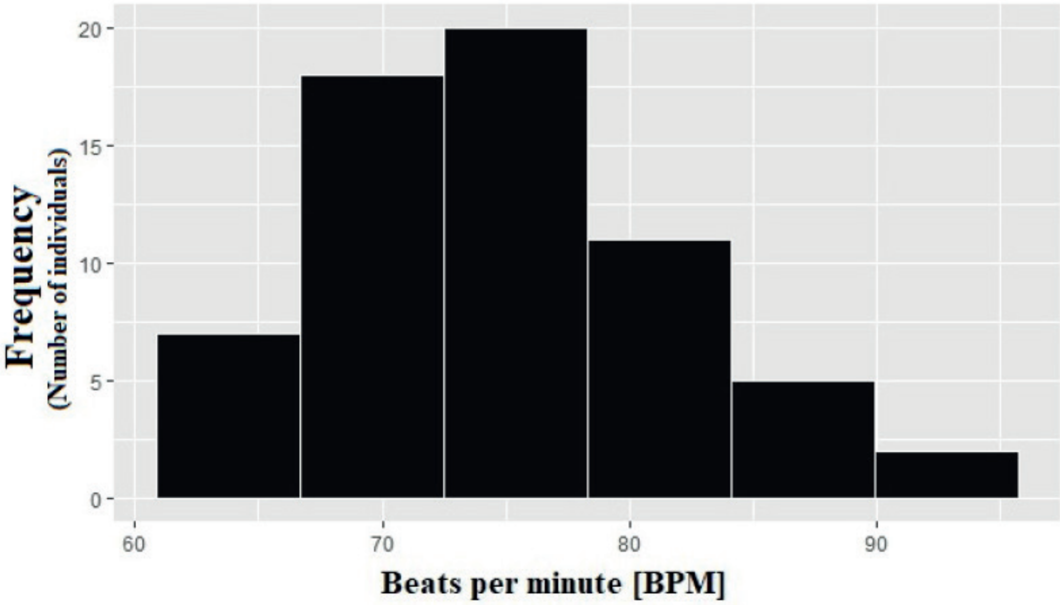

Figure 7. BPM Histogram; a normal data distribution is observed; thus, the ANOVA statistical method is carried out.

three types of sensors, whereas our alternative hypothesis establishes that at least one the three types of sensors is significantly different from the rest.

By comparing the values from each sensor, we obtain an F value of 0.07; then, our null hypothesis is not rejected. This F value, when compared with the distribution table F value, with a statistical alpha significance of $\alpha = 0.05$, shows that $0.07 = F < F\alpha = 3.52$. This indicates that the test of the relationship between the three types of sensors that measure the pulse rate is statistically acceptable. We calculate the p-value in relation to the rANOVA statistical method using the R software environment, resulting in a p-value of 0.9326. Table 3 shows the results of the rANOVA, inferring that the PCS is optimal for cardiac pulse detection. Figure 8 offers a clearer view of why the null hypothesis is not rejected; there is a high probability that the data provided by the PCS are reliable.

Table 3. The subject F value of 9.92E-04 shows that the volunteers' data values are very consistent, probably, because of the age range of 19 to 22 years. Table 4 shows that the effect of going from the oximeter to the PCS is 1 BPM, which is considered statistically irrelevant; likewise, the effect of going from the XD-58C sensor to the PCS is 0.42 BPM and considered irrelevant.

We measured an effect size of 0.0035, which allows us to compare the sum of squares and relate the variance percentage affecting the response when we change from one sensor to the other. Thus, we observe a positive impact on the total variability that has changed from one sensor to the other.

Furthermore, we measured an effect size of 0.005 for the volunteers, indicating a relationship between the volunteers' variance with a minimum variance percentage. Thus, we conclude that the three sensors produce statistically equivalent results for every individual. So, there is no evidence from the statistical analysis that allows us to reject the null hypothesis.

The means of the measures from the three types of sensors are considered statistically similar, as the null hypothesis wasn't rejected. Figure 9 shows each sensor's measures using a box plot.

Figure 9 shows the comparison between the data from the three types of sensors; we estimate they are equivalent. Therefore, we conclude that the values registered by the PCS are statistically acceptable. In figure 9, all the collected data have been considered; there are no statistically unusual or strange values (outliers) that lead to readjustments. However, the PCS shows a slight increase in its BPM measures, which means that although the sensor is optimal for everyday use, it is still possible to improve it. The sensor's operation can be retouched and optimized for future work, either by hardware calibration or a software improvement. The slight increase is not significant for the analysis presented in this paper.

Monte Carlo Simulation Analysis (MCS)

After structuring costs, the most influential cost component was direct labor, representing 53% of the total cost. The cost of culture media was 12% of the total, IMC represented 5%, and operating expenses, including administrative expenses and infrastructure, were 30% (Figure 2).

Plants propagated by SE. Figure 3 shows that the cost of plants per unit can be inferred between USD $0.6835 and USD $0.7786, with an average USD $0.7290 (Sheet 1 S2: Total cost), due to the production process's cost structure. If strict control is maintained over the variables while executing the productive lot as es-tablished in this study, the average price per plantlet has been proposed to be USD $0.7290, with a 95% reliability. However, as one may observe, there is a certain asymmetry towards the right, which indicates that the process could increase in cost. That is to say, the cost may have deviated over the average or over USD $0.7290 after moving the lot.

On the other hand, a regression was performed on the correlation coefficients of each of the cost model's variables to identify which ones influence the variable response, which is to say cost the most. This analysis showed that the most significant variables are in the productive process' last stages, corresponding to ger-mination and acclimation, followed by the maturation stage. It was specifically found that the plantlet growth (-0.69) and plantlet development (-0.60) phases, as well as the plantlet conversion phase (0.35) had more significant effects on cost, with 95% reliability. Therefore, when these variables, which are expressed as the percentage of explants' response, rise above 60%, 50%, and 50%, respectively, the variable of cost per plantlet decreases. During the embryos' development phase, both the multiplication coefficient (-0.07) and percentage of explants' response (-0.07) tend to decrease cost per plantlet as their prices increase. They are currently at 10% and 70%, respectively. Besides, it was observed that the RMR (0.15) has a positive effect on cost. Cost per plantlet will increase as RMR increases (Figure 4).

Discussion

The proposed system was tested with statistical quality measurement methods and gave positive results when calculating the heart pulse beats per minute in BPM. Compared with traditional sensors that exist today, the PCS achieves reliable results in detecting and observing the patient's BPM. The main objective of this paper is to introduce a heart rate system that employs piezoelectric signal identification as an alternative to traditional sensors; according to the GUM guide[28], based on the usual uncertainty error propagation rule, it offers us an uncertainty of 1.44 with 10 degrees of freedom, which suggests that the sensor may achieve the popular market level, given that the oximeter is the most marketed globally. However, due to the electromechanical properties of the PCS, the system works correctly under the following condition: the patient has to stay and maintain the sensor in its original position. The PCS has to remain unmoved during the heart rate detection because there is a strong relationship between the patient's move-

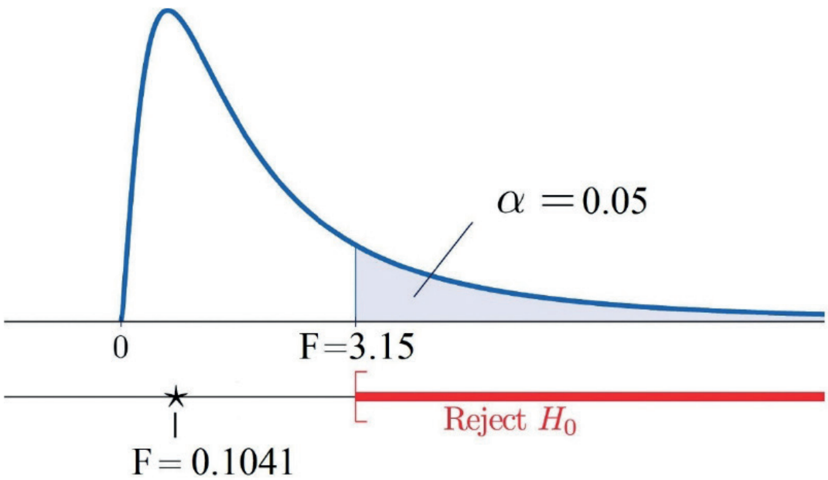

Figure 8. F-value is falling outside of the rejection region.

Resource	SS	Df	MS	F	F-table	p-value
Sensor	10.57	2	5.29	0.07	3.52	0.933
Subject	1.51	20	0.08	9.92E-04	1.84	0.999
Error	3045.63	40	76.14			
Total	3057.71	62				

Table 3. Analysis of Variance ANOVA results.

Sensor	Estimated	Error	T	Pr>|t|
PCS	1.00	2.19	0.46	0.65
XD-58C	0.42	2.19	0.19	0.85

Table 4. Statistical Analysis.

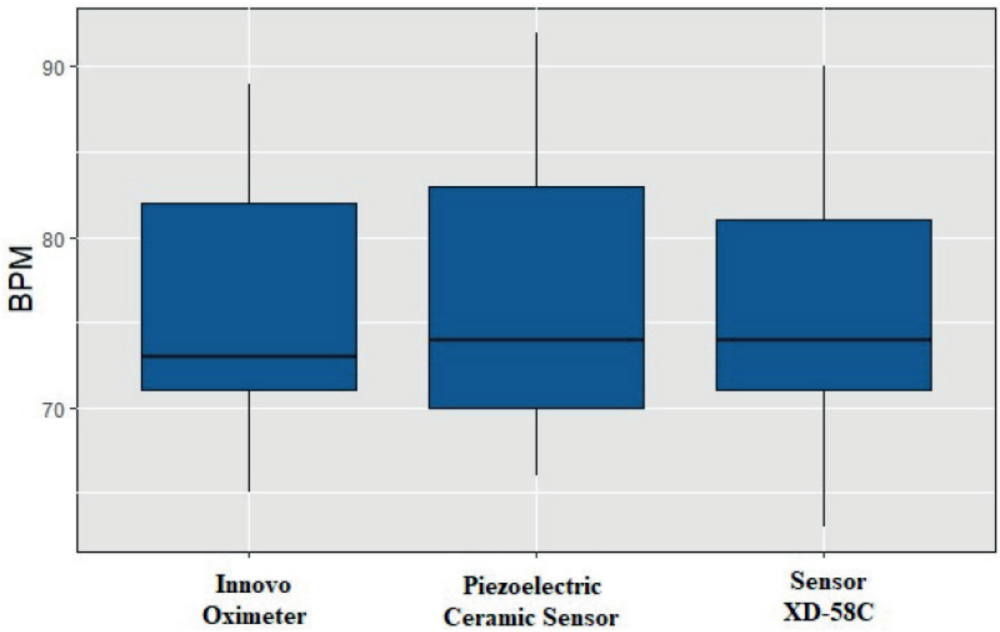

Figure 9. Statistical box plot. BOM was measured with the three types of sensors, two conventional ones for comparison with the piezoelectric ceramic sensor.

ment and the heart rate detection. PCS indicates a little rise in its BPM readings, which suggests that while the sensor is appropriate for everyday usage, there is still potential for development, so for future work, the sensor performance may be tuned and enhanced, either by hardware validation or by software updating. As for the hardware, it is advised to use a Bakelite and add more elaborated stabilizers and filters for this purpose; on the other hand, a different software must be highly beneficial to make the data acquired more trustworthy despite the rapid movement that the human may make.

Conclusions

In this paper, we implement a heart rate system employing piezoelectric signal identification to detect a patient's heart rate. The primary motivation for developing the system was to propose a low-cost, portable and immediate solution to detect possible cardiovascular diseases; the innovator oximeter costs around $20 on the market; the suggested system without the Arduino costs less than or equivalent to $5 per unit since the electrical components used are meager cost as does its sensor, which costs less than 50 cents. It is a possible alternative to the current traditional sensor that detects the pulse signal. The proposed pulse system can monitor the heart rate in real-time and thus prevent cardiovascular diseases. We carried out an experiment with 21 patients to analyze the functionality and performance of the proposed pulse system, measures of comparison and quality were implemented, and these gave positive results; We propose a comparison between the PCS, the XD-58C pulse sensor, and the Innovo oximeter, demonstrating that the PCS is an exact and reliable heart rate sensor for continuous pulse monitoring.

We conclude that the system produces positive results for pulse rate monitoring as long as the patient does not manipulate the sensor while it is monitoring the data; the patient must not make any sudden movement not correct the device location. This heart rate system is essential for people who want to know their heart rate's current status and prevent cardiovascular diseases. An experienced doctor can read this data and reach meaningful conclusions. However, not everyone can detect abnormal values within the data; therefore, for future research, we propose improving the system so that anyone can recognize the signs of abnormal heart rates. We also propose adjusting the software or the hardware to correct the non-significant increase that the PCS of the heart pule shows at the time of measuring the BPM. Finally, we suggest fixing the wristband so that the sensor remains stable and measures the BPM despite sudden arm, hand or wrist movements.

Author Contributions

EC: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing-original draft preparation, DHPO, PRM, MAB, AUC, and LR: writing-review and editing, visualization, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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