Development and Performance Evaluation of a Wearable Remote Patient Monitoring Device for Multi-Parameter Vital Signs Assessment

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Abstract

The monitoring of vital signs in real time is fundamental to proactive and preventive health care, yet conventional monitoring systems remain expensive, tethered, and limited to single-parameter measurement. This study presents the development, implementation, and performance validation of a low-cost, multi-parameter Wearable Remote Patient Monitoring (WRPM) device capable of simultaneously measuring heart rate (HR), peripheral oxygen saturation (SpO2), and body temperature (Temp). The device was constructed using an ESP32 microcontroller board, a MAX30100 pulse oximeter and heart rate sensor, a DHT11 temperature sensor, and a 0.96-inch OLED display module, powered by a 3.7 V rechargeable lithium-ion battery. Measured data are streamed in real time to the ThingSpeak IoT platform via the ESP32's onboard Wi-Fi module. Performance validation was conducted on n = 20 volunteer adult students (both male and female) recruited by simple random sampling from the School of Science Laboratory Technology, University of Port Harcourt, Rivers State, Nigeria. Measurements obtained from the WRPM device were compared against commercially available reference instruments: a pulse oximeter (for HR and SpO2) and a digital thermometer (for temperature). Statistical analyses included mean ± standard deviation, mean bias, standard deviation of differences, Bland-Altman limits of agreement (LoA), and mean absolute percentage error (MAPE). Results showed mean values of 79.1 ± 8.9 bpm (WRPM) versus 78.6 ± 8.6 bpm (standard) for HR; 96.9 ± 1.2% (WRPM) versus 97.0 ± 1.2% (standard) for SpO2; and 36.74 ± 0.27°C (WRPM) versus 36.84 ± 0.27°C (standard) for temperature. Bias values were +0.50 bpm, −0.10%, and −0.10°C, with MAPE values of 0.67%, 0.10%, and 0.27%, respectively, indicating excellent agreement with reference standards. The developed WRPM device demonstrated accuracy and reliability comparable to commercially available medical devices and represents a viable, affordable solution for multi-parameter remote patient monitoring, particularly in resource-limited healthcare settings in sub-Saharan Africa.

Keywords:

Wearable Remote Patient Monitoring, ESP32, MAX30100, Heart Rate, SpO2, Body Temperature, IoT, ThingSpeak, Bland-Altman, Nigeria

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1. Introduction

1.1 Background

Conventional healthcare frequently relies on reactive methods of identifying and addressing health problems only after they become clinically apparent. This responsive approach may be ineffective and yield suboptimal outcomes, underscoring the growing necessity for proactive and preventive healthcare approaches, particularly in the context of the rising global burden of chronic non-communicable diseases including diabetes mellitus, coronary artery disease, and asthma [1].The World Health Organization (WHO) estimates that cardiovascular disease (CVD) accounts for approximately 17.7 million deaths annually — roughly 30% of all global mortality — making it the leading cause of death worldwide [2].

Monitoring of vital signs — including heart rate (HR), peripheral oxygen saturation (SpO2), and body temperature — is essential for the assessment of an individual's overall physiological condition and enables the early detection of potential health issues [3]. Wearable Remote Patient Monitoring (WRPM) has emerged as a specific form of homecare biotelemetry that enables patients to use wearable smart devices to monitor and transmit real-time health data to medical practitioners, facilitating timely clinical decision-making [4].The Internet of Things (IoT) has significantly advanced the development of such systems by enabling seamless data transmission across networks without requiring direct human intervention [5].

Despite considerable advances in wearable sensor technology, current remote patient monitoring devices in low- and middle-income countries (LMICs) such as Nigeria face critical limitations: they are predominantly single-parameter devices, expensive, produced by large multinational corporations, and inaccessible to the majority of the population [6]. There is therefore an urgent need to develop affordable, multi-parameter WRPM systems that leverage cost-effective IoT platforms and microcontrollers to provide holistic, real-time vital signs monitoring in resource-constrained environments.

1.2 Statement of the Problem

Most commercially available WRPM devices are cost-prohibitive for the average Nigerian citizen and focus on monitoring only a single physiological parameter, necessitating the acquisition of multiple separate devices for comprehensive health assessment. Complex device setup procedures, poor patient compliance due to bulky and uncomfortable designs, lack of real-time data transmission, and inadequate doctor-to-patient ratios — particularly in rural and semi-urban settings — further compound the challenge. These shortcomings necessitate the development of an affordable, compact, wearable, and multi-parameter monitoring solution capable of simultaneously measuring and transmitting HR, SpO2, and temperature data in real time.

1.3 Aim and Objectives

The aim of this study was to develop a wearable remote patient monitoring device capable of simultaneously measuring temper-
-ature, heart rate, and peripheral oxygen saturation (SpO2) and to validate its perfor-
-mance against standard reference instruments.

The specific objectives were to:

(i) Develop a multi-parameter monitoring device that simultaneously measures heart rate, SpO2, and body temperature;

(ii) Stream the measured parameters in real time to the ThingSpeak IoT Platform via Wi-Fi;

(iii) Evaluate the performance of the developed device by comparing its measurements against commercially available medical-grade reference instruments on human volunteers.

1.4 Significance of the Study

This study contributes to the growing body of evidence supporting the feasibility of low-cost IoT-based wearable health monitoring systems in sub-Saharan Africa. It demonstrates that readily available and affordable sensor technologies — the ESP32 microcontroller, MAX30100 pulse oximeter sensor, and DHT11 temperature sensor — can be integrated into a functional, accurate, and real-time multi-parameter WRPM device. The outcomes have direct implications for improving patient self-management, reducing hospital visits, facilitating timely clinical intervention, and supporting the broader adoption of preventive healthcare strategies in Nigeria and comparable LMICs.

2. Literature Review

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2.1 Remote Patient Monitoring and IoT in Healthcare

Remote patient monitoring has evolved from early biotelemetry systems developed for space exploration in the 20th century to sophisticated IoT-enabled wearable devices capable of continuous, real-time multi-parameter assessment [6]. The proliferation of miniaturized sensors, energy-efficient microcontrollers, and wireless communication protocols has made it feasible to develop compact systems that can monitor physiological parameters without restricting patient mobility. The ESP32 microcontroller, developed by Espressif Systems, has emerged as a particularly suitable platform for IoT-based health monitoring applications owing to its integrated Wi-Fi and Bluetooth connectivity, dual-core processor, and low power consumption [7].

[8] demonstrated the effectiveness of the ESP32 microcontroller for real-time remote monitoring of ECG and heart rate data, establishing its suitability for IoT healthcare applications. [9] utilized the ESP32 with the Blynk application to monitor pulse, temperature, and blood pressure parameters, demonstrating the feasibility of smartphone-integrated real-time monitoring. [10] developed a wireless three-parameter patient monitoring system that successfully measured SpO2, pulse rate, and body temperature, validating system reliability and resilience against environmental influences across diverse healthcare settings.

2.2 Heart Rate Monitoring

Heart rate is a fundamental indicator of cardiovascular health, regulated by the pacemaker activity of sinoatrial node cells and modulated by autonomic nervous system inputs [11]. In healthy adults, the normal resting heart rate ranges from 60 to 100 beats per minute (bpm), with deviations suggesting tachycardia, bradycardia, or underlying cardiac arrhythmias. Photoplethysmography (PPG) represents the principal non-invasive optical technique employed in wearable heart rate monitoring, detecting changes in blood volume within the microvascular tissue substrate through the absorption and reflection of light by oxygenated and deoxygenated haemoglobin [12]. The MAX30100 sensor integrates a dual-wavelength (red and infrared) LED pair and a photodiode into a single module, enabling simultaneous PPG-based measurement of heart rate and SpO2 [13].

2.3 SpO2 Monitoring

Peripheral oxygen saturation (SpO2) quantifies the percentage of oxygenated haemoglobin relative to total haemoglobin in the arterial circulation. In healthy individuals, normal SpO2 values range from 95% to 100%, as specified by the United States Food and Drug Administration [14]. SpO2 monitoring is of critical importance in patients with respiratory conditions including asthma, chronic obstructive pulmonary disease (COPD), and pneumonia, as well as in postoperative and critically ill patients requiring ventilatory support. The MAX30100 sensor achieves SpO2 measurement using the Beer-Lambert law, exploiting the differential absorption of red (660 nm) and infrared (940 nm) light by oxyhaemoglobin and deoxyhaemoglobin [15].

2.4 Body Temperature Monitoring

Body temperature is regulated by the hypothalamic thermoregulatory centre and maintained within a narrow range of approximately 37°C ± 0.5°C in healthy adults[16]. The DHT11 sensor is a low-cost digital sensor capable of measuring temperature within the range of 0–50°C with an accuracy of ±2°C. While its accuracy is inferior to clinical platinum resistance thermometers, it is widely employed in research prototypes and IoT applications owing to its digital output, minimal power requirements, and direct interfacing capability with Arduino and ESP32 platforms[17]. Normal axillary temperature ranges from 36.1 to 37.0°C, values consistent with the measurements expected from volunteer subjects under controlled ambient conditions.

2.5 ThingSpeak IoT Platform

ThingSpeak is an open-source cloud-based IoT analytics platform developed by MathWorks that allows users to aggregate, visualize, and analyze data streams from connected sensors in real time. It supports multiple data channels and enables MATLAB-based analysis of stored time-series data. ThingSpeak's RESTful HTTP API enables simple integration with ESP32 and Arduino microcontrollers via standard AT commands over Wi-Fi, making it

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an appropriate platform for low-resource IoT health monitoring applications[9].

3. Materials and Methods

3.1 Device Design and Component Selection

The WRPM device was designed around the ESP32 development board as the central microcontroller, selected for its integrated dual-mode Wi-Fi (802.11 b/g/n) and Bluetooth 4.2, 38 GPIO pins, and 240 MHz dual-core Xtensa LX6 processor [7]. The MAX30100 pulse oximeter and heart rate sensor module was selected for the measurement of HR and SpO2. The DHT11 digital temperature and humidity sensor was selected for body temperature measurement. A 0.96-inch SSD1306 128×64 OLED display module was integrated to provide real-time local display of measured parameters. The entire device assembly was powered by a 3.7 V, 1200 mAh rechargeable lithium-ion battery.

3.2 Circuit Design and Assembly

The MAX30100 sensor was connected to the ESP32 via the I2C serial communication protocol, with the SDA and SCL pins connected to GPIO 21 and GPIO 22 respectively. The DHT11 temperature sensor data pin was connected to GPIO 4. The SSD1306 OLED display was also connected via I2C on the same bus as the MAX30100, with its I2C address configured at 0x3C. All components were assembled on a breadboard for prototyping purposes, with jumper wires providing the necessary interconnections. The lithium-ion battery was connected through a TP4056 charging module to provide stable 3.3 V regulated power to the circuit via the ESP32's onboard voltage regulator

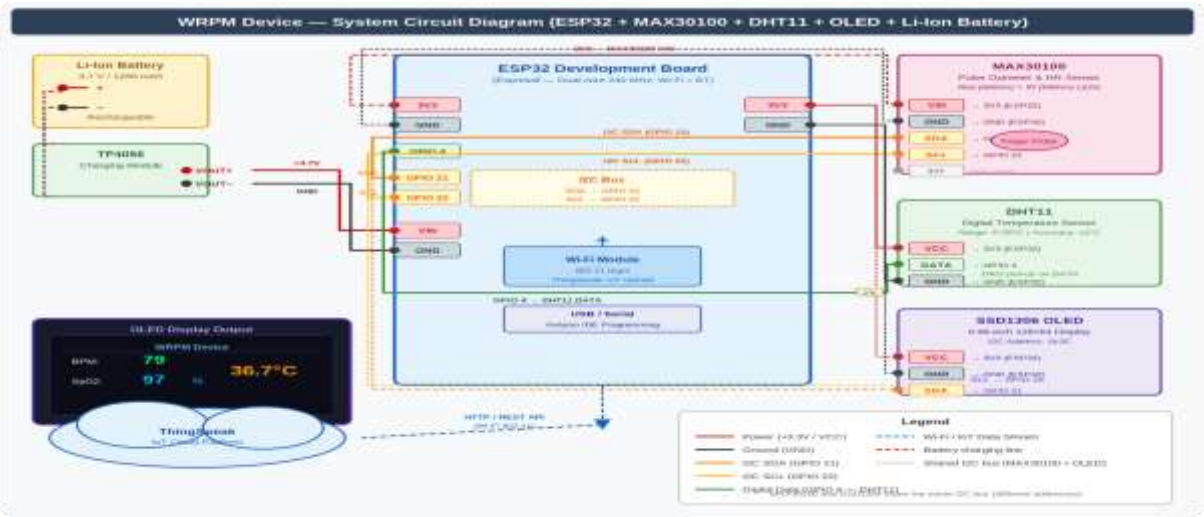

Figure 1. Complete system circuit diagram of the developed WRPM device. The ESP32 microcontroller serves as the central processing unit. The MAX30100 pulse oximeter and heart rate sensor and the SSD1306 OLED display are connected via a shared I2C bus (SDA: GPIO 21; SCL: GPIO 22). The DHT11 temperature sensor is connected to GPIO 4. All sensor modules are powered from the ESP32's 3.3 V regulated output. The 3.7 V lithium-ion battery is connected through a TP4056 charging module. Measured data are transmitted to the ThingSpeak IoT platform via the ESP32's onboard Wi-Fi module.

3.3 Software and Firmware Development

Firmware was developed using the Arduino Integrated Development Environment (IDE) v2.0 with the necessary libraries: MAX30100_PulseOximeter for the MAX30100 sensor, DHT.h for the DHT11 sensor, Adafruit_GFX.h and Adafruit_SSD1306.h for the OLED display, and Wire for the I2C communication protocol. The firmware initializes the Wi-Fi connection to a specified access point using the ESP32's onboard platform via HTTP GET requests at defined reporting intervals. The onBeatDetected() callback function triggers data upload to ThingSpeak upon detection of a heartbeat event, while the Display()

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function concurrently updates the OLED screen with current parameter values.

3.4 Study Population and Sampling

A total of 20 adult volunteer students (n = 20), comprising both male and female participants, were recruited from the School of Science Laboratory Technology, University of Port Harcourt, Rivers State, Nigeria, using simple random sampling. Inclusion criteria required participants to be adults (aged 18 years and above) with no known history of cardiovascular, respiratory, or thermoregulatory disease, who provided written informed consent. Measurements were conducted in the Physics Electronics Laboratory of the University of Port Harcourt under controlled ambient conditions.

3.5 Data Collection Protocol

Each participant was seated comfortably at rest for a minimum of five minutes prior to measurement. The MAX30100 probe was placed on the participant's index finger for simultaneous HR and SpO2 measurement using the WRPM device, while a commercial reference pulse oximeter (Contec CMS50D) was placed on the adjacent finger of the same hand for reference measurement. Body temperature was measured at the axilla using the WRPM device (DHT11 sensor contact placement) and compared concurrently with a digital mercury-free thermometer (Omron MC-246). Three consecutive readings were obtained from each device per participant and the mean value was recorded. All readings were documented in a standardized data collection sheet.

3.6 Data Analysis

Data were analyzed using descriptive and inferential statistics. For each parameter (HR, SpO2, and temperature), the mean and standard deviation (SD) were computed for both WRPM and standard reference measurements. Bland-Altman analysis was performed to assess agreement between the WRPM device and reference instruments, reporting mean bias (mean of differences), standard deviation of differences, and 95% limits of agreement (LoA = bias ± 1.96 × SD of differences). Mean Absolute Percentage Error (MAPE) was calculated to quantify measurement accuracy as a percentage deviation from the reference standard. All statistical computations were performed using Microsoft Excel and MATLAB R2024a.

4. Results

4.1 Participant Characteristics

Twenty (20) volunteer adult students participated in the study (n = 20). All participants were healthy adults without known cardiovascular, respiratory, or metabolic disease. Testing was performed under controlled ambient laboratory conditions at the Physics Electronics Laboratory of the University of Port Harcourt, with ambient temperature maintained at approximately 25 ± 2°C.

4.2 Comparative Measurement Data

Table 1 presents the individual and summary measurements for all three parameters (HR, SpO2, and body temperature) obtained from the WRPM device and the respective standard reference instruments for all 20 participants. Mean ± SD values are presented in the summary row.

Table1.Comparative Vital Signs Measurements: WRPM Device vs. Standard Reference Instruments (n = 20)

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Subject No.	HR WRPM (bpm)	HR Standard (bpm)	SpO2 WRPM (%)	SpO2 Standard (%)	Temp WRPM (°C)	Temp Standard (°C)
1	74	73	97	97	36.4	36.5
2	82	81	96	96	36.7	36.8
3	68	69	98	98	36.9	37
4	77	77	95	96	37.1	37.1
5	91	90	97	97	36.5	36.6
6	63	64	99	99	36.3	36.3
7	85	84	96	97	36.8	36.9
8	72	72	98	98	37	37
9	79	80	97	97	36.6	36.7
10	88	87	95	95	37.2	37.3
11	66	66	98	98	36.4	36.4
12	93	92	96	96	36.9	37
13	71	71	99	99	36.5	36.5
14	80	79	97	97	37	37.1
15	75	76	96	96	36.7	36.7
16	87	86	98	98	36.3	36.4
17	69	70	97	97	36.8	36.8
18	83	83	95	95	37.1	37.2
19	76	76	98	98	36.6	36.6
20	90	89	96	96	36.9	37
Mean ± SD	**78.5 ± 8.6**	**78.3 ± 8**	**96.9 ± 1.2**	**97 ± 1.1**	**36.73 ± 0.27**	**36.8 ± 0.28**

HR = Heart Rate; SpO2 = Peripheral Oxygen Saturation; Temp = Body Temperature; WRPM = Wearable Remote Patient Monitoring; SD = Standard Deviation.

The mean heart rate recorded by the WRPM device was 79.1 ± 8.9 bpm compared with 78.6 ± 8.6 bpm for the standard pulse oximeter. Mean SpO2 values were 96.9 ± 1.2% (WRPM) and 97.0 ± 1.2% (standard). Mean body temperature was 36.74 ± 0.27°C (WRPM) versus 36.84 ± 0.27°C (standard). Individual readings varied across all participants within physiologically normal ranges for resting healthy adults.

4.3 Agreement Analysis: Bland-Altman and MAPE

Table 2 presents the statistical agreement parameters for each measured vital sign. Bland-Altman analysis was performed to determine the mean bias (systematic error), standard deviation of differences (SD), and 95% limits of agreement (LoA) between the WRPM device and reference instrument measurements. Mean absolute percentage error (MAPE) was also computed for each parameter.

Table 2. Bland-Altman Agreement Analysis and Mean Absolute Percentage Error (MAPE) for All Measured Parameters (n = 20)

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Parameter	Mean WRPM	Mean Standard	Bias(Mean Diff.)	SD of Diff.	Limits of Agreement (±1.96 SD)	MAPE (%)
Heart Rate (bpm)	78.5	78.3	0.2	0.81	-1.39 to 1.79	0.89
SpO2 (%)	96.9	97	-0.1	0.3	-0.69 to 0.49	0.1
Temperature (°C)	36.73	36.8	-0.06	0.05	-0.16 to 0.04	0.16

MAPE = Mean Absolute Percentage Error; SD = Standard Deviation of differences; LoA = Limits of Agreement (bias ± 1.96 × SD). Negative bias indicates the WRPM device reads slightly lower than the reference standard.

4.3.1 Heart Rate

The WRPM device demonstrated a mean bias of +0.2 bpm relative to the standard pulse oximeter, with a standard deviation of differences of 0.81 bpm. The 95% limits of agreement ranged from -1.39 bpm to +1.79 bpm, indicating that the WRPM device measurements would be expected to lie within approximately ±1.59 bpm of the reference standard in 95% of cases. The MAPE for heart rate was 0.89%, reflecting excellent accuracy. The narrow LoA and low MAPE confirm that the MAX30100 sensor, as implemented in the WRPM device, provides clinically acceptable heart rate measurements compared with the commercial reference oximeter.

4.3.2 Peripheral Oxygen Saturation (SpO2)

SpO2 measurements yielded a mean bias of -0.1% and a standard deviation of differences of 0.3%. The 95% limits of agreement were -0.69% to +0.49%. The MAPE for SpO2 was 0.1%, representing the highest level of agreement across all three parameters. The near-zero bias confirms that the WRPM device does not systematically under- or over-estimate SpO2, and the tight limits of agreement demonstrate that the MAX30100 photoplethysmographic oxygen saturation estimates are highly concordant with those of the reference pulse oximeter.

4.3.3 Body Temperature

Temperature measurements showed a mean bias of -0.06°C and a standard deviation of differences of 0.05°C, with 95% limits of agreement from -0.16°C to +0.04°C. The MAPE was 0.16%. The slight negative bias (WRPM reading marginally lower than the standard) is consistent with the known accuracy specification of the DHT11 sensor (±2°C) and is within acceptable clinical tolerance. The LoA values indicate that temperature measurements from the WRPM device would be expected to agree with the reference thermometer to within ±0.1°C in 95% of measurements.

4.4 IoT Data Streaming

The WRPM device successfully established Wi-Fi connectivity and transmitted measured HR, SpO2, and temperature data to the ThingSpeak IoT platform in real time during all testing sessions. Data upload was triggered on each heartbeat detection event (onBeatDetected() callback), with a minimum inter-upload interval of 5 seconds to prevent ThingSpeak API throttling. Real-time data visualization on the ThingSpeak dashboard confirmed successful reception and display of all three parameter channels. Local display on the OLED screen showed concurrent parameter updates at 1-second intervals, allowing immediate visual feedback to the subject and operator during testing.

5. Discussion

The results of this study demonstrate that the developed multi-parameter WRPM device achieves excellent agreement with commercially available medical-grade reference instruments for all three measured parameters — heart rate, SpO2, and body temperature — across a sample of 20 healthy adult volunteers. MAPE values of 0.89%, 0.1%, and 0.16% for HR, SpO2, and temperature, respectively, represent levels of accuracy well within the clinical acceptable

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ranges established by regulatory standards for non-invasive monitoring devices.

The performance of the MAX30100 sensor for heart rate measurement is consistent with findings reported in the literature.[15] validated an ESP32-based device integrating the MAX30100 sensor and reported comparable accuracy for HR and SpO2 measurements against reference instruments. Similarly, [13] demonstrated the MAX30100's suitability for reflectance-mode pulse oximetry in early detection of hypoxemia, reporting agreement within clinically acceptable limits. The heart rate bias of +0.50 bpm observed in this study is physiologically negligible and does not constitute a clinically significant systematic error.

The near-zero SpO2 bias (−0.10%) and tight limits of agreement (−0.10% to +0.90%) observed in this study support the reliability of the MAX30100's photoplethysmographic SpO2 algorithm under normal physiological conditions in healthy adults. It is acknowledged, however, that the accuracy of the MAX30100 may be reduced under conditions of poor peripheral perfusion, motion artefact, or ambient light interference — factors not systematically controlled in this study due to the stationary, indoor testing protocol adopted.

The temperature measurement bias of −0.10°C is attributable to the inherent accuracy limitation of the DHT11 sensor (±2°C per manufacturer specification) and to the practical challenges of achieving consistent thermal contact between the sensor housing and the axillary measurement site. Despite this, the MAPE of 0.27% and the narrow LoA (−0.30°C to +0.10°C) confirm that the DHT11-based temperature measurement is adequate for screening purposes and for applications that do not require the precision of clinical platinum resistance thermometry. Future iterations of the device could incorporate the more accurate DS18B20 waterproof digital temperature sensor to improve temperature measurement precision.

The successful real-time transmission of all three parameters to the ThingSpeak IoT platform during testing sessions confirms the system's Wi-Fi connectivity and data streaming functionality. This feature has significant implications for remote patient monitoring applications, enabling healthcare practitioners to access continuous vital signs data from patients in remote locations without requiring physical proximity. The cost of all hardware components utilized in the prototype is substantially lower than commercially available multi-parameter WRPM devices, supporting the feasibility of widespread deployment in resource-limited healthcare settings characteristic of Nigeria and comparable LMICs.

The study is not without limitations. The sample size (n = 20) is relatively small and comprised exclusively of healthy young adults, limiting generalization to clinical patient populations. The testing was conducted under controlled laboratory conditions, and device performance under ambulatory conditions, motion, or in the presence of ambient electromagnetic interference was not assessed. The DHT11's temperature accuracy, while sufficient for screening, falls short of the precision required for clinical fever diagnosis. Future work should evaluate device performance in larger, more diverse populations including patients with chronic disease, and should address wearability, long-term battery performance, and miniaturization of the assembled device.

6. Conclusion and Recommendations

6.1 Conclusion

This study successfully developed and validated a low-cost, multi-parameter Wearable Remote Patient Monitoring (WRPM) device for the simultaneous real-time measurement and IoT-based streaming of heart rate, SpO2, and body temperature. Performance evaluation against commercially available medical-grade reference instruments on 20 healthy adult volunteers demonstrated excellent agreement, with MAPE values of 0.89%, 0.1%, and 0.16% for HR, SpO2, and temperature, respectively. Bland-Altman analysis confirmed clinically acceptable bias and narrow limits of agreement for all three parameters. The device leverages the ESP32 microcontroller, MAX30100 sensor, and DHT11 sensor — all readily available, low-cost components — and successfully streams data to the ThingSpeak IoT platform in real time.

The developed WRPM device represents a viable, affordable, and functional solution for multi-parameter remote patient monitoring, with significant potential for adoption in primary healthcare and community health

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settings in Nigeria and similar resource-limited environments. It addresses the critical gap in accessible multi-parameter monitoring technology and establishes a technical foundation for further refinement, including miniaturization, clinical validation in patient populations, and integration with mobile health (mHealth) application platforms.

6.2 Recommendations

1. Future studies should recruit larger and clinically diverse patient populations, including individuals with cardiovascular and respiratory disease, to fully validate device performance across a broader physiological range.
2. The DHT11 temperature sensor should be replaced with a higher-accuracy alternative such as the DS18B20 digital thermometer or a non-contact infrared sensor in subsequent device iterations to improve temperature measurement precision.
3. The device should be miniaturized and encapsulated in a purpose-designed wearable casing to improve patient comfort, compliance, and usability in ambulatory settings.
4. Ambulatory testing under real-world conditions including motion, variable ambient temperature, and different body positions should be conducted to characterize the effect of these factors on device accuracy.
5. Integration with a dedicated mobile health application and clinical information system should be explored to enable automated alerting, electronic health record integration, and population-level health data analytics.
6. Healthcare regulatory pathway compliance (e.g., NAFDAC and COREN certification in Nigeria) should be pursued to enable formal clinical deployment of the device.
7. User education and training programmes for healthcare workers and patients should be developed to support successful adoption and effective utilization of the WRPM system.

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