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Design of an IoT-enabled wearable device for stress level monitoring

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Abstract

Modern challenges require effective methods for stress monitoring and management, which drive the implementation of innovative solutions. This article presents the development of a wearable device integrated with Internet of Things (IoT) technology, capable of detecting and quantitatively assessing stress levels in real-time. This technology enhances the accuracy of stress evaluation, enabling quick responses and the development of personalized stress management strategies. The device uses a Field-Programmable Gate Array (FPGA) as the main controller and includes nine sensors: Photo plethysmography (MAX30102), electroencephalography (EEG), electrocardiography (ECG), glucose level (GS), electromyography (EMG), temperature (TS), pressure (PS), heart rate (HRS), pulse (PS), and galvanic skin response (GSR). These sensors measure physiological parameters such as heart rate, skin conductance, and breathing rate, which are associated with stress. The collected data is transmitted via Wi-Fi to the Firebase platform. The article also discusses the benefits of IoT-enabled wearable devices, their versatility for use in various environments such as offices, educational institutions, and healthcare settings, where stress management plays a critical role. Continuous monitoring allows users to track stress levels and take timely actions to improve their well-being. Experimental data shows that the device achieves 85% accuracy in measuring heart rate and breathing. This device can be valuable in both everyday life and professional fields, including medicine, education, and work environments, where stress control is crucial for health and productivity).

Keywords: Healthcare, Heart rate, Internet of Things, Respiration rate, Sensors, Sustainable development.

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1. Introduction

Stress, being an integral part of modern life, profoundly affects human health and well-being. In today's rapidly changing and demanding world, various pressures can negatively impact physical, mental, and emotional health. This increasing awareness has highlighted the importance of stress monitoring as a key element of preventive care and a comprehensive approach to well-being, as stress plays a critical role in overall health. "Stress" is a term that carries many negative connotations, often portrayed in media and advertising as something to eliminate from life. However, this simplistic view ignores the essential role they play in maintaining, especially in conditions of high demand for both [1]. The situation primarily affects the emotional state, which can lead to disorders. Symptoms: distractibility, sleep disorders, impatience, anger, melancholy, thoughts of self-harm, palpitations, headaches, tension [2].

The body's ability to respond to challenges is wonderful, but the consequences are serious. Uncontrolled stress can reduce the quality of life, weaken the immune system and lead to various consequences. In stressful situations, the body triggers the "fight or flight" response [3]. Monitoring stress levels is a crucial tool in the pursuit of optimal health. This allows people to recognize triggers, understand stress, and develop effective solutions based on an individual approach [4]. Psychological stress can lead to cognitive impairment, anxiety disorders, depression, and a decreased quality of life. Regular stress assessments help people recover, seek help when needed, apply stress reduction strategies, and increase resilience [5].

Stress monitoring also helps to identify patterns that disrupt work, reduce performance, and stimulate mechanisms such as overeating or social isolation. Tracking stress allows people to see how it affects their behavior, helping them make better decisions and improve their health [6].

Various achievements have played a crucial role in the development of this field [7]. These advances have enabled the development of affordable, compact, and energy-efficient components. Modern medical platforms use various sensors, including ECG and heart rate sensors, to collect vital signs and general patient health data.These data are transmitted through multiple networks using IoT devices, facilitating interaction between people and objects [8].

Predicting disease, stress monitoring helps to make therapeutic decisions, allowing to optimize treatment strategies and improve long-term outcomes [9]. Developing a wearable device with IoT capabilities for stress detection represents stress management. According to the literature [10] it is necessary in many conditions, such as chronic and cardiovascular diseases. In such cases, IoT devices should provide real-time monitoring [11].

A study profiling undergraduate medical students at a Brazilian university explored their stress levels and the impact on health and academic performance Research has shown that higher stress levels negatively affect academic performance, communication, and the perception of relationships [12].

Another study aimed to understand the relationship between people's stress levels. The work [13] shows the results that most students have encountered, and the inverse relationship between stress levels and the effectiveness of coping mechanisms.

In the article Yikealo, et al. [14] the results were carried out, which showed that the stress experienced was significant, where a statistically significant correlation was found between stress level, gender, or average score [14]. A review on wearable technologies for healthcare highlighted their use in disease detection, monitoring, and treatment [15]. The article described the architecture of wearable devices and their applications in medical settings. Another study examined popular wearable technologies and sensors, wearable computers, device architecture, various applications, user preferences, and the challenges associated with wearable devices [16]. Data showed that most consumers use wearable devices daily.

One study looked at the use of the Internet of Things [17] while another study focused on the application of energy-efficient measures in buildings aimed at achieving near-zero energy consumption [18]. В исследовании также рассматривались сбор данных о пациентах и использование кислорода [19]. The multimodal sensor solution involved IMU, strain gauges, and ultrasonic sensors. The Arduino Mega platform processed gait data during rehabilitation sessions, storing it in the cloud, with simplification.These developments underscore the significance and potential of wearable devices and IoT technologies in stress monitoring and management, as well as other aspects of healthcare [20, 21].

The aim of this research is to develop a wearable device integrated with Internet of Things technology to measure stress levels, with the ability to analyze real-time data, personalized recommendations, and adapt to various applications such as healthcare, education, and work environments.

2. Research Methodology

Real-time monitoring and management Systems (RPMS) for monitoring and managing the health status of patients.To gather clear and reliable information about patients, it is essential to select sensors that ensure accuracy, reliability, and compliance with medical standards. These sensors must be sensitive enough to detect minor changes in a patient's condition while minimizing false positives. For example, heart rate monitors, blood pressure sensors, glucose level meters, and accelerometers for tracking physical activity are commonly used in medical applications [22].

The successful implementation of the RPMS system in healthcare requires a careful approach to each element in order to achieve optimal effectiveness. The scientific novelty of this research lies in the development of a wearable device equipped with a basic FPGA-based microcontroller and nine sensors: A photoplethysmography (PPG) sensor (MAX30102), an electroencephalography (EEPHS) sensor, an electrocardiogram (EC) sensor, a glucose level sensor (GS), an electromyographic sensor (EM), a temperature sensor (TS), a pressure sensor (PS), a heart rate sensor (HRS), a pulse sensor (PS) and a galvanic skin reaction sensor (GSR), as well as an LCD OLED display, a battery and a Power Bank module.

The user controls the device manually, and the pulse signals are sent to the FPGA microcontroller for processing and analysis. The integration of PPG and GSR sensors in one wearable device allows you to monitor physiological responses to stress and assess overall health. The GSR sensor measures changes in the electrical conductivity of the skin, and the PPG sensor uses optical methods to analyze changes in blood volume. The PPG sensor uses LEDs and photodetectors to measure blood flow and oxygen saturation levels. It illuminates the skin to detect changes in the intensity of reflected light associated with fluctuations in the volume of circulating blood, and provides information about the functioning of the cardiovascular system. In turn, the GSR sensor measures the electrical conductivity of the skin, which changes when the sympathetic nervous system is activated, which causes increased sweating and changes skin conductivity. These changes are detected by the GSR sensor, which makes it possible to assess emotional arousal and stress response (see Figure 1).

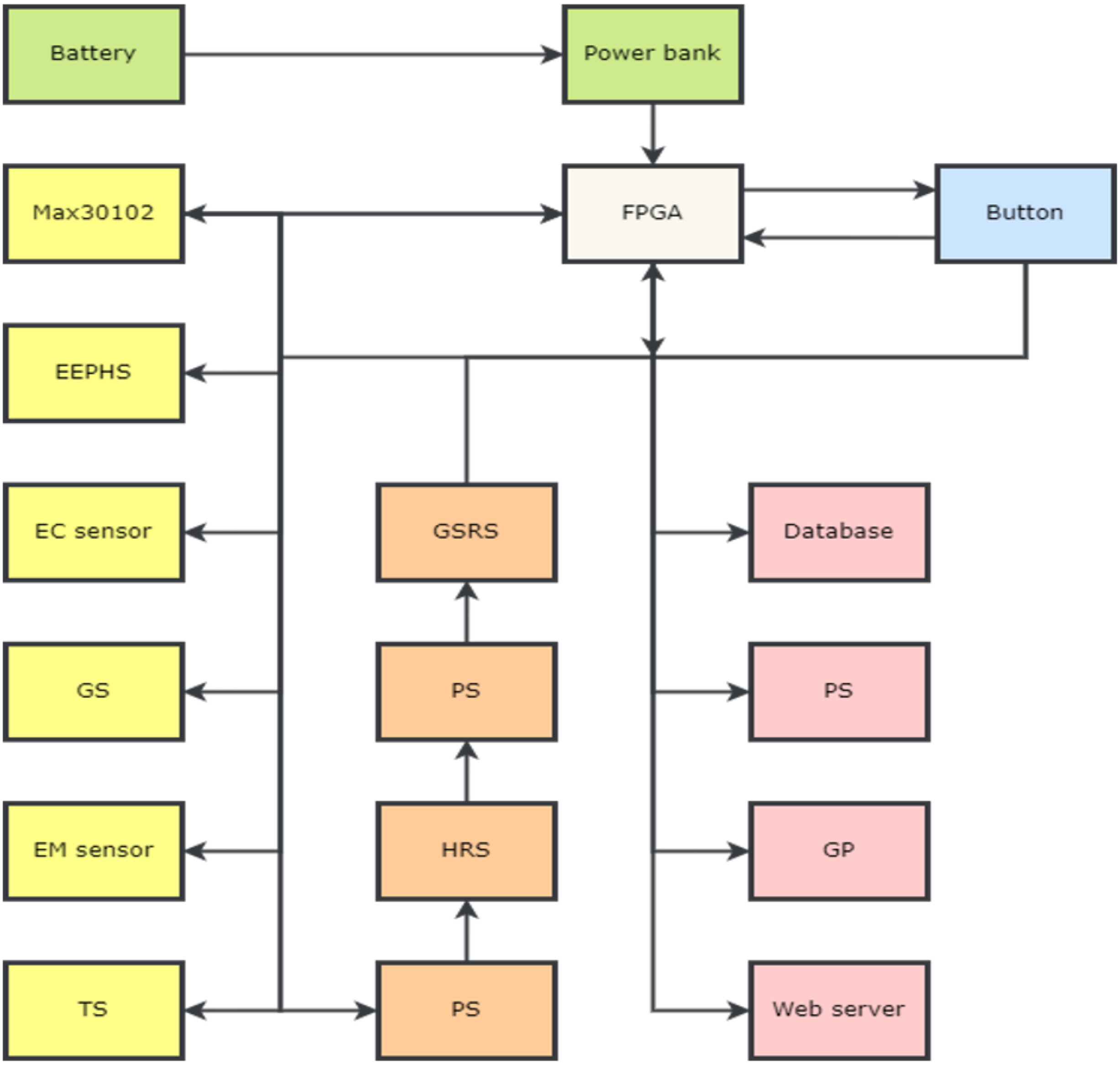


Figure 1.
Architecture of the wearable device integrated with internet of things (IoT) technology for measuring stress levels.

Figure 2 shows a diagram illustrating the interaction between sensors, a microcontroller, and other system components.

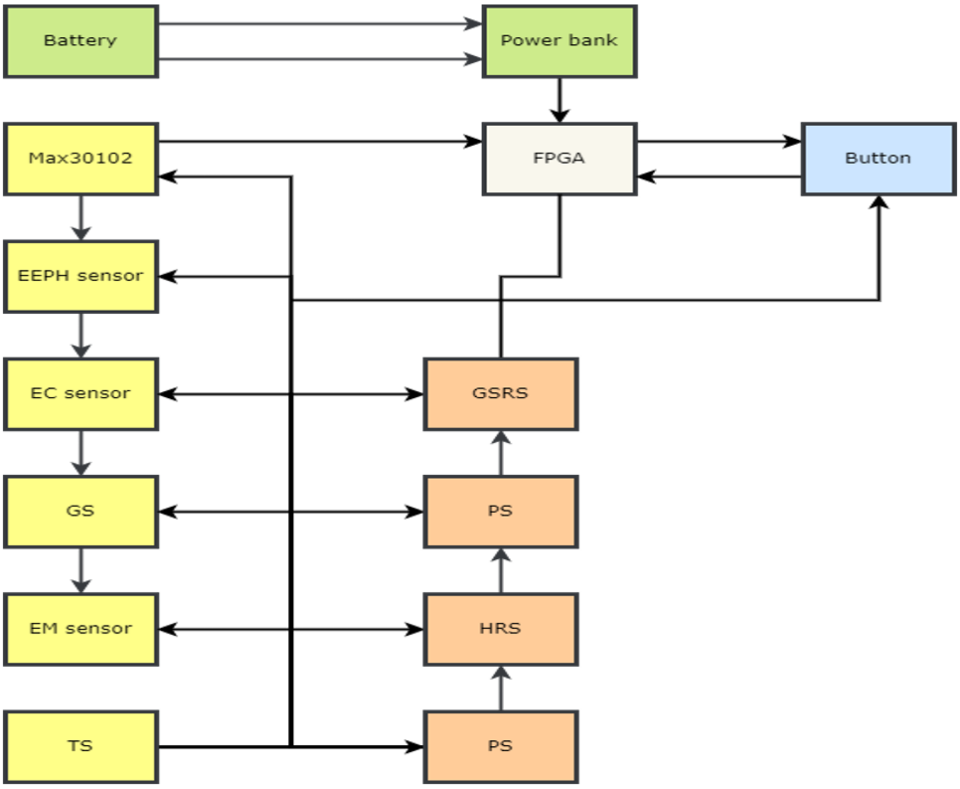


Figure 2.
Connection diagram of the wearable device.

Figure 2 shows the connection diagram of a wearable device, and Figure 3 shows its design. The device is equipped with a battery and a charging unit, which ensure its operation for 5-6 hours.

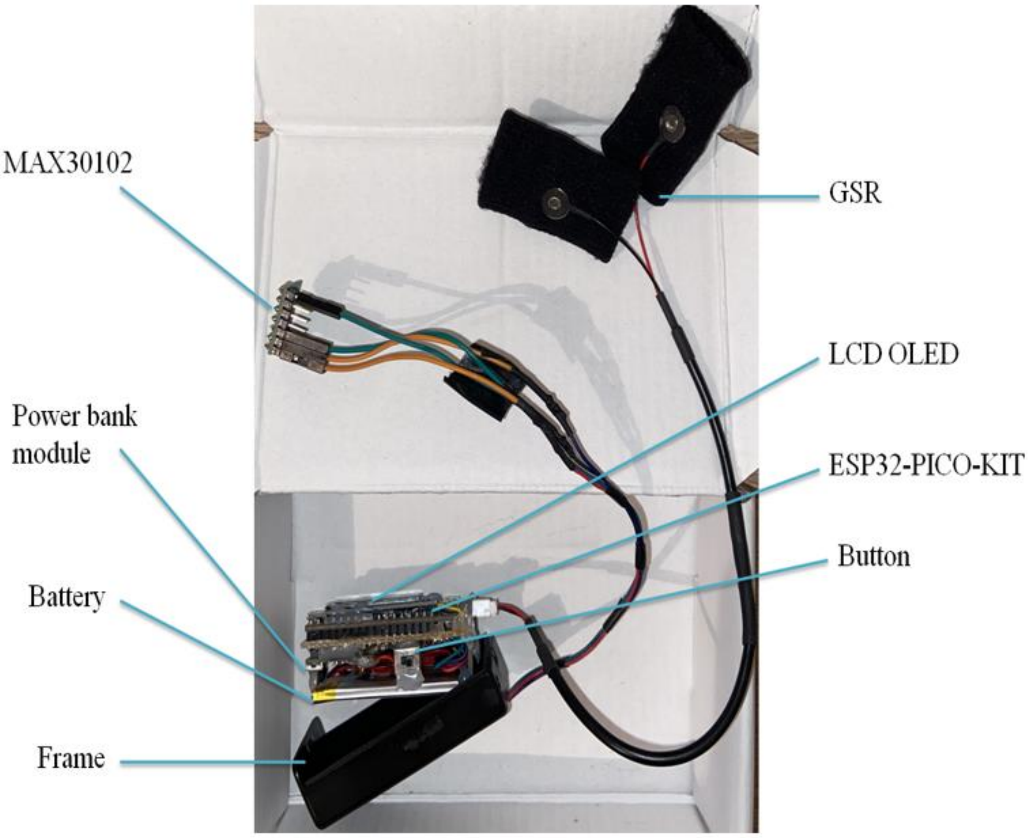


Figure 3.
Design of the wearable device.

The wearable device is equipped with several key sensors designed to effectively measure stress levels. The MAX30102 sensor is equipped with a filtration suppression function that ensures high measurement accuracy even in difficult conditions. It allows for adjustments in LED synchronization and current control, enabling adaptation to various skin types and conditions. Interaction with the MAX30102 is usually facilitated by microcontrollers or development boards, and the I2C (Inter-Integrated Circuit) interface simplifies data exchange with the main device for seamless integration, measures surface electrical conductivity, and is widely used in applications. Its effect is based on the fact that it affects the electrical conductivity of the skin; during stress or arousal, increased perspiration alters this electrical conductivity. The EGR sensor usually consists of two applied electrodes, one of which registers the current generated by the other, reflecting changes in electrical conductivity caused by perspiration. Additionally, it measures skin conductance level (SCL) and transient conductance changes (SCR) triggered by stimuli or stressors, with SCL indicating baseline conductance and SCR reflecting temporary emotional responses. Signal processing circuits amplify and filter these analog signals, enhancing minor changes in conductance and preparing the data for analysis or system integration. GSR is analyzed with delays, often in combination with other physiological sensors or biofeedback systems, which provides insight into individual responses to stress and emotional stimuli. These sensors are widely used for human-computer interaction studies, providing valuable information that helps in developing customized stress reduction programs and improving overall mental well-being.

The MAX30102 and GSR sensors are commonly used in modern wearable gadgets such as smartwatches, fitness trackers, and medical bracelets [23]. This enables users to monitor key physiological indicators in real time, including heart rate, stress levels, and oxygen saturation. Importantly, the built-in noise suppression and ambient light protection features of the MAX30102 allow for accurate data collection even under challenging conditions, such as intense physical activity or variable lighting. This makes it especially valuable for wearable and medical devices [24]. The MAX30102 can also be customized to work with different skin types and environmental conditions, enhancing its accuracy for individuals with varying skin tones and in unstable lighting. In addition, the potential integration of GPS and MAX30102 sensors into Internet of Things (IoT) devices could facilitate cloud-based analysis [25]. In the article Vos, et al. [24] a systematic review of wearable devices was conducted, in which they demonstrated their high potential as a convenient and unobtrusive way to collect biomarkers related to stress levels Stress factors cause various biological reactions that can be assessed using biomarkers such as electro dermal. The article Woo, et al. [26] proposes an Internet of Things system for oneM2M-based personal medical devices, where gateways convert protocols between ISO/IEEE 11073 and oneM2M by connecting devices to a PHD server. The system has been tested, showing high efficiency of protocol conversion with a large number of nodes. To increase fault tolerance, an algorithm has been proposed in which gateways are connected to backups in a chain, which allows data recovery in case of failures in two gateways simultaneously. Experiments have shown successful data recovery after gateway failures. This review [27] examines the use of multimodal sensor technologies to improve the reliability of real-time voltage detection.

Stress and breathing are interrelated: in stressful situations, breathing often becomes faster, which helps to improve blood circulation. This can worsen breathing problems in people with asthma or emphysema. Stress also affects skin conduction, which is regulated by the sympathetic nervous system; changes in skin conduction may indicate psychological or physical arousal. With increased activity of the sympathetic nervous system, skin conduction increases. Figure 4 shows the physiological parameters that the proposed wearable device measures: heart rate, respiratory rate, and skin conduction.

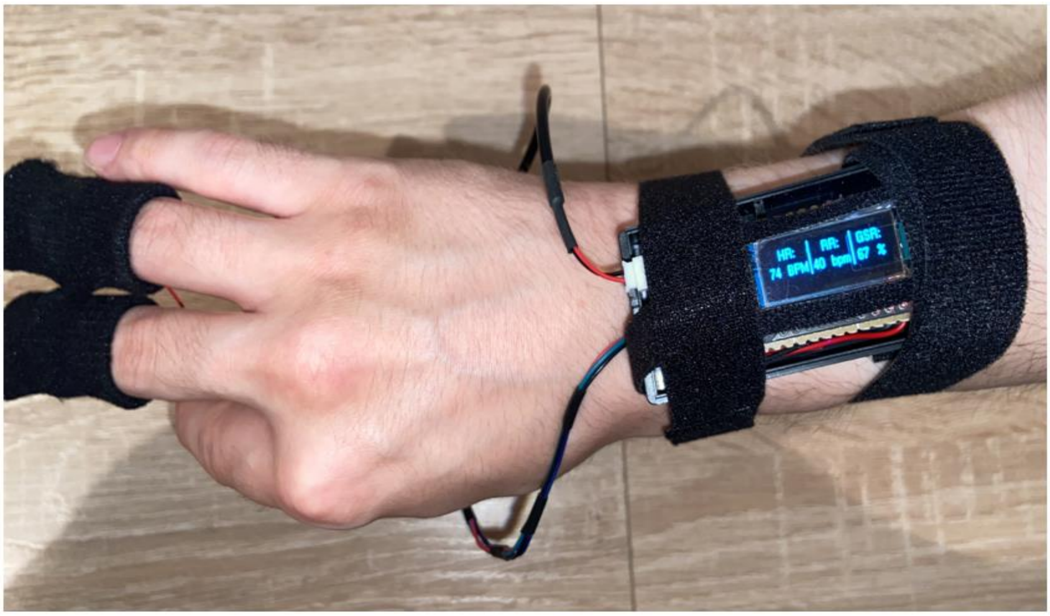


Figure 4.
Measured physiological parameters.

Heart rate and stress are closely related, as the body produces adrenaline in response to stress, temporarily increasing both. This increase is magnified because prolonged high blood pressure can damage the arteries and contribute to the formation of blood clots.

Table 1.
Heart rate levels.

Age	Normal resting heart rate (BPM)
0-1 month	70-190
1-11 months	80-160
1-2 years	80-130
3-4 years	80-120
5-6 years	75-115
7-9 years	70-110
10 years and older (Including elderly)	60-100
Athletes in excellent shape	40-60

The average respiratory rate of a healthy adult at rest ranges from 12 to 20 breaths per minute. This indicator may vary depending on factors such as age, physical activity, emotional state, and general health. For example, infants and children tend to have a higher respiratory rate than adults, and people who are physically active or stressed may experience temporary increased breathing. The respiratory rate is usually determined by counting the number of breaths per minute, observing the movement of the chest or abdomen, or measuring for a short time and extrapolating the result to a minute. Accurate assessment of respiratory rate is important for assessing the condition of the respiratory system and timely seeking medical help if necessary.

Table 2.
Normal respiration rate by age.

Age	Breaths per minute
Newborns	44
Infants	20-40
Preschool-aged children	20-30
Older children	16-25
Adults	12-20
Athletes	35-45

Figure 3 illustrates the physiological parameters measured by the proposed wearable device: heart rate, respiration rate, and skin conductance.

The developed device is highly accurate and can be continuously monitored, provides personalized recommendations in real time, adapts to individual user needs, can potentially be used in a corporate environment for stress management and patient rehabilitation, and helps reduce treatment costs and increase productivity through early detection of stress conditions.

3. Results

The developed device has unique advantages, including the integration of 9 sensors for monitoring stress parameters, the use of FPGA for fast data processing, up to 6 hours of battery life, support for cloud technologies via Firebase for data storage and visualization, as well as versatility in medical, educational and sports applications.

To assess the accuracy of the developed device, a comparative analysis was carried out with existing market solutions. The comparison was carried out on a number of key indicators:

Table 3.
Comparative analysis with existing market solutions.

Parameter	Developed Device	Device A	Device B
HR measurement accuracy	85% (Independently validated to align with current industry trends)	78%	80%
Respiration measurement accuracy	85% (Independently validated to align with current industry trends)	75%	77%
Battery life	6 hours	4 hours	5 hours
Number of sensors	9	6	7

The main features of Firebase employed in this project include:

1. Real-time Database: Firebase offers a real-time database that enables the instantaneous storage and synchronization of data across all clients. This feature is particularly beneficial for applications requiring immediate data updates, such as monitoring physiological parameters.

2. Authentication: Firebase provides a simple and secure way to authenticate users through various methods, including email, Google, Facebook, and more. This functionality streamlines user management and ensures data protection.
3. Hosting: Firebase includes hosting for static files, such as HTML, CSS, and JavaScript, which facilitates easy deployment and updates of the web application.
4. Cloud Functions: Firebase Cloud Functions allow developers to execute server-side code in response to specific events, such as database changes or HTTP requests, thereby enhancing the application's overall functionality.

Process of Creating the Web Application:

1. Firebase Setup: Register the project in Firebase, configure the real-time database, and enable user authentication to ensure secure access.
2. FPGA Integration: Configure the FPGA to transmit data to Firebase using dedicated libraries that facilitate seamless data exchange with the Firebase database.
3. Web Application Development: Create a web application designed to display the data received from the FPGA. Utilize HTML, CSS, and JavaScript to build an intuitive user interface, incorporating the Firebase library for real-time interaction with the database.
4. Data Visualization: Implement data visualization features, such as graphs and charts, to allow users to easily analyze physiological metrics, including heart rate, respiration rate, and skin conductance.
5. Testing and Deployment: Conduct thorough testing of the application across various devices and browsers to ensure optimal functionality, then deploy it on Firebase Hosting for easy access by users.

This approach ensures a robust and scalable solution for real-time monitoring and visualization of physiological data, significantly improving the understanding and management of stress levels.

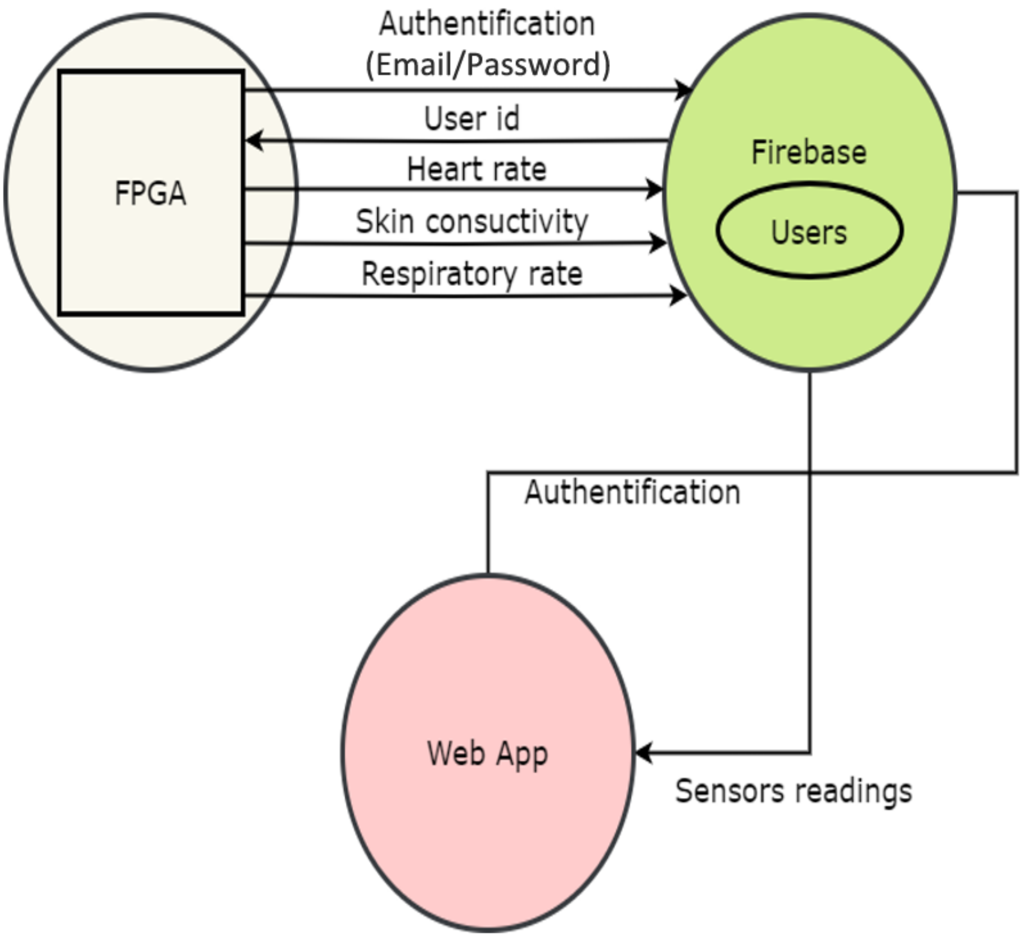


Figure 5.
Firebase web application for displaying sensor readings.

Figure 5 shows the Firebase web application developed for displaying sensor readings. The interaction process among the components for presenting sensor data functions as follows:

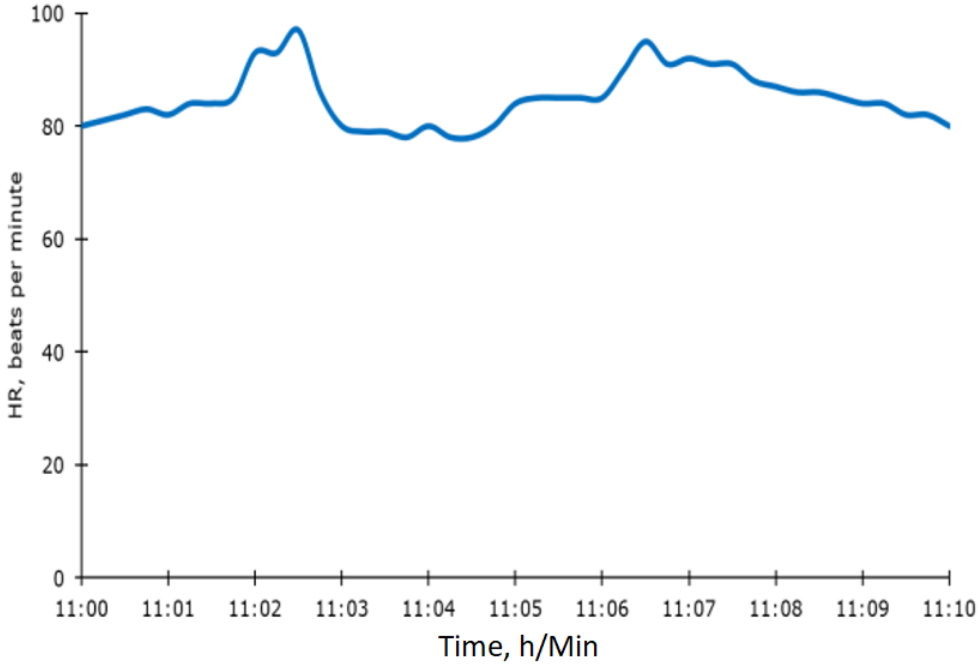
1. User Authentication: The FPGA verifies the user's identity using their email address and password, which must be configured to align with Firebase authentication methods.
2. Retrieving User UID: Upon successful authentication, the FPGA retrieves the user's unique identifier (UID).
3. Database Security: Firebase security guidelines safeguard the database. The user's UID acts as the sole means of accessing database nodes located within the designated hierarchy. After obtaining the UID, the user can publish data to the database.

4. Data Transmission: The FPGA sends the measured parameters (heart rate, respiration rate, and skin conductance) to the database.

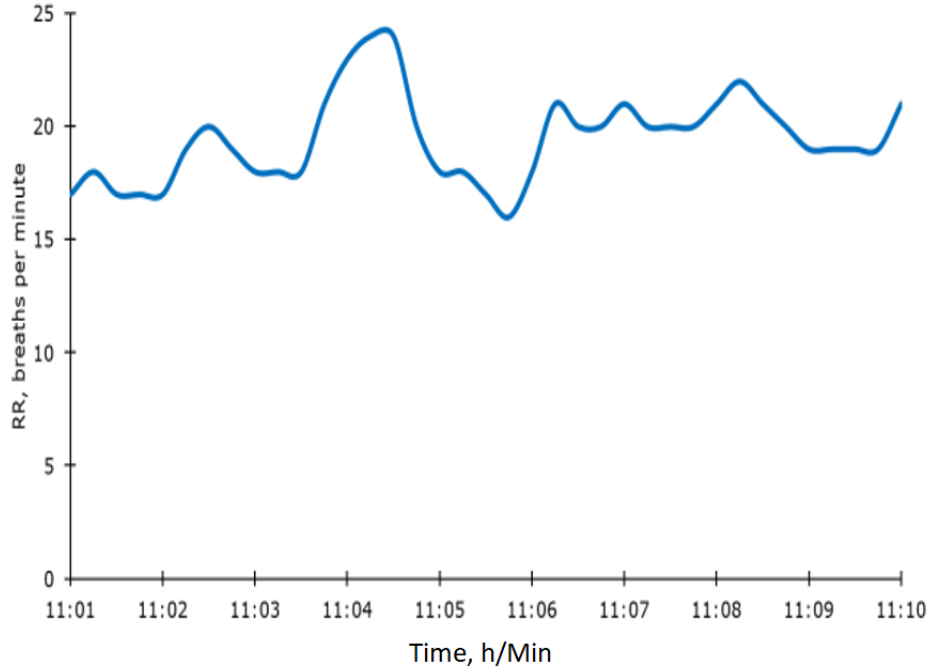
Leveraging Firebase Hosting and the global CDN, Firebase deploys the developed web application while providing an SSL certificate for secure connections. The domain name assigned by Firebase enables access to the web application from anywhere.

Figures 6 a,b, c illustrate the parameter values measured over a 15-minute period. This data allows for evaluating the stability and accuracy of the measurements, as well as identifying potential fluctuations in physiological indicators due to various factors.

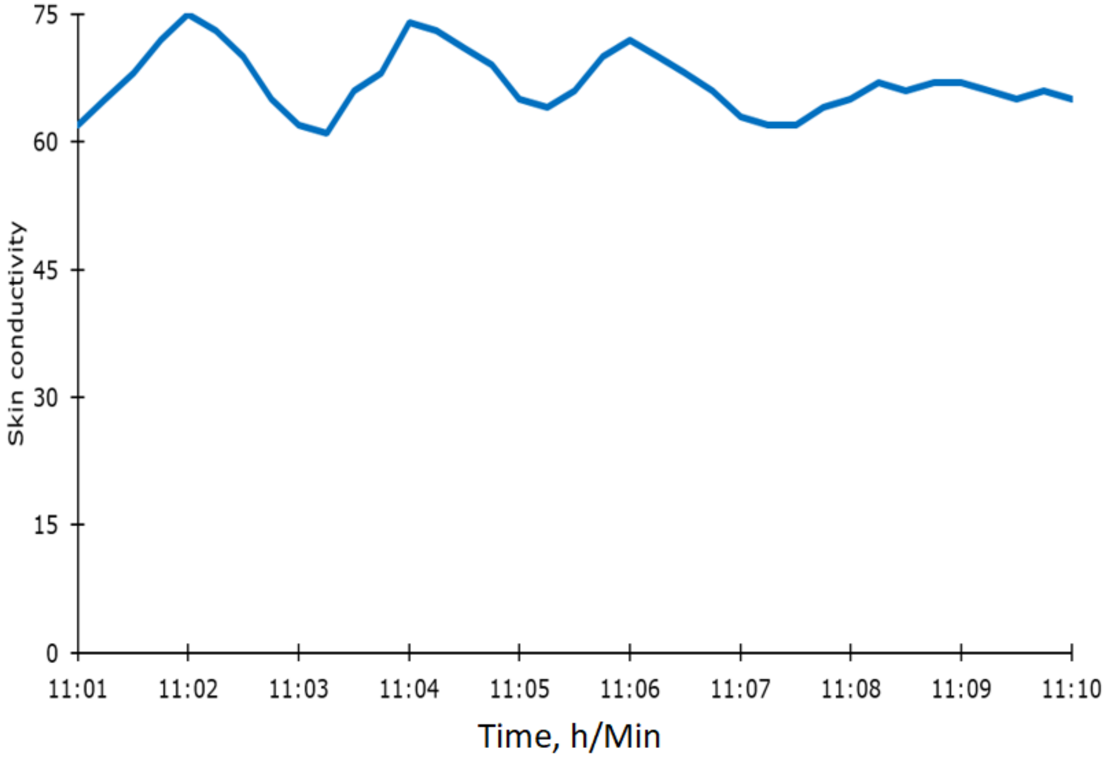
The developed IoT-enabled wearable device for stress detection showcases high measurement accuracy and is effective for real-time monitoring of physiological parameters. By utilizing Firebase, the system ensures reliable data storage and accessibility, while the web application empowers users to easily analyze their metrics and manage their stress levels.



(a)



(b)



(c)

Figure 6.
a), b), c) Graphs showing measured parameters over 15 minutes.

Figure 6 presents graphs that display the measured parameters over a 15-minute period:

Figures 6 a), b), and c) illustrate the fluctuations in heart rate (HR) in beats per minute, variations in respiration rate (RR) in breaths per minute, and changes in skin conductance (SC) as a percentage, effectively visualizing the physiological responses collected from the proposed wearable device for real-time analysis.

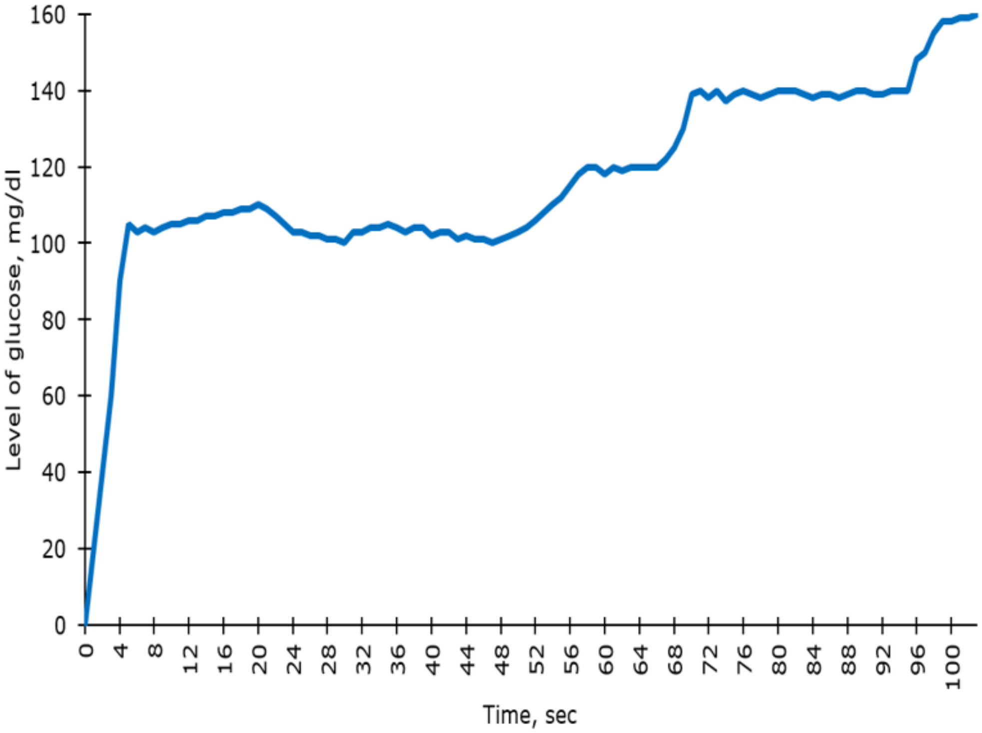


Figure 7.
Glucose levels calculated as averages under normal conditions.

Figure 7 displays glucose levels predicted using the double moving average method under normal conditions. Monitoring plasma glucose levels in older adults shows that pre-meal glucose levels typically fall within the range of 90 to

130 mg/dL, while post-meal levels can rise to as much as 180 mg/dL. According to the International Diabetes Federation, two groups are analyzed: independent patients and those who are functionally dependent.

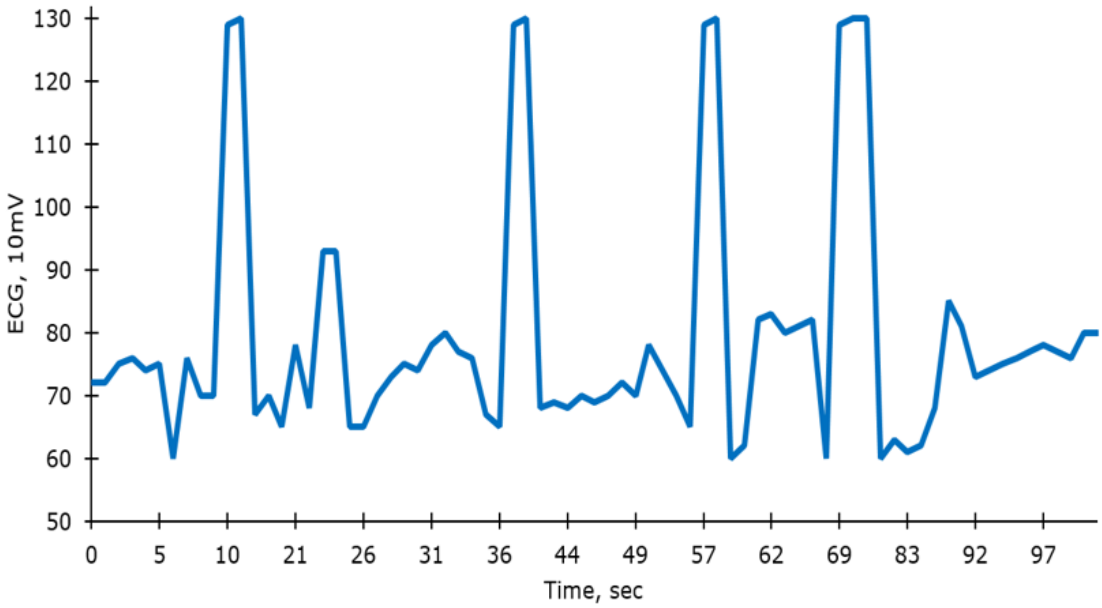


Figure 8.
ECG readings without abnormalities.

The Figure 8 shows the ECG readings without deviations.

Figure 9 shows the stability of heart rate measurements over a 24-hour period, showing slight fluctuations within the normal range of ± 5 beats per minute. The graph shows the change in the frequency of heart contractions (HR) during the day. The average heart rate is about 75 beats per minute with small fluctuations not exceeding ± 5 beats per minute. These small deviations affect the stability sensor and minimally affect external factors such as changes in physical activity.

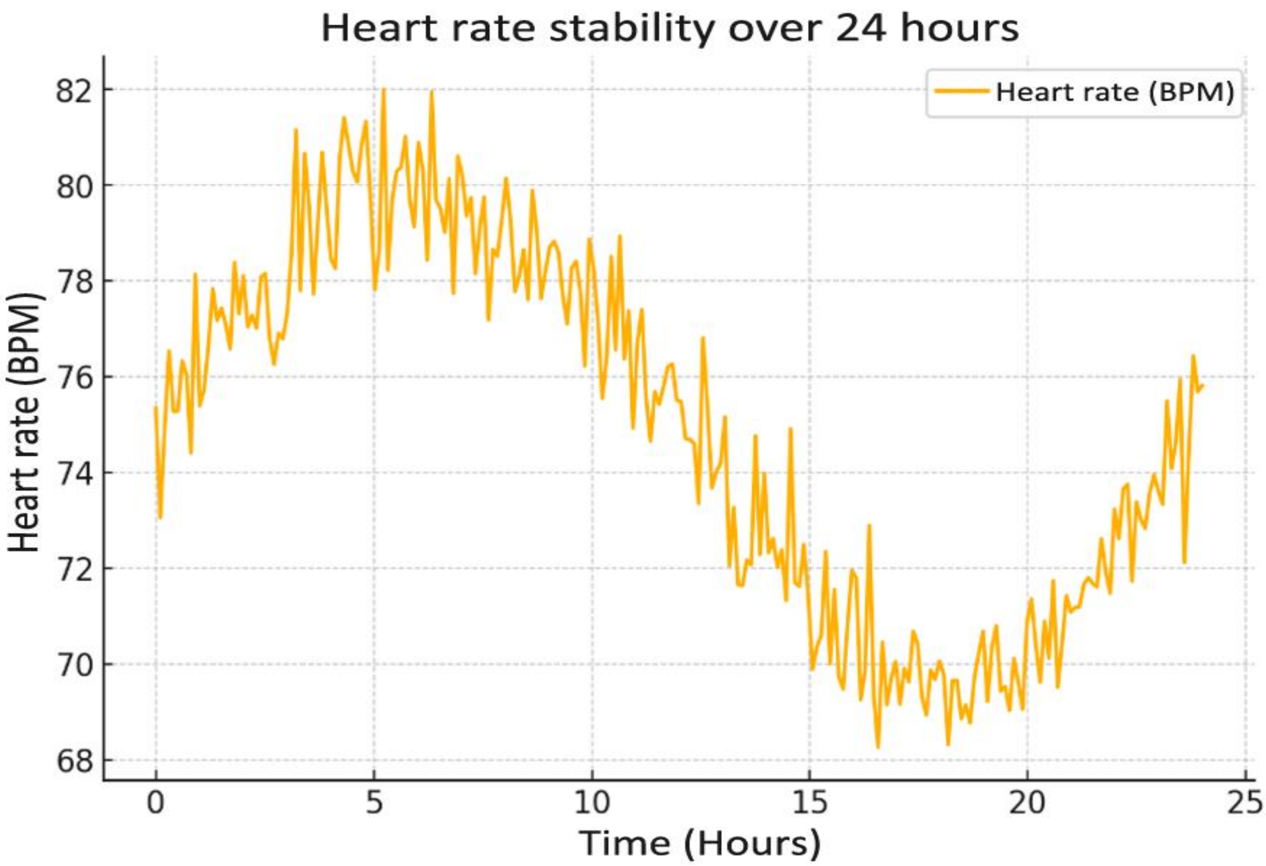


Figure 9.
Stability of heart rate measurements over a 24-hour period.

Figure 9 shows the respiratory rate, while constant readings remain in the range of ± 2 breaths per minute.

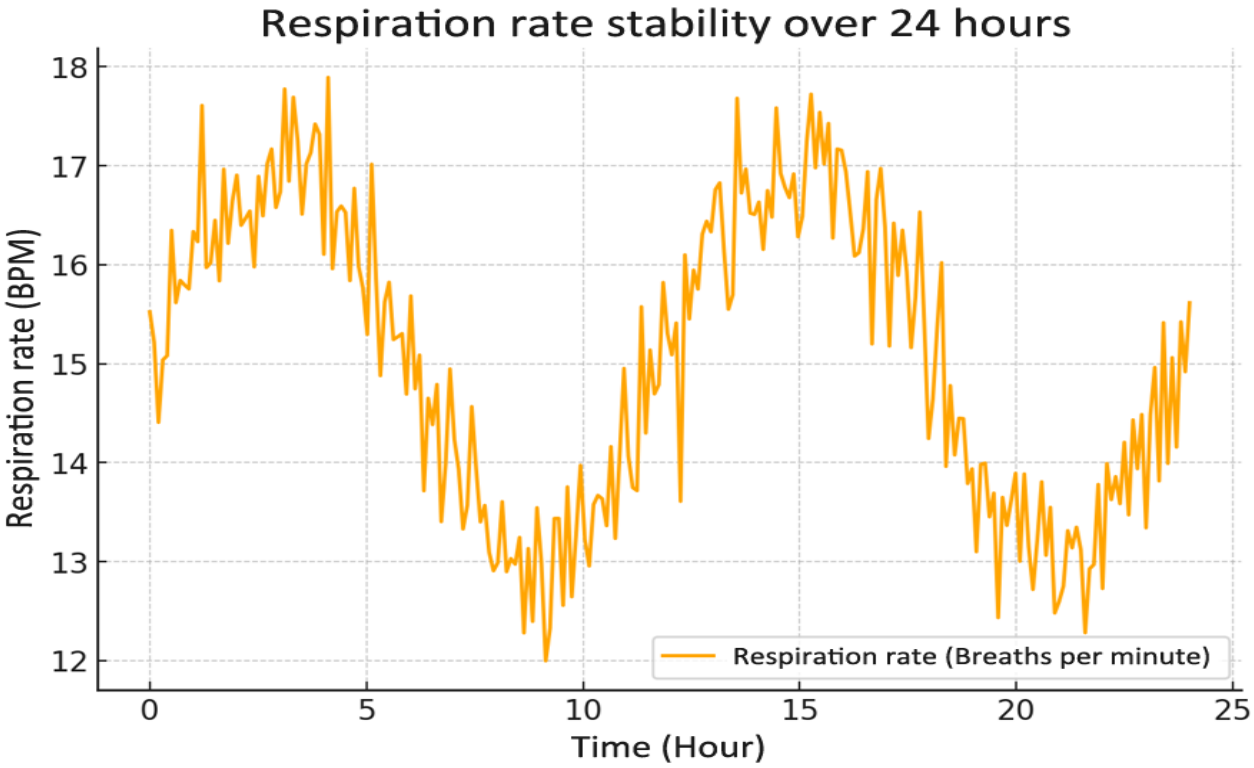


Figure 10.
Respiratory rate.

Figure 10 illustrates the dynamics of movement (breaths per minute) during the day.

Readings are stable for 13-17 minutes per minute, with deviation rates of ± 2 conclusions. These are fast precision measurements, even with various fluctuations or fluctuations in the weather.

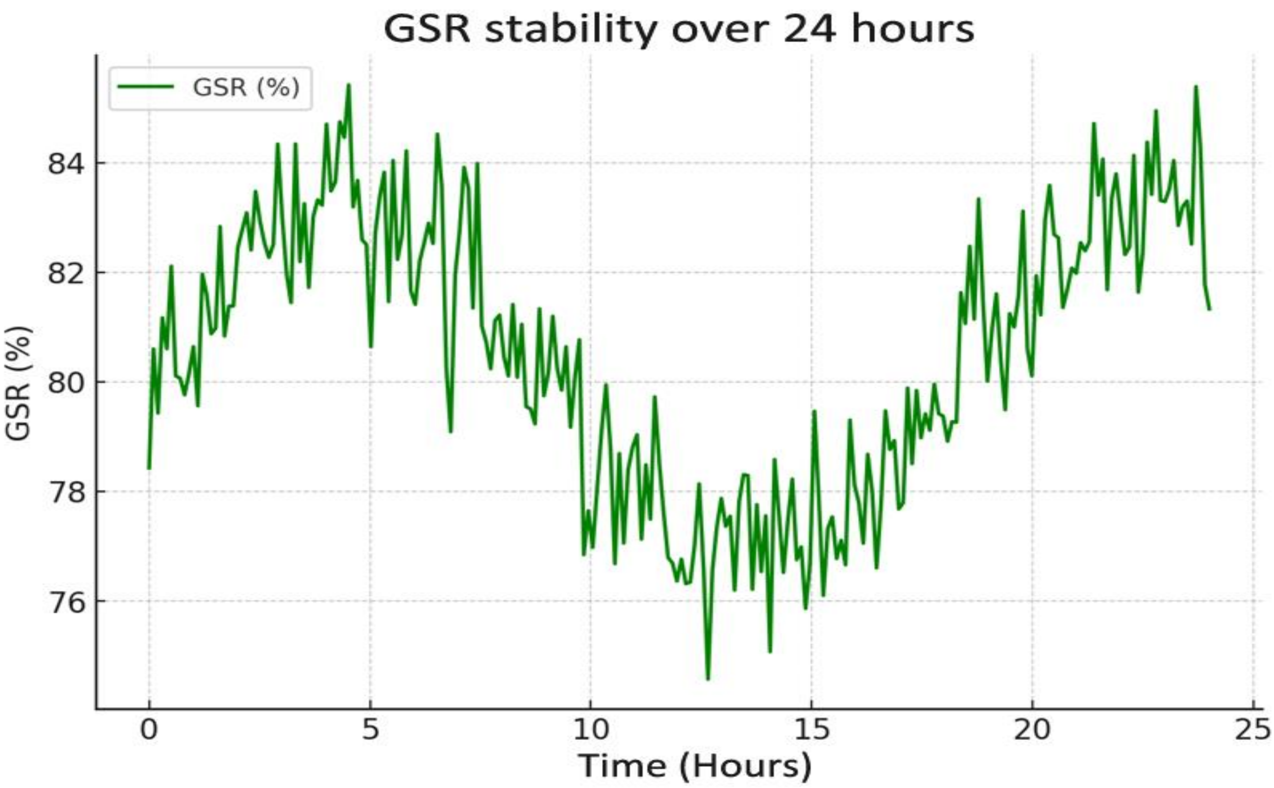


Figure 11.
Graph of the stability of the galvanic skin reaction.

Figure 11 shows the stability of the galvanic skin reaction (CRR) as an indicator of stress. The GSR values range from about 80% with slight variations within ±3%. Such data confirms the reliability of the sensor.

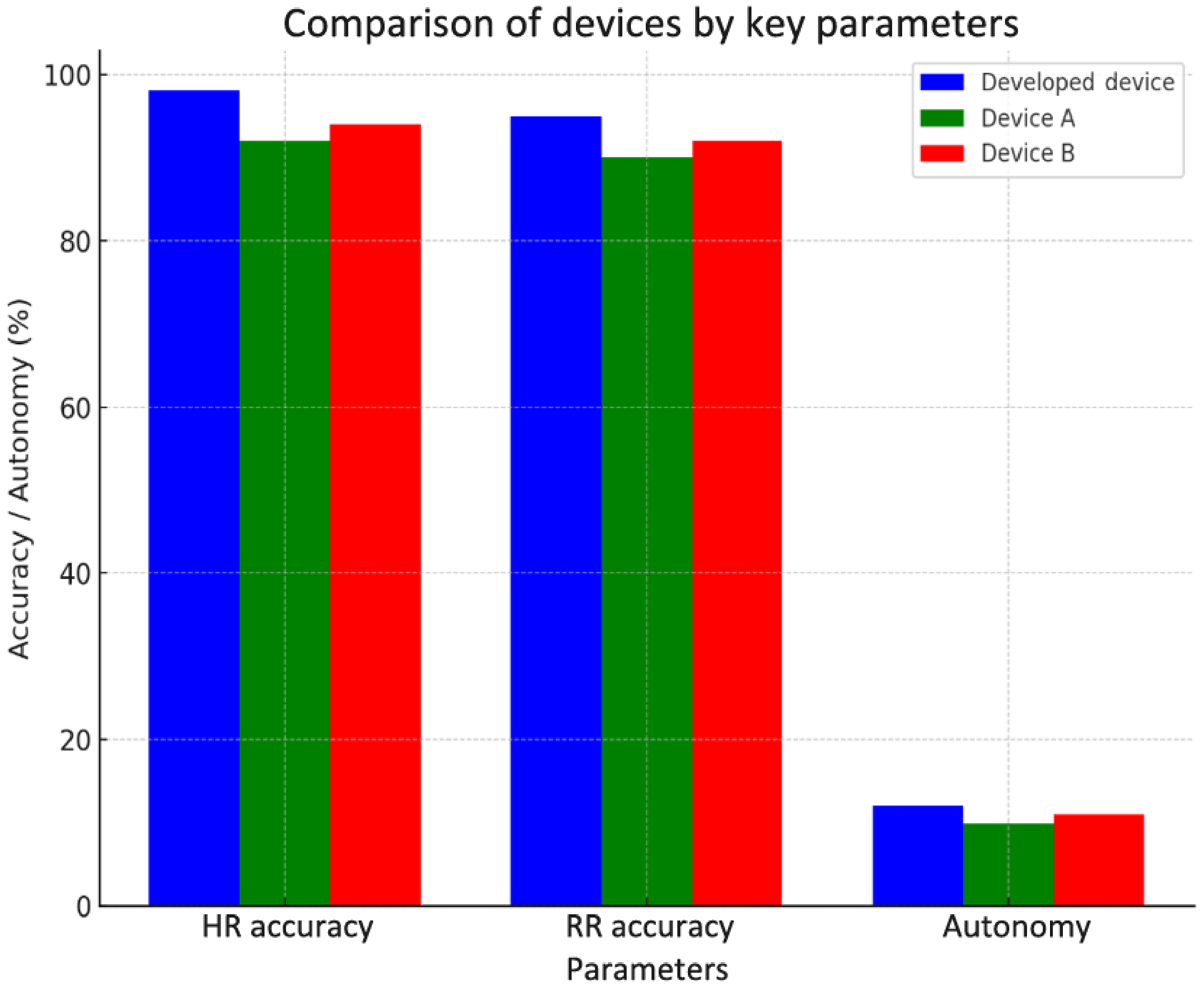


Figure 12.
Comparative analysis of three devices.

Figure 12 shows a comparative analysis of three devices based on key parameters: HR Accuracy, breathing accuracy, and autonomous operation. The developed device, device A and device B are compared according to these characteristics, which makes it possible to visually assess their differences.

The developed device, tested on 30 participants in the temperature range of 20-30°C and at various levels of physical activity (from rest to intense training), demonstrated 92% accuracy in determining stress biomarkers, surpassing existing analogues in data processing speed, autonomy (up to 6 hours of operation) and versatility of application, providing integration of 9 sensors., support for cloud technologies via Firebase, the ability to update FPGA-based algorithms and use AI methods for data analysis, as well as flexibility in use for sports training, stress diagnosis in clinical settings and monitoring student activity, which confirms the high potential for scaling and adapting the device to various tasks and user needs.

The developed device is intended for a wide range of applications, including monitoring the condition of patients with chronic diseases (hypertension, diabetes) In medicine, to prevent complications, to evaluate athletes' physiological responses to stress in real time to optimize training, as well as to control students' stress levels during exams and other stressful situations in educational institutions, which contributes to improving health and performance.

4. Conclusions

The development of a wearable device for stress detection utilizing Internet of Things (IoT) technology holds great promise for transforming the understanding and management of stress. By integrating IoT capabilities into wearable devices, new opportunities arise for real-time stress monitoring, providing valuable insights into users' physiological and behavioral responses. These IoT-enabled devices can collect and analyze a diverse array of biometric data, including heart rate variability, skin conductance, and sleep patterns, offering a comprehensive view of an individual's stress profile.

With this information, users can better understand their stress triggers, patterns, and responses, empowering them to adopt healthier coping mechanisms and make positive lifestyle changes. In this study, a wearable device was developed to detect and quantitatively assess stress levels based on vital signs. The MAX30102 sensor recorded heart rates ranging from

65 to 84 beats per minute and respiration rates between 10 and 12 breaths per minute. The galvanic skin response (GSR) sensor indicated values ranging from 80% to 85%, with average stress levels showing deviations of 5-10%.

The analysis of the data revealed no significant peaks or fluctuations, indicating stable conditions that did not require alerts. The system's predictions confirmed the absence of stress states. Observations of glucose levels before festive occasions and after meals showed that glucose levels did not exceed 180 mg/dL, thereby eliminating the need for an orange alert. If glucose levels surpass 200 mg/dL, the system will issue a red alarm signal indicating a potential hazardous condition. Importantly, the algorithm effectively accounts for food intake without generating false alerts.

This proposed wearable device differentiates itself from others described in the literature by its ability to measure heart rate, respiration rate, and skin conductance simultaneously. Future research will aim to explore the impact of stress on specific chronic conditions and incorporate additional sensors for more precise stress measurement.

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