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INTEGRATING WEARABLE SENSOR NETWORKS INTO FIREFIGHTER UNIFORMS: DESIGN, DEVELOPMENT AND EVALUATION OF A SMART E-TEXTILE SYSTEM

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Abstract

Firefighters operate in hazardous environments characterised by extreme heat, low visibility, and high physical demand. This study presents the design, fabrication, and evaluation of a smart e-textile prototype aimed at improving firefighter safety through real-time physiological and environmental monitoring. A sensor-integrated garment was developed using a 100% cotton base and an Adafruit Circuit Playground Bluefruit microcontroller with pulse, temperature, and motion sensors. The system transmits data to a cloud-based web interface via Bluetooth Low Energy (BLE) for remote monitoring. Evaluation covered comfort, mobility, system responsiveness, and accuracy of sensor data. Results indicated reliable signal transmission and comfort, though challenges remained with sensor alignment and accelerometer-based location accuracy. This research contributes to the growing field of smart protective clothing and outlines a scalable framework for integrating wearable technologies into emergency responder uniforms.

Keywords: Smart textiles, Firefighter PPE, Wearable sensors, Bluetooth communication, Protective clothing, Sustainable design

1. INTRODUCTION

Firefighting is among the most physically demanding and hazardous occupations, requiring personnel to work in environments characterised by extreme heat, toxic gases, and limited visibility. Although conventional personal protective equipment (PPE) provides thermal and mechanical protection, it does not monitor the wearer's physiological state or environmental parameters in real time (Walker et al., 2016). This limitation can delay early intervention during critical incidents such as heat stress, cardiac strain, or entrapment. Advances in e-textiles and flexible sensors offer new opportunities to embed monitoring systems directly into garments, thus transforming traditional PPE into intelligent protective systems. The UK government has invested in a new Emergency Services Network (ESN), which is being rolled out gradually across police, fire, and ambulance services, with full transition now expected by 2029. The ESN uses a 4G-based system rather than traditional radio communication, providing significantly wider coverage, including rural and remote regions. The network is also designed to operate in locations previously not covered—such as underground and metro transport systems. These improvements are expected to enhance inter-service communication and strengthen the speed, effectiveness, and quality of emergency response (National Audit Office, 2023).

Smart textiles, defined as textiles capable of sensing, reacting, and adapting to external stimuli, are increasingly being adopted in healthcare, sports, and defence applications (Pervez et al., 2024). These systems integrate conductive fibres, sensors, and microcontrollers into fabric structures to measure physiological signals such as temperature, heart rate, or movement (Stoppa & Chiolerio, 2014). In protective clothing, early research initiatives such as the European PROeTEX project demonstrated the feasibility of integrating temperature and motion sensors into firefighter suits (Voirin, 2015). However, early prototypes were limited by bulkiness, low signal accuracy, and difficulties in laundering and maintenance. Recent advancements in miniaturisation, wireless communication, and conductive materials have enabled lighter, more flexible systems (Azani & Hassanpour, 2024).

Despite this progress, there remains a research gap in integrating multi-sensor e-textile systems that balance comfort, mobility, and data reliability while being practical for routine use in fire services. This study aims to address this by developing and testing a prototype garment that combines a wearable sensor network with user comfort and safety considerations.

2. MATERIALS AND METHODS

A multidisciplinary approach combining textile design, electronics engineering, and software development was adopted to construct and evaluate the smart e-textile prototype.

2.1 GARMENT DESIGN AND FABRIC SELECTION

In a recent test for police officers' uniform, cotton was found the most comfortable for carrying out daily activities, that to be the favourite amongst those tested as it was the most comfortable overall, tested high in areas such as humidity and moisture controls (Derfashi, et al, 2025). As the daily activities of police officers are similar to that of firefighters, it was concluded that this would be a strong indication that cotton would be a good choice for this study. 100% cotton is commonly used for emergency services workers' base uniforms even though it is not fireproof. Cotton can be treated with fire retardant cyclodextrin and phytic acid to increase the oxygen index of cotton fabric (Ma, et al, 2023). These fabrics are still being developed and so are not easily available to be used in firefighter uniforms yet.

In this study, a fitted long-sleeve shirt made **of** 100% cotton (156 g/m²) was made as the base due to its breathability, softness, and ease of maintenance. Although cotton is not inherently flame-retardant, it is suitable for the inner layer of multi-layered firefighter clothing systems. All components were detachable to allow easy laundering, following BS 8617:2019 recommendations.

2.2 ELECTRONIC COMPONENTS

The Adafruit Circuit Playground Bluefruit BLE microcontroller was chosen for its integrated sensors and Bluetooth communication capabilities. The system architecture is summarised in Table 1.

Table 1. Various components of in a Smart Firefighter Uniforms

Component	Function	Specification
Adafruit Circuit Playground Bluefruit	Central control and data acquisition	Built-in accelerometer, thermistor, BLE connectivity
Pulse Sensor	Heart rate monitoring	Analog optical sensor, 0–220 BPM range
Battery Pack	Power supply	3.7V rechargeable Li-ion, 500 mAh
Cotton Fabric	Garment base	156 g/m², plain weave

The Adafruit Circuit Playground Bluefruit BLE was ultimately selected due to several specific advantages over the others. Firstly, the circuit board contains integrated sensors including an LIS3DH triple-axis accelerometer, thermistor, phototransistor, and microphone, enabling movement, temperature, light, and sound data to be recorded without the need for additional components. The Bluefruit operates on a 3.3V ATSAMS21 ARM Cortex M0 Processor, contains 2MB of SPI Flash storage and possesses a MicroUSB port for storing custom programming and debugging. However, the circuit board contains some limitations such as being susceptible to damage from water or moisture, requiring removal for laundering.

The pulse sensor was incorporated to track and monitor the user's heart rate for critical safety, allowing alerts to the external monitor if the users' heart rate deviates from the expected safe range. This real-time access enables the immediate dispatch of backup responses or First Aiders ensuring rapid response times in emergency situations. The pulse sensor selected for this project was a plug-and-play heat rate sensor chosen for its compact size enabling it to be easily embedded within the garment. There is also extensive support and documentation by Adafruit, Circuit Python and PulseSensor.com for this sensor. It is compatible with the Adafruit Circuit Board.

2.3 SOFTWARE AND DATA TRANSMISSION

Sensor readings were collected using the CircuitPython library and transmitted every ten seconds via BLE to a Flask-based Python server. Data was visualised on a web dashboard developed using Tailwind CSS and Google Maps API, allowing real-time tracking and alert generation when parameters exceeded safe thresholds. The architecture is illustrated in Figure 1.

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2.4 TESTING PROTOCOL

A volunteer wore the prototype for 30 minutes under simulated activity conditions to assess comfort, range of motion, and data accuracy. Sensor accuracy was validated by comparing pulse readings to a commercial smartwatch. Temperature and light sensors were calibrated under laboratory conditions. User comfort was evaluated via a questionnaire using a 5-point Likert scale.

2.5 OVERALL SYSTEM

As shown in Figure 1, the pulse sensor was connected to the board at the Ground (GND) pin, the A1 analogue-input pin which receives data from the sensors and the VOUT which is the output voltage which sends power to the sensor. The external battery was connected using the battery input at the bottom of the board.

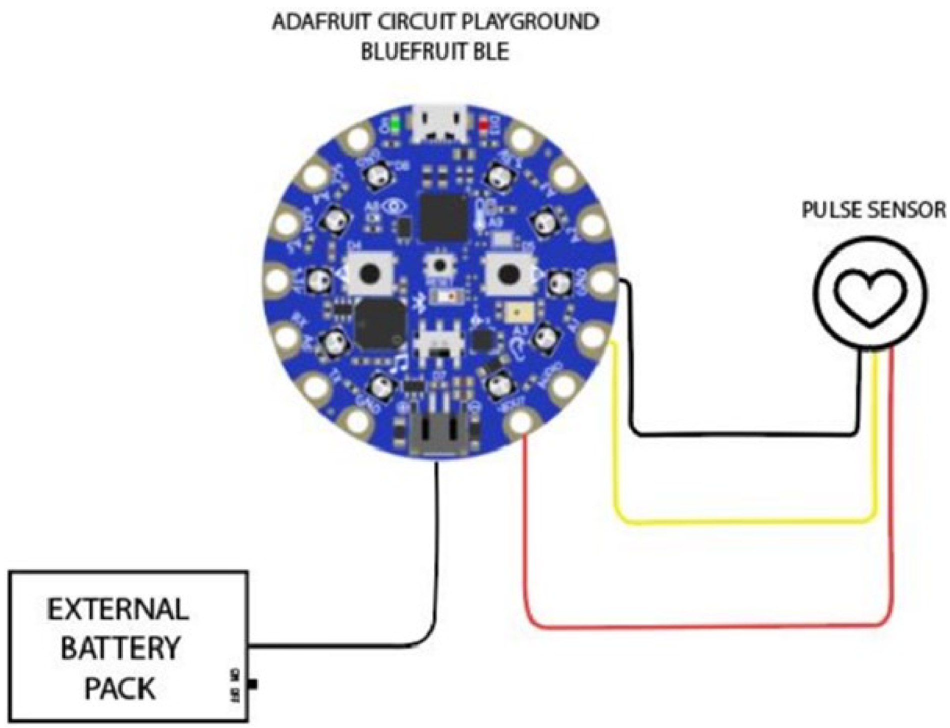

Figure 1. System circuit showing the Adafruit Circuit Playground Bluefruit BLE connected to the external battery pack and pulse sensor.

demonstrate how sensor data is transferred and processed to the web interface.

3. RESULTS AND DISCUSSION
3.1 TECHNOLOGIES

The E-Textile system was successfully constructed and incorporated into a garment. The pulse sensor was connected to the Adafruit Circuit Playground Bluefruit at the GND, A1 and the VOUT pins, and the external battery pack was connected at the power input at the bottom of the board, as shown in Figure 2 (a). Power was consistent throughout the length of testing and data from the pulse sensor was sent to the board with no issues, showing that the system is functional. Figure 2 (b) shows the positioning of the pulse sensor on base garment sleeve. For optimal sensor accuracy the recommended sensor placement is on the fingertip or earlobe, however these locations are impractical for firefighters uniform as it would hinder the job of the firefighters and reduce mobility. Therefore the wrist was chosen for sensor placement. The sensor works by shinning a small light into the skin and detecting how much light is reflected back, measuring the changes in blood volume within the capillaries to detect the pulse. As a result. To achieve accurate results the sensor requires optimal alignment and consistent contact, and any displacement of sensor could interfere with results.

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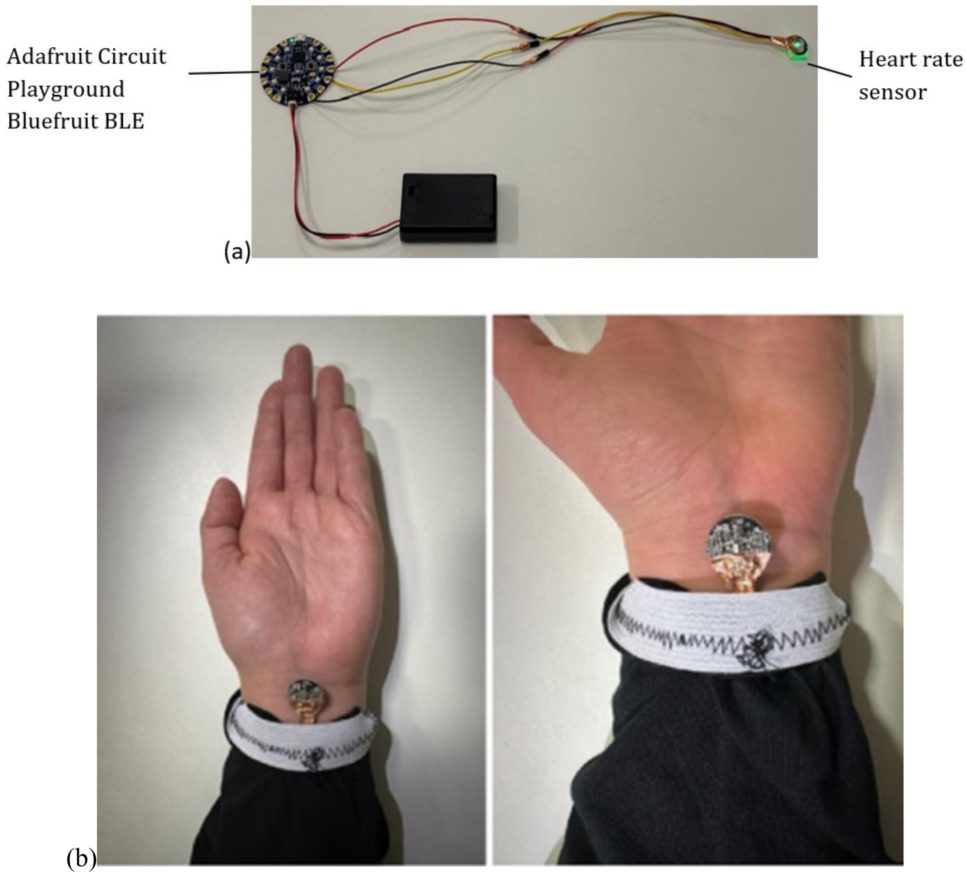

Figure 2. (a) Adafruit Circuit Playground Bluefruit connected to the pulse sensor and external battery, and (b) placement of pulse sensor on sleeve.

3.2 CODING

The circuit board utilized the Adafruit_Circuitplayground library to interface with its onboard sensors, including the accelerometer, thermistor, phototransistor, and microphone. These sensors were sampled every 10 seconds for their readings.

For the heart rate sensor, the Board library is used to access the circuit board input output pin A1, where the sensor was connected. The sensor measures the light refraction value from the skin which fluctuates with the blood pressure in the circuitry system. A heartbeat can be detected when this value crosses the zero threshold. The sensor was programmed to be sampled every 0.75 seconds averaging 10 oversamples per reading over 20 samples which was done to balance performance with accuracy. The 0.75 second interval was chosen to avoid overloading the circuit board while maintaining data accuracy. Every 10 second the system would extrapolate the beats per minutes (8PM) by multiplying the number of detected beats by 6, proving near real-time accurate heart rate data.

The Bluetooth connection interface class was implemented to facilitate communication between the Circuit Board and Python server over Bluetooth Low Energy (BLE) using the Bleak library. The two primary class variables were a UART RX UUID for idendifying incoming BLE notifications, and a DataHandler object which was used for thread-safe data storage and retrieval. The connect function utilized the BleakScanner to discover nearly BLE devices and filtered to connect to the target device. The system subscribed to notifications using the specified UART RX UUID when connected, enabling data transfer between the circuit board and server. Any data received would be asynchronously handled by a separate function which would decode the data and extract relevant data values based on its data label (pulse, motion, light, temp, sound). This data was then stored into the appropriate buffer within the DataHandler object. The modular approach to the system design enables maintainability and scalability for any future development as it promotes high cohesion and low coupling.

For data handling, the DataHandler class was created to manage and store incoming sensor data in a thread-safe and modular manner. The class contained 5 dedicated buffers, one for each data type i.e. from each of the five sensors, with each buffer protected by a semaphore lock to ensure data integrity during concurrent access. The semaphore lock allowed asynchronous data to be written and read without conflicts. The class performed three core functions. Firstly it would safely store incoming data via the lock to the appropriate buffer. Secondly it would return the last value from each buffer, and finally it would export all the stored data to CSV format for record keeping or later analysis. This modular and thread-safe approach increases cohesion and reduces coupling, improving maintainability and enabling future development.

The Graphical User Interface (GUI) was created using HTM, Tailwind CSS, JavaScript, AJAX, and Google Maps API. The GUI provides real-time data visualization of the sensor data collected from the garment. The interface displayed pulse, temperature, light, sound and accelerometer data in a dashboard layout along with a map that visualises the wear's location and movements. HTML was used to create the elements and structure while Taiwind CSS was utilized to style the interface as it provides a consistent and professional appearance. Tailwind also allows the interface to be compatible across various device sizes as it will auto adjust for screen size. The interface also has dismissible alert banners which are triggered when the sensor data exceeds a predefined safety threshold. These alerts can inform the user when abnormal data is recorded such as dangerous temperature conditions or irregular heart rates. After being dismissed, a 5 second cooldown period was added to the alerts before they would reappear, to reduce spamming. JavaScript was utilized to handle the asynchronous data acquisition by sending periodic AJAX HTTP GET requests to the backend server endpoint (/data_req) which was created using Flask. The acquired data was then extracted and used to update the interface dashboard and map. The data was also checked to determine if any thresholds had been exceeded for the alert banners. The GUI integrated the Google Maps API to visulise the wearers movements using the accelerometer data to estimate the relative displacement from the user's initial location. This was calculated by multiplying velocity by time to get the distance moved which was then converted to longitude and latitude coordinates. The new user's coordinates were used to reposition and update the map accordingly. The real-time data monitoring and interactive alerts allows the user to determine the wearers status and location allowing aid to be sent during emergencies. The GUI was also designed with modularity to allow future integration of additional sensors and further development.

3.3 PROTOTYPE CONSTRUCTION AND PLACEMENT

A tight-fitting long-sleeve shirt was chosen as the garment base of this study as it allows the sensors to be closely contact to the skin in order to obtain as accurate readings as possible. The circuit board was placed in a small pocket on the left sleeve of the shirt as shown in Figure 3, which allows for the sensors on the circuit board to easily take the required data from its surroundings while keeping it in a good location to be reached by the external pulse sensor. The pulse sensor is held in place by elastic and Velcro on the wrist of the left-hand sleeve, which can be easily attached and removed for laundering purposes. All of the hardware and sensors can be removed from the prototype for easy cleaning and laundering.

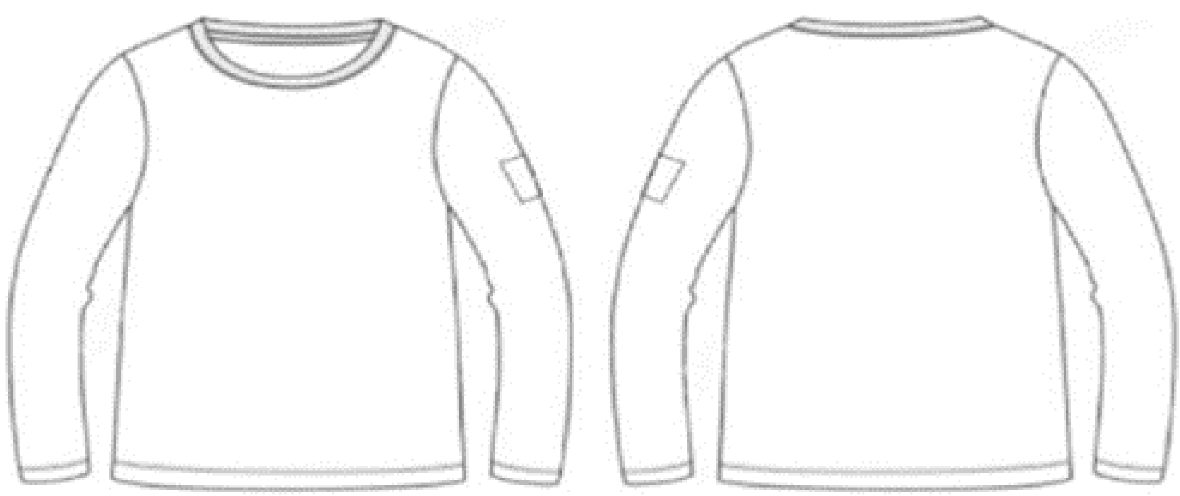

Figure 3. Technical drawing of prototype shirt with pocket: front view (left) and back view (right).

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The prototype transmits sensor data to a computer server using BLE. The server then sends the data to the storage system, where it is stored and processed, shown in Figure 4. Communication between the server and the web interface is handled using HTTP requests – data is sent to the web interface using HTTP POST and retrieved using HTTP GET.

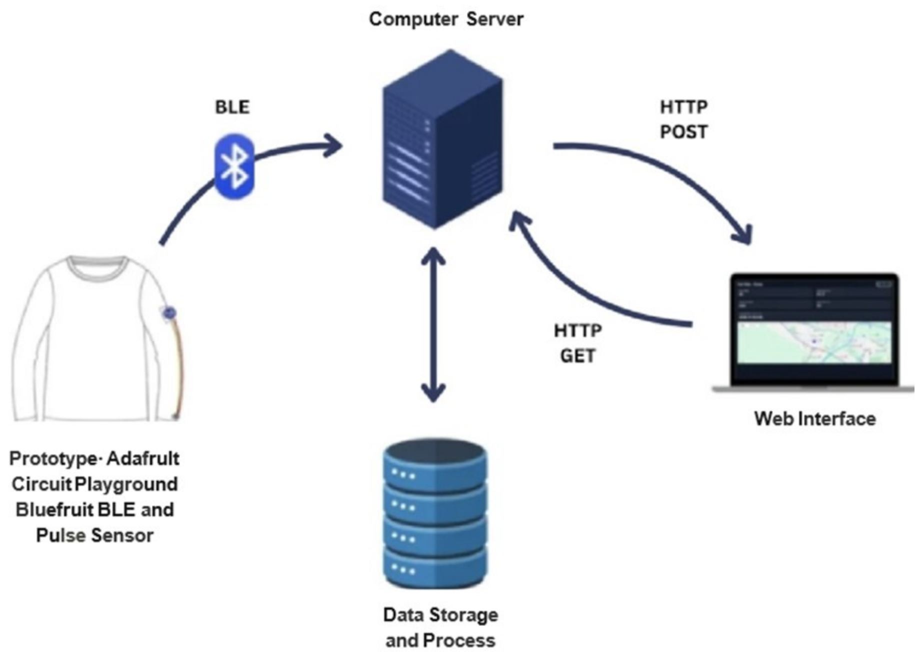

Figure 4. How the sensor data is transferred and processed to the web interface.

One wore the prototype for 30 minutes, during which time the data on the web interface was closely monitored to assess the accuracy and credibility of the results. The temperature, light Figure 5 is a screenshot of web interface clearly displays the pulse, temperature, light and sound sensors successfully recorded data which was transmitted to the interface via the microcontroller. Overall, the data collected exhibited a reasonable degree of accuracy, this can be seen in Figure 6, which shows the web interfacing clearly displaying the data sent from the sensors on the garment worn.

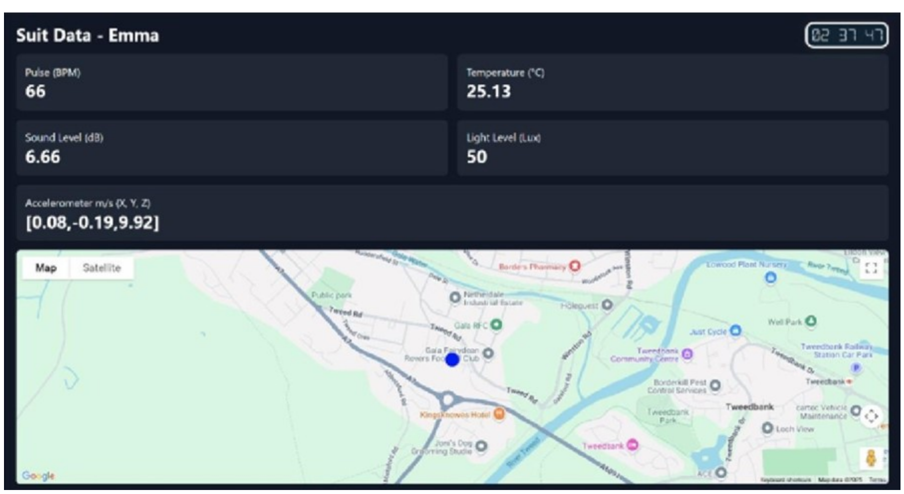

Figure 5. Screenshot of web interface showing data from sensors.

Table 2 provides feedback from users. Overall, the user feedback indicated high comfort and wearability. However, long-term wear trials are required to evaluate durability and sweat resistance. Figure 4 shows the temperature response recorded during activity compared to ambient laboratory temperature, demonstrating sensitivity to environmental change.

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Table 2. User evaluation of comfort and mobility (n=5).

Parameter	Mean Rating (1–5)	Comments
Comfort	4.6	Soft and breathable fabric, minimal irritation
Mobility	4.8	Unrestricted arm and torso movement
Sensor placement	4.2	Slight pressure in wrist area
System stability	4.5	Consistent Bluetooth connection
Sustainability	4.2	All hardware is easily detachable and replaceable from both the system and the garment, garment can be washed and reused, last long

4. CONCLUSIONS

This study demonstrated the successful design and implementation of a sensor-integrated garment capable of real-time monitoring of heart rate, temperature, and motion. The prototype balanced functionality with comfort and showed reliable BLE-based data transmission. Future work should focus on integrating GPS tracking, waterproofing, and developing a fully fire-retardant textile base. These developments would allow practical deployment in operational firefighter uniforms and further enhance safety outcomes.

5. CONFLICT OF INTEREST STATEMENTS

The authors can confirm that there is no conflict of interest for this research work.

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