EPiC Series in Built Environment
Volume 7, 2026, Pages 644–653
Proceedings of Associated Schools of Construction 62nd Annual International Conference

Design and Implementation of a Low-Power Multi-Sensor Wearable with Real-Time BLE Data Streaming for Construction Safety Applications

Rizwan Farooqui[1], Abid Hassan[1], Abhinav Dhakal[1] and Asad Malik[1]
[1]Mississippi State University

The construction industry remains one of the most hazardous occupational sectors, with high rates of injuries and fatalities caused by heat stress, fatigue, and unsafe movements. Although wearable technologies have shown promise in improving worker safety, most existing devices store data locally and do not provide real-time access, limiting their usefulness for immediate intervention. This study was initiated to address that limitation through the development of a custom, low-power wearable device capable of streaming multi-sensor data continuously in real time. The prototype integrates a MAX30102 photoplethysmography (PPG) sensor for heart rate and blood oxygen saturation, an MLX90614 infrared temperature sensor for skin temperature, and a six-axis inertial measurement unit (IMU) for motion tracking. These components are embedded on a compact printed circuit board (PCB) centered on an nRF52840 microcontroller with Bluetooth Low Energy (BLE) for efficient data transmission. Firmware was developed to synchronize sensor sampling and structure BLE packets for stable streaming. Preliminary tests confirmed reliable real-time transmission, consistent signal quality, and low power consumption, demonstrating the feasibility of continuous physiological and motion monitoring. The system provides an accessible foundation for proactive, data-driven safety management in construction environments.

Keywords: Wearable devices, Construction safety, Real-time data access, Bluetooth Low Energy, Physiological monitoring

Introduction

The construction industry is inherently hazardous, characterized by significant risk factors that contribute to elevated accident rates, fatalities, and health hazards for workers. To illustrate the dangers faced by construction workers, data from the Occupational Safety and Health Administration (OSHA) and the Bureau of Labor Statistics indicate that falls remain the leading cause of fatalities, accounting for approximately one-third of construction deaths in 2020 (Bureau of Labor Statistics [BLS], 2022; OSHA, 2024). Furthermore, 41,400 nonfatal workplace injuries were recorded due to slips, trips, and falls in construction during 2020, highlighting the severe risks workers encounter daily (Le et al., 2025). Additionally, a substantial increase in nonfatal injury rates from 94.8 cases per 10,000 full-time workers to 127.2 cases per 10,000 was reported for construction laborers in that timeframe (Le et al., 2025).

W. Collins, A. Perrenoud and J. Posillico (eds.), ASC 2026 (EPiC Series in Built Environment, vol. 7), pp. 644–653

Construction workers are also significantly impacted by heat stress, driven by prolonged exposure to high ambient temperatures. Research suggests that the likelihood of heat-related health complications escalates with extended periods in high-heat environments, with an incidence rate of 35% among individuals exposed to occupational heat stress experiencing symptoms of heat strain (Tsoutsoubi et al., 2024). Additionally, a recent scoping review emphasized risk factors and health consequences related to extreme heat exposure among construction workers, underscoring the critical need for effective monitoring and intervention strategies (Nazneen, 2025). Recognizing these high-risk factors, timely physiological and motion monitoring emerges as a vital intervention to prevent many of these incidents.

Fatigue (Martins et al., 2021), heat strain (OSHA, 2024), and prolonged physical workload (Martins et al., 2021) can degrade overall physical stability (Jo & Kim, 2024), which can elevate the risk of slips, trips, and falls (Karim et al., 2025). Continuous physiological and motion monitoring wearable devices equipped with physiological sensors can detect early warning signs of fatigue or stress, such as elevated heart rate and abnormal skin temperature fluctuations (Friedrich et al., 2025). For instance, Aghimien et al. (2024) highlighted that intelligent wearable technologies can assess variations in workers' physical responses and alert supervisors to potential risks before incidents occur. The integration of real-time sensors can proactively inform workers of heat strain or significant physical exertion, fostering a safer working environment. Moreover, strategies in ergonomic assessments often advocate preemptive measures that can avert exhaustion and ensure worker well-being (Aghimien et al., 2024; Friedrich et al., 2025).

Although wearable technologies have become increasingly common in construction safety, most existing systems focus on a single data domain—either physiological or motion sensing—without offering an integrated view of a worker's condition. For instance, the IoT-enabled smart helmet developed by Raghunath and Ghaffar (2025), successfully monitors environmental conditions and head movement, yet it does not incorporate physiological indicators such as heart rate or body temperature. This single-domain approach limits the ability to detect early signs of fatigue, heat strain, or stress, which often emerge from the combined effects of physical activity and physiological overload. Bridging these dimensions through a unified, real-time sensing platform is therefore essential to achieve comprehensive, data-driven safety management and timely intervention in construction environments.

In occupational environments, continuous monitoring devices must sustain multi-hour operation without access to charging infrastructure, making energy efficiency essential for field deployment (Todorovic, 2023). Bluetooth Low Energy (BLE) offers substantially lower wireless power consumption than Wi-Fi or cellular radios, enabling long-duration wearable streaming (Siekkinen et al., 2012). These characteristics support the development of custom, low-power, real-time wearable platforms suitable for rugged construction settings, where immediate access to safety-critical information is needed to enable timely intervention (Todorovic, 2023). Recent work has also demonstrated the feasibility of such systems in demanding field environments (Aghimien et al., 2024), including heat-stress monitoring applications in outdoor occupations where continuous physiological feedback has been shown to promote safer work practices (Friedrich et al., 2025; Notley et al., 2025).

Furthermore, numerous studies indicate specialized wearable monitoring systems are adept for outdoor workers, particularly in sectors with high exposure to thermal stressors like construction and agriculture (Morrissey et al., 2023; Notley et al., 2025; Ierardi & Pavilonis, 2025). This investigation recognizes the necessity for further research into wearable technologies that are resilient, easy to use, and capable of collecting valuable data that can prevent heat-related illnesses and accidents associated with fatigue.

In conclusion, the alarming statistics surrounding construction safety underline the pressing need for intervention through continuous physiological and motion monitoring. Through real-time data access from comprehensive wearable platforms can potentially revolutionize the approach to worker safety by addressing the dual challenges of monitoring physiological health and mitigating movement-related risks. As technology in this domain evolves, the integration of both types of data will be pivotal for preventing occupational accidents and promoting a safer work environment.

Research Gap and Objectives

Despite the growing use of wearable technologies in the construction sector, current systems still face fundamental limitations. Many commercial and research prototypes record sensor data locally and rely on post-event analysis, restricting their usefulness for proactive safety intervention and failing to address real-time conditions such as heat strain and fatigue. Moreover, existing devices typically monitor either physiological signals or motion characteristics independently, providing only a partial view of the worker's condition and limiting their ability to detect impairment during physically demanding tasks. Prior studies have shown that fatigue (Martins et al., 2021), heat strain (OSHA, 2024), and prolonged physical workload (Martins et al., 2021) can reduce physical stability (Jo & Kim, 2024) and elevate the likelihood of slips, trips, and falls (Karim et al., 2025). These findings highlight the importance of recognizing when workers are approaching conditions that may compromise balance or coordination so that timely assistance or intervention can be provided. Consequently, there is a strong need for continuous access to both physiological and motion data to support early detection and preventive action. Another persistent challenge lies in hardware optimization, having all the needed sensors in a compact size that can be worn by the construction workers without any problem while working on site.

This project addresses these limitations by designing and validating a custom, low-power wearable device that can monitor and transmit physiological and motion data in real time. By enabling continuous data streaming, the system supports the early detection of slips, trips, falls, and other unsafe events, by analyzing sensor data in real-time and allowing on-site intervention before injuries occur. The specific objectives of this study are to:

1. Design and integrate a compact, energy-efficient wearable system that combines physiological and motion sensors on a single PCB.
2. Develop optimized firmware for synchronized data sampling and Bluetooth Low Energy (BLE)–based real-time transmission; and
3. Evaluate system functionality and performance under controlled conditions to establish its feasibility for future field deployment in construction environments

Methodology

System Overview

The proposed system is a compact wearable device developed to continuously capture and transmit physiological and motion data in real time. It integrates three sensors—a MAX30102 for heart rate and SpO_2, an MLX90614 for skin temperature, and a six-axis IMU (ST LSM6DS3TR-C) for motion tracking—interfaced with an nRF52840 microcontroller. Embedded Bluetooth Low Energy (BLE) enables efficient wireless transmission to a receiver for real-time visualization and analysis. All components operate at 3.3 V and are powered by a 3.7 V, 200 mAh lithium-ion battery, supporting long-duration portable use. The overall system architecture is shown in Figure 1

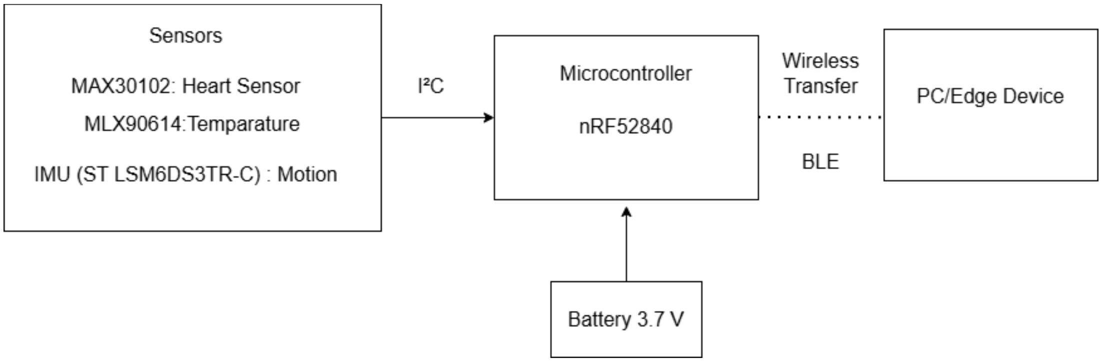
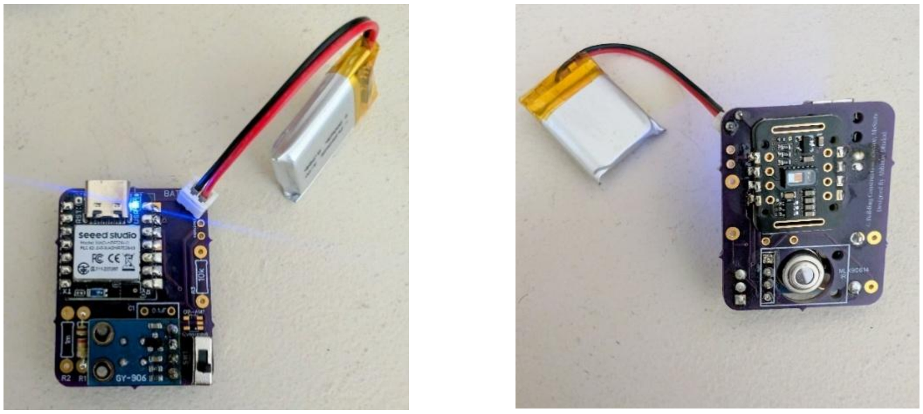


Figure 1. System architecture of the proposed wearable device

Hardware Design

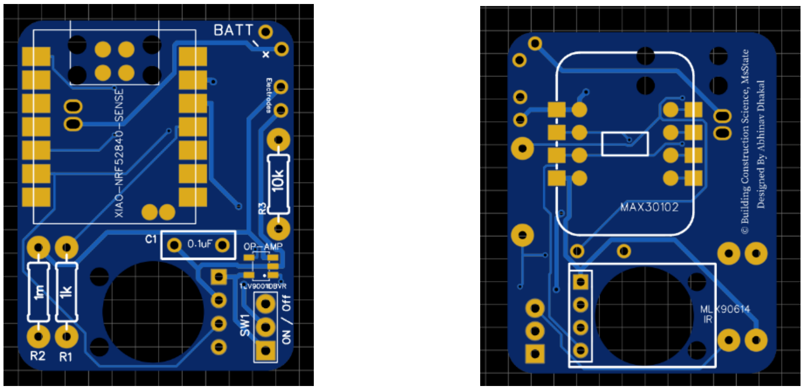
The hardware design of the wearable system was carried out using EasyEDA, which enabled schematic drafting and two-layer PCB layout optimization. The final board measures 30.1 × 38.1 mm (1.19 × 1.50 in) and was configured for compactness, low power consumption, and minimal signal interference between analog and digital lines. Figure 2 illustrates the front and back PCB layouts, highlighting the placement of the main components and sensor routing. The MAX30102 and MLX90614 sensors were interfaced with the nRF52840 microcontroller through the I²C protocol, while the IMU (ST LSM6DS3TR-C) is embedded within the microcontroller itself. The layout was designed to ensure optimal sensor positioning and stable signal acquisition. The MAX30102, used for heart rate and SpO_2 measurement, is placed on the back side of the PCB to maintain consistent skin contact. The MLX90614, which measures infrared skin temperature, is mounted on the front side of the board with a dedicated cutout that allows the sensor to maintain an unobstructed line of sight to the skin surface.



Front Part Back Part that touches skin

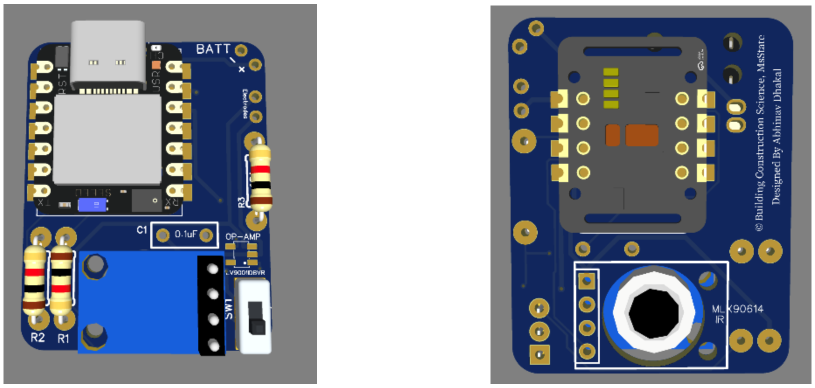
Figure 2. Assembled prototype of the wearable device showing the nRF52840 microcontroller board, integrated MLX90614 infrared temperature sensor, MAX30102 PPG sensor, and connected Li-ion battery

All components operate at 3.3 V, supplied by a 3.7 V, 200 mAh Li-ion battery. No additional voltage regulator was required, as the microcontroller provides internal power regulation and an integrated USB-C charging circuit. The overall assembly is shown in Figure 3, which presents the fully assembled prototype with the battery and sensor modules connected. To enhance usability and durability, an enclosure is being developed that will secure the PCB, protect it from external impact, and maintain consistent pressure between the sensors and the skin. The enclosure will leave openings for the optical (MAX30102) and infrared (MLX90614) sensors, allowing unobstructed measurements while ensuring adequate ventilation and comfort during prolonged use.



Front Part Back Part

Figure 3. Front and back PCB layout of the custom two-layer board designed in EasyEDA, showing component placement for the MAX30102, MLX90614, and nRF52840 module



Front Part Back Part

Figure 4. Front and back PCB layout of the assembled prototype of the wearable device

Firmware and Communication Design

Firmware was developed using the Arduino IDE in C++, incorporating the following libraries: SparkFun MAX30105 (for MAX30102), Adafruit MLX90614, SparkFun LSM6DS3, and ArduinoBLE. The firmware handles sensor initialization, synchronous data sampling, packet formation, and BLE transmission.

Sampling and notification rates were optimized for stability and energy efficiency:

- MAX30102 (IR & Red): 50 Hz (every 20 ms)
- MLX90614 (Temperature): 5 Hz (every 200 ms, °C × 100)
- IMU: 5 Hz (every 200 ms, 6 float32 values for acceleration and gyroscope)
- Battery voltage: 5 Hz (every 200 ms)

The data packet structure contained 40 bytes per transmission, including IR and Red LED readings (4 bytes each), temperature (4 bytes), IMU data (24 bytes), and battery voltage (4 bytes). To maintain communication reliability, each packet included a sequence number and checksum for error detection, with acknowledgment (ACK) and retransmission logic handled by the receiver.

The BLE service, titled "BCS-Watch," used notification-enabled characteristics for all sensors. The IMU characteristic required a minimum MTU size of 27 bytes to accommodate single-frame delivery. Synchronization logic followed a sequential sampling order—temperature → PPG → IMU—executed within a fixed transmission interval. An internal 50-sample circular buffer was used for real-time SpO_2 computation but not for BLE queuing, maintaining minimal latency.

Receiver and Data Processing

A custom Python script was developed using bleak, numpy, scipy, and matplotlib libraries to receive, decode, and visualize incoming BLE packets. The script computed real-time heart rate and SpO_2 values from rolling IR/Red data buffers (~2.5 s at 50 Hz) and generated continuous waveform plots for live observation. Battery voltage was translated into percentage levels through a linear mapping of 3.0–4.2 V. The program logged any missing packets and flagged corrupted transmissions through checksum validation.

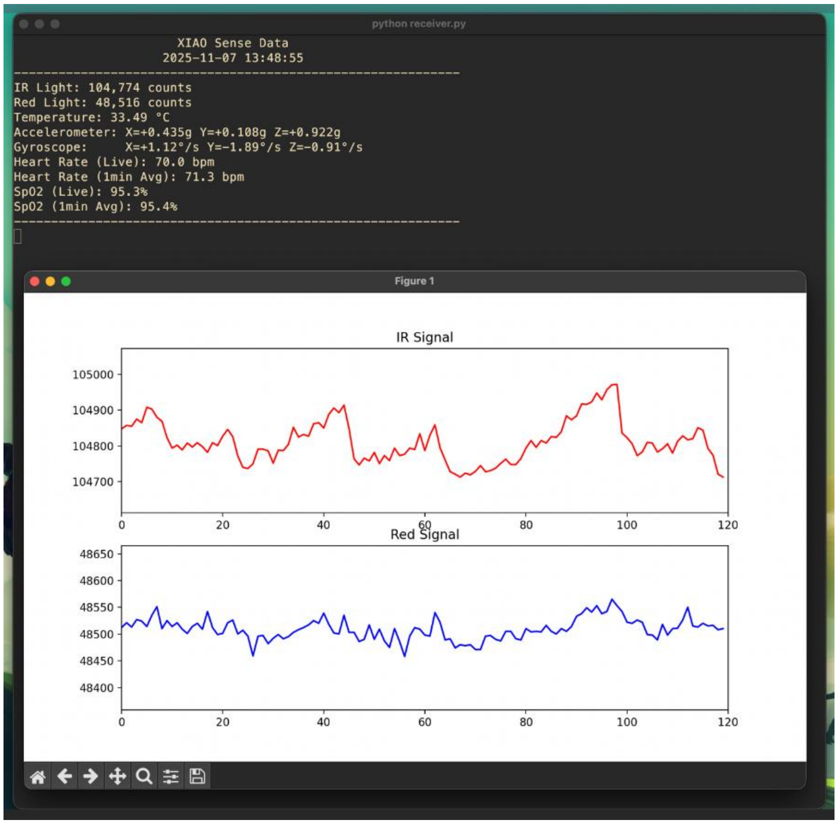
Preliminary Validation and Results

Validation Setup

A comparative test was conducted to evaluate the heart rate and SpO_2 readings of the prototype against a Mi Band 9 Pro, which served as the reference device. Both devices were worn simultaneously on the same wrist under controlled indoor lighting conditions. As the custom 3D-printed enclosure is still under development and the current version does not include a mounting hook, the prototype was positioned securely inside a wristwatch strap to maintain stable contact with the skin during testing. Data were recorded over multiple short trials with minimal movement, followed by a basic motion test to assess stability. Figure 5 Presents the setup for the evaluation

Figure 5. Experimental setup showing the prototype positioned inside a wristwatch strap and worn alongside a Mi Band 9 Pro for preliminary validation of heart-rate and SpO_2 measurements

The Mi Band 9 Pro was chosen for comparison due to its widespread use and built-in optical sensors for heart-rate and SpO_2 monitoring, which are functionally comparable to the MAX30102 used in the prototype. While consumer-grade and not intended for clinical accuracy, it provides a practical baseline for assessing the relative performance and stability of the prototype under similar conditions.



```
                  XIAO Sense Data
                2025-11-07 13:48:55
------------------------------------------------------------
IR Light: 104,774 counts
Red Light: 48,516 counts
Temperature: 33.49 °C
Accelerometer: X=+0.435g Y=+0.108g Z=+0.922g
Gyroscope:     X=+1.12°/s Y=-1.89°/s Z=-0.91°/s
Heart Rate (Live): 70.0 bpm
Heart Rate (1min Avg): 71.3 bpm
SpO2 (Live): 95.3%
SpO2 (1min Avg): 95.4%
------------------------------------------------------------
```

Figure 6. Python receiver interface displaying sensors signal data in real time

```
                  XIAO Sense Data
                2025-11-07 13:48:55
------------------------------------------------------------
IR Light: 104,774 counts
Red Light: 48,516 counts
Temperature: 33.49 °C
Accelerometer: X=+0.435g Y=+0.108g Z=+0.922g
Gyroscope:     X=+1.12°/s Y=-1.89°/s Z=-0.91°/s
Heart Rate (Live): 70.0 bpm
Heart Rate (1min Avg): 71.3 bpm
SpO2 (Live): 95.3%
SpO2 (1min Avg): 95.4%
------------------------------------------------------------
```

Figure 7. Closer look on the sensor data readings from the sensors

Figure 6 shows the Python-based receiver application displaying live BLE data streaming from the wearable prototype. The console reports raw sensor values and computed metrics, while the lower plots visualize real-time infrared (IR) and red photoplethysmography (PPG) signals. The periodic IR peaks correspond to heartbeats, and comparison with the red signal enables estimation of blood oxygen saturation (SpO_2). Figure 7 presents a closer look at the numerical readings for the MAX30102 (IR & Red), MLX90614 (Temperature), IMU: ST LSM6DS3TR-C (Motion) sensors.

Performance and Signal Quality

The prototype successfully streamed all sensor data in real time over BLE with no visible delay within a range of approximately 5–10 m. The IR and Red signals exhibited clean periodic peaks corresponding to heartbeats (Figure 6), confirming correct sensor operation. Heart rate and SpO_2 readings from the prototype closely matched the Mi Band measurements during static conditions (Table 1). The average difference was within 5–8 bpm for heart rate and within 1–2 % for SpO_2. Motion introduced minor fluctuations in signal amplitude, consistent with expected motion artifacts, which can be mitigated with future digital filtering.

Table 1. Comparison of Heart Rate and SpO_2 Between the Prototype and Mi Band 9 Pro.

Trial	Mi Band HR (bpm)	Prototype HR (bpm)	Mi Band SpO_2 (%)	Prototype SpO_2 (%)
1	78	~70	98	~96
2	79	~74	99	~99.2
3	82	~74.4	98	~95
4	70	~60	98	~99

BLE transmission remained stable during the tests, and no packet loss was observed visually in the receiver logs. The system maintained consistent performance for over one hour of continuous operation without overheating or signal drift.

Power and Efficiency Results

The current draw during operation was measured at 16.2 mA, aligning with the design expectation. Based on this measurement, the estimated battery life exceeds 10 hours, sufficient for typical work-shift monitoring. Reducing temperature sampling frequency (e.g., once per minute) could further extend runtime without compromising data relevance.

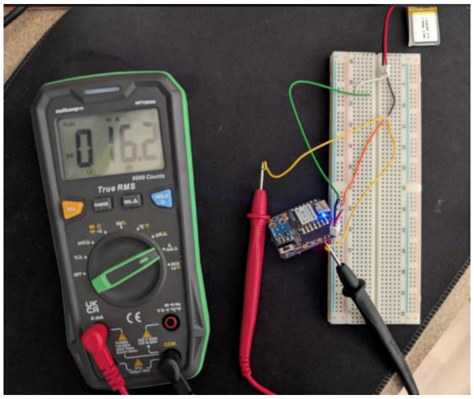


Figure 8. Power measurement setup for the wearable prototype

Discussion

The prototype successfully demonstrated real-time acquisition and wireless transmission of physiological and motion data, addressing a major limitation of current construction wearables that rely on post-event analysis. The device produced clear IR and red PPG signals with distinct heartbeat peaks and consistent SpO_2 readings when compared with the Mi Band 9 Pro, validating the MAX30102 sensor's performance under static conditions. Minor discrepancies observed during movement were attributed to motion artifacts and contact pressure variation, which will be mitigated through enclosure refinement and signal filtering. Although no fall or motion classification was performed in this initial device evaluation, Figure 7 shows the real-time data reading accelerometer and gyroscope data streamed over BLE from the IMU sensor, confirming synchronized multi-axis sampling and wireless transmission. Power testing showed an average current draw of 16.2 mA, supporting over ten hours of continuous operation with a 200 mAh Li-ion battery—sufficient for a full work shift. BLE transmission remained stable and responsive, confirming the feasibility of continuous on-site data streaming. The integration of physiological and motion sensors within a single compact PCB demonstrates strong potential for correlating worker strain, fatigue, and activity in real time.

Immediate next steps include the design of a 3D-printed enclosure and strap system to ensure consistent skin contact, protection from environmental exposure, and user comfort. This prototype also forms the foundation of a larger research initiative in which the team, in collaboration with clinical psychology experts, aims to analyze construction workers' physiological responses to stress and fatigue. The device's real-time streaming capability will support the development of predictive models that anticipate unsafe physical and psychological states, advancing toward proactive, data-driven safety and well-being management in construction environments.

Conclusion

This study presented the design and validation of a compact, low-power wearable system capable of real-time physiological and motion data streaming for construction workers. The prototype successfully demonstrated stable BLE transmission, accurate heart rate and SpO_2 estimation, and efficient power performance suitable for full-shift operation. By integrating multiple sensing modalities within a single custom PCB, the system establishes a foundation for continuous and proactive safety monitoring.

Future work will bring the system closer to field deployment. First, secure wireless transmission will be added to protect personal health information. Second, the device's temperature behavior will be tested outdoors to ensure the enclosure remains comfortable in hot weather. Third, Bluetooth packets will be updated to include device identifiers so that multiple units can be managed at the same time. Fourth, longer-range Bluetooth modes will be explored to improve connectivity on large or interference-heavy sites. We will also examine the best placement for the motion sensor, because a wrist-mounted IMU can pick up tool-use motions like hammering and may not always reflect whole-body movement. Activity recognition methods will be explored to separate tool-use motions from walking and balance-related motion. In parallel, ongoing collaboration with psychology researchers will inform future modeling of stress and fatigue using physiological and motion signals. Together, these improvements will support future predictive analytics for fatigue and unsafe motion, helping shift safety monitoring from reactive incident reporting to proactive risk management.

References

Adão Martins, N. R., Annaheim, S., Spengler, C. M., & Rossi, R. M. (2021). Fatigue monitoring through wearables: a state-of-the-art review. *Frontiers in Physiology*, *12*, 790292.

Aghimien, L., Ngcobo, N., & Aghimien, D. (2024). Intelligent Wearable Technologies for Workforce Safety in Built Environment Projects in South Africa. *Sustainability*, *16*(8), 3498.

Bureau of Labor Statistics. (2022). *Workplace injuries and job requirements for construction laborers*. U.S. Department of Labor. https://www.bls.gov/spotlight/2022/workplace-injuries-and-job-requirements-for-construction-laborers/

Friedrich, J., Schick, T. S., Mess, F., & Blaschke, S. (2025). Wearable device-based interventions in heat-exposed outdoor workers—a scoping review and an explanatory intervention model. *BMC Public Health*, *25*(1), 2893.

Ierardi, A. M., & Pavilonis, B. (2025). New York City occupations at-risk of heat stress: integrating O* NET and BLS data for occupational insights. *Annals of Work Exposures and Health*, wxaf022.

Jo, D., & Kim, H. (2024). The influence of fatigue, recovery, and environmental factors on the body stability of construction workers. *Sensors*, *24*(11), 3469.

Karim, R., Guo, X., & Wu, H. (2025). Advancing Physical and Mental Fatigue Analysis in Construction Workers: Insights, Technologies, and Future Directions. *Developments in the Built Environment*, 100808.

Le, A. B., Shkembi, A., Scott Earnest, G., Garza, E., Trout, D., & Choi, S. D. (2025). Nonpharmacological pain management approaches among US construction workers: A cross-sectional pilot study. *American Journal of Industrial Medicine*, *68*, S158-S170.

Morrissey, M. C., Kerr, Z. Y., Brewer, G. J., Tishukaj, F., Casa, D. J., & Stearns, R. L. (2023). Analysis of exertion-related injuries and fatalities in laborers in the United States. *International Journal of Environmental Research and Public Health*, *20*(3), 2683.

Nazneen, S., Choi, S. D., & Ibarra-Mejia, G. (2025). Extreme Heat Exposure in the Construction Industry: A Scoping Review on Risk Factors and Heat-Related Health Consequences. *International Journal of Environmental Research and Public Health*, *22*(11), 1651.

Notley, S. R., Meade, R. D., Looney, D. P., Chapman, C. L., Potter, A. W., Fogarty, A., ... & Kenny, G. P. (2025). Physiological monitoring for occupational heat stress management: recent advancements and remaining challenges. *Applied Physiology, Nutrition, and Metabolism*, *50*, 1-14.

OSHA (2024). Heat injury and illness prevention in outdoor and indoor work settings: Notice of proposed rulemaking (Docket No. OSHA–2021–0009). U.S. Department of Labor, *Occupational Safety and Health Administration*.

Raghunath, S., & Ghaffar, S. H. (2025). Developing an IoT-Enabled Smart Helmet for Worker Safety: Technical Feasibility and Business Model. *Safety*, *11*(3), 89.

Siekkinen, M., Hiienkari, M., Nurminen, J. K., & Nieminen, J. (2012, April 1). *How low energy is bluetooth low energy? Comparative measurements with ZigBee/802.15.4*. IEEE Xplore. https://doi.org/10.1109/WCNCW.2012.6215496

Todorovic, A. (2023). 'Remote workplaces' – How wirelessly connected wearable monitoring devices provide insight and context to the occupational hygienist on potential workplace exposures. *Annals of Work Exposures and Health, 67*(Suppl. 1), i12–i13.

Tsoutsoubi, L., Ioannou, L. G., Ciuha, U., Fisher, J. T., Possnig, C., Simpson, L. L., Flouris, A. D., Lawley, J., & Mekjavic, I. B. (2024). Validation of formulae predicting stroke volume from arterial pressure: With particular emphasis on upright individuals in hot ambient conditions. *Frontiers in Physiology, 15*, 1398816.