

# SMART TEXTILES FOR HEALTH MONITORING IN INDUSTRIAL ENVIRONMENTS: A FRAMEWORK FOR WEARABLE SENSOR INTEGRATION

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## ABSTRACT

The occupational health and safety of workers in industrial plants are increasingly compromised through exposure to thermal, physical, and psychological stressors. Wearable sensors embedded in garments have been introduced as a promising technology for real-time, continuous health monitoring without compromising workers' mobility or comfort. This paper reviews recent literature on wearable sensor technologies embedded in textiles, with a focus on their applicability in industrial settings. The paper identifies the key physiological parameters commonly monitored (e.g., heart rate, skin temperature, respiratory rate, and skin conductance), the materials and sensor types used, as well as the methods of integration into garments. Based on the findings, a conceptual model for a smart textile monitoring system tailored to industrial workers is proposed. The aim is to support the development of ergonomic, accessible, unobtrusive, and effective solutions that promote occupational health and prevent work-related illnesses.

## KEYWORDS

Wearable sensors; Smart textiles; Physiological monitoring; Industrial environments; Stress detection; Respiratory monitoring

## 1. INTRODUCTION

The development of wearable devices for monitoring the health of factory workers, integrating sensors, communication devices, processing units, memory, and a battery (or other energy supply device) contributes to creating a work environment that avoids health risks and prevents occupational accidents that may arise due to working conditions or the worker's health status. Using biomedical sensors integrated into clothing, along with data acquisition and associated signal processing, the device will allow the evaluation of the comfort conditions of factory workers during their daily work activities.

Occupational health issues are a significant concern, particularly in industrial environments where workers are subjected to constant exposure to high temperatures, prolonged physical strain, repetitive strain, and unfavorable conditions. Exposure may lead to physiological stress, fatigue, and long-term conditions. Therefore, there is a growing need for real-time physiological monitoring technologies to anticipate and prevent work-related health risks (Sharma, Suri et al. 2022).

Recent developments in wearable technologies have paved the way for the integration of physiological sensors directly into textiles, creating a new category of "smart garments". These systems enable the continuous and unobtrusive collection of vital health data such as heart rate, respiratory rate, skin temperature, and even electrodermal activity without restricting the wearer's mobility or comfort (Pinnelli, Lo Presti et al. 2024).

Textile-integrated sensors have been effectively applied in several contexts. For example, wearable systems have been deployed to monitor heat stress in Swiss railway workers, offering insight into the physiological impact of thermal exposure under controlled conditions (Vázquez, Fujs et al. 2024). In another study, conducted in India, a combination of environmental sensors and physiological data collection was used to predict worker stress using machine learning algorithms (Sharma, Suri et al. 2022). Furthermore, a large-scale study in Egypt demonstrated the feasibility of using wearable biosignal sensors for stress detection in diverse real-world populations (Abd Al-Alim, Mubarak et al. 2024).

These promising results underscore the growing relevance of smart textiles in occupational health. Despite their potential, challenges such as durability during washing, sensor calibration, energy consumption, and data privacy must be addressed. This paper aims to review current advancements in textile-based sensor systems applied to health monitoring of factory workers (mainly based on their respiratory performance data) and propose a conceptual monitoring model tailored to industrial plant work environments.

The remainder of this manuscript is organized as follows. In section 2 the methodological part of the paper is addressed. In section 3, the wearable sensor technologies and implemented techniques to be embedded into the garment are described. Section 4 proposes a novel approach for industrial workers' health monitoring through a conceptual model for the proposed wearable monitoring system. The conclusions are drawn in section 5 where suggestions for further research are also discussed.

## 2. METHODOLOGY

This study is based on a literature review focused on scientific publications between 2018 and 2024. Articles were retrieved from databases such as PubMed, IEEE Xplore, and ScienceDirect using keywords including "wearable sensors", "smart textiles", "occupational health", and "physiological monitoring". The inclusion criteria required that the selected studies: (i) employ wearable sensors for physiological monitoring; (ii) involve integration of sensors into textile or flexible substrates; and (iii) be applied in industrial environments or controlled laboratory simulations replicating workplace conditions. The primary parameters investigated in these studies were heart rate, respiratory rate, skin temperature, and skin conductance, the known indicators of physiological and thermal stress.

The study further detailed the use of different types of sensors, including piezoresistive, capacitive, thermal, and optical sensors, which have different advantages in the case of monitoring physiological parameters as shown in Figure 1. Piezoresistive sensors, for example, are highly effective in sensing strain and breathing motion, while capacitive sensors respond greatly to pressure variations. Thermal and optical sensors are useful in sensing skin temperature and blood flow, respectively, in contributing to overall health monitoring.



Figure 1. Wearable sensors for monitoring health physiological parameters.

From an integration perspective, the techniques were widely distributed: textile lamination allows multilayering; embroidery with conductive yarns assures durability and washability; inkjet and screen printing allow precise positioning of conductive materials; and weaving of fibers provides seamless integration of sensors. These processes must be chosen based on the foreseen application of the garment, the degree of durability, and comfort.

Elastomers, carbon nanotubes, conductive polymers, and silver nanowires were selected on the basis of their high electrical conductivity, stretchability, and biocompatibility. For instance, carbon nanotubes in elastomeric matrices yield high sensitivity with mechanical robustness, while silver nanowires yield high thermal and electrical conductivity with minimal rigidity. An ideal approach to future applications can be the merging of silver nanowire meshes with breathable polymer substrates for the realization of both signal fidelity and comfort during long-term industrial applications.

Furthermore, the review also looked at the facilitating technological infrastructure surrounding wearable sensors. These are power supply subsystems such as flexible batteries and energy harvesting modules (e.g., triboelectric nanogenerators or thermoelectric generators) that provide smooth operation without compromising mobility. Data acquisition platforms usually rest on low-power microcontrollers (e.g., ESP32, STM32), enabling analog-to-digital conversion, pre-processing, and data compression at the edge to prevent transmission overload.

Wireless communication protocols such as Bluetooth Low Energy (BLE) and LoRa were utilized the most since they are appropriate for different industrial environments—BLE for short-range, low-latency applications and LoRa for long-distance, low-power transmission in large facilities.

On the software side, data interpretation is heavily reliant on native machine learning algorithms. These can run locally or in the cloud and are themselves trained to recognize abnormal patterns within physiological signals. Decision trees, support vector machines, and deep learning algorithms (e.g., LSTM networks for time-series physiological data) are typical examples. Incorporation of these systems not only facilitates real-time feedback on health but also predictive alerts, making the monitoring exercise proactive rather than reactive.

### **3 WEARABLE SENSOR TECHNOLOGIES IN TEXTILES**

Wearable sensors integrated into textiles can monitor multiple physiological parameters. Piezoresistive sensors, for example, have shown high sensitivity in detecting respiratory movements and skin pressure, especially when combined with flexible substrates such as liquid elastomers and carbon nanotubes (Selvan T, Sharma et al. 2022). Authors of the study presented the development of a stencil-printable multifunctional adhesive sensor based on carboxylated multiwalled carbon nanotubes (c-CNTs) and functionalized liquid isoprene rubber (LIR). The methodology involved solvent-free fabrication using planetary centrifugal mixing and stencil printing techniques, followed by heating for characterization. Rheological studies identified the percolation threshold at 0.42 vol% c-CNT, correlating filler concentration with polymer chain mobility. Electrical properties were evaluated experimentally and through finite element simulations, demonstrating strong agreement and confirming a 3D percolation network. The sensor exhibited high sensitivity to temperature (0.347%/°C) and strain (gauge factor of 62.4 up to 40% strain), alongside excellent adhesion to various substrates. Its multifunctionality was validated through physiological monitoring, including pulse, respiratory rate, and phonetics detection. The robust methodology highlights the potential for scalable, cost-effective fabrication of wearable sensors for healthcare applications.

Capacitive and thermal sensors are also employed to detect temperature alteration and body heat distribution and play an important role in the identification of thermal stress. Their functionality has been established under environmental stressors and mechanical deformation by numerous studies. (Sharma, Thapa et al. 2024) works are particularly remarkable for having developed a stencil-printable graphene–liquid elastomer-based strain sensor for unobtrusive respiration monitoring that was also effective under dynamic thermal conditions.

Furthermore, authors from (Cui, Poblete et al. 2019) showed a breathable, stretchable temperature sensor utilizing silver nanowires specifically for thermoresistive sensing and with no effect of strain on sensing. Their method allowed accurate measurement of skin temperature under motion and is consequently most suitable for wearable technology in the industrial environment where thermal stress is the top priority.

The study presented the development of a stencil-printable graphene–liquid elastomer-based strain sensor for unobtrusive respiratory monitoring. The sensor addresses challenges like crosstalk, noise, and environmental interference (temperature and humidity) that limit the accuracy of flexible strain sensors. It is designed for mass utility using frugal engineering and avoids complex fabrication processes. The sensor was mounted on an N95 mask and demonstrated the ability to detect respiratory profiles at room and sub-ambient temperatures ( $-26\text{ }^{\circ}\text{C}$ ) with high sensitivity and stability over 500 cycles. It can accurately determine respiratory conditions like eupnea and tachypnea and transmit data wirelessly via Bluetooth. In terms of materials and composition, liquid polyisoprene rubber (LIR) was used as the matrix, and graphene served as the functional filler. Dicumyl peroxide (DCP) was employed as a crosslinker. The composition was mixed using hand blending and a planetary centrifugal mixer to create bubble-free ink. Sensor fabrication encompassed using stencil printing to print sensors on polyethylene terephthalate (PET) substrates. The sensors were cured at  $185\text{ }^{\circ}\text{C}$  for 8 minutes, and silver paste was applied as electrodes. Encapsulation with SYLGARD™ 517 gel was performed to eliminate humidity interference. Electrical conductivity has been assessed, showing a percolation threshold at 0.56 vol% of graphene. Dynamic mechanical analysis revealed changes in elastic modulus upon strain application. The sensors demonstrated gauge factors of  $-196.56$  and  $117.49$  for strain ranges of  $0\text{--}0.17\%$  and  $0.17\text{--}0.35\%$ , respectively. Environmental Testing has also been a concern. The sensors were tested for low-temperature performance using liquid nitrogen and humidity sensitivity using a humidifier. Encapsulation successfully eliminated humidity interference, while a Wheatstone bridge configuration compensated for temperature effects. The study also encompassed breath monitoring. Sensors were attached to an N95 mask and tested on a volunteer. The breathing waveform was accurately detected, including respiratory rate, depth, inhalation/exhalation times, and total breathing time. FFT analysis was used to calculate respiratory rates for different breathing patterns. As simple wireless monitoring setup was explored. Using Arduino UNO and a Bluetooth module, the sensors transmitted respiratory data wirelessly to a smartphone, showcasing their applicability in real-time healthcare monitoring.

Smart textiles often employ printing techniques to embed these sensors directly into garments, ensuring minimal interference with workers' movement. Materials such as silver nanowires and graphene composites have demonstrated excellent conductivity and stretchability, ideal for demanding industrial plant settings (Cui, Poblete et al. 2019, You, Lu et al. 2025).

The reviewed literature reveals a growing trend toward using smart textiles for health monitoring in the workplace. For instance, research involving Swiss railway workers under controlled conditions demonstrated successful detection of perceived heat stress and physiological strain through wearable devices (Vázquez, Fujs et al. 2024).

In India, environmental and physiological data collected through embedded sensors enabled machine learning algorithms to predict stress conditions and adjust workloads accordingly (Sharma, Suri et al. 2022). Additionally, large-cohort studies in Egypt employed biosignal sensors to evaluate stress patterns in diverse populations, confirming their scalability and reliability (Abd Al-Alim, Mubarak et al. 2024).

Despite these successes, challenges remain, including the durability of textile-integrated sensors during washing, power management, data privacy, and user acceptability. Addressing these issues is essential for transitioning from experimental setups to real-world deployment.

When comparing the proposed conceptual model with the systems analyzed in the literature, its modularity, adaptability to different work functions and simultaneous integration of physiological and environmental sensors stand out. Unlike previous approaches focusing on controlled laboratory environments or specific applications (such as N95 masks or single sensors), this model aims for uniform integration into conventional workwear, with an emphasis on ergonomics, low cost and simplified maintenance. The combination of BLE and LoRa also allows for a hybrid solution adaptable to different scales of industrial space.

Several studies have investigated not only the technical feasibility but also the real-world adoption of wearable health-monitoring systems. (Sharma, Suri et al. 2022) reported positive reception among factory workers in India, highlighting improved stress management and workload regulation. Similarly, (Vázquez, Fujs et al. 2024) documented effective use of wearables for heat stress detection in Swiss railway workers, with high compliance and minimal discomfort reported. These examples demonstrate growing worker acceptance when systems are integrated seamlessly and with proper training. The proposed model addresses similar needs by emphasizing ergonomic design, real-time feedback, and minimal user intervention, aiming to facilitate successful adoption.

## 4 PROPOSED TEXTILE-BASED MONITORING SYSTEM

Based on the findings, a conceptual model for the wearable monitoring system is proposed. The system includes:

- **Sensor modules** embedded in key garment areas (chest, back, limbs), designed to monitor heart rate, temperature, respiratory rate, and skin conductance;
- **Flexible interconnections** using conductive threads or printed circuitry to connect the sensors to the processing unit without compromising comfort;
- **A processing unit** composed of a lightweight microcontroller capable of analog-to-digital conversion, basic signal processing, and wireless transmission (e.g., via Bluetooth or LoRa);
- **A mobile or web-based interface** that receives and visualizes data in real time, with functionalities for trend tracking, alerts, and personalized dashboards for occupational health professionals;
- **Machine learning algorithms** embedded in the application or server backend to learn individual baseline physiological profiles and detect anomalies indicative of thermal stress, fatigue, or overexertion.

The suggested system architecture is modular, scalable, and adaptable to different job profiles and environmental situations. It prioritizes low-cost production, extended wearability over time, and simple integration into existing workwear. Battery optimization and washability of sensorized textiles are also addressed in the design for longer lifetimes of the devices and greater user acceptance.

This comprehensive solution combines physiological sensing, real-time analytics, and human factors design to offer an active health monitoring system for workers in factories. The long-term objective of the solution is to help detect noxious conditions at an early stage and allow timely interventions that reduce occupational risk and enhance worker safety.

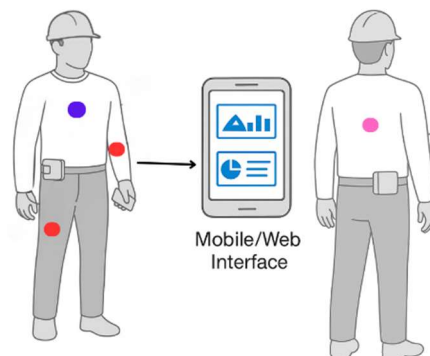


Figure 2. Proposal for the monitoring system with intelligent textiles for occupational health

Figure 2 shows the conceptual design of an occupational health monitoring system using smart textiles. Wearable sensors are incorporated in individual zones of the body, i.e., the chest, back, arms, and legs, to monitor vital physiological parameters like heart rate, body temperature, respiration activity, and joint movement in real time. Data collected is transmitted via Bluetooth or LoRa to a waist-mounted central processing unit, which forwards the information to a digital interface (web or mobile). The interface provides real-time visualization of the vital signs, detection of risk conditions at early stages, and alert generation. The system is modular, ergonomic, and compatible with professional workwear to provide user comfort, mobility, and unobtrusive health monitoring during the working day.

The long-term success of the proposed system depends significantly on its usability. Factors such as the comfort of wear, the ease of donning and doffing the smart garment, and the intuitiveness of the data interface are critical to ensure worker adoption. Preliminary usability guidelines were defined considering ISO 9241 ergonomic standards and ISO 62366 for medical systems usability. We propose involving both workers and occupational health professionals in co-design sessions to identify barriers and expectations. Usability studies will include both qualitative interviews and System Usability Scale (SUS) assessments during pilot testing.

Applying the model in a real environment faces significant challenges. The size of the central processing unit, as well as the weight and positioning of the power source, must ensure worker comfort and mobility. Integration in the waist area is proposed with a lightweight belt, detachable for washing. The durability of the sensors, resistance to washing and thermal comfort are essential criteria to be validated experimentally. Acceptability of the system by workers also depends on co-design processes, training and continuous involvement of end users.

## 5 ONGOING EXPERIMENTAL VALIDATION

As part of the ongoing development, preliminary fabrication and integration attempts have been carried out, as shown in Figure 3. One of the first prototypes showed significant limitations in sensor adhesion and signal stability, especially under repeated strain cycles and washing conditions. This sample, although not fully functional, provided critical insights into material compatibility and integration techniques. Current empirical efforts are focused on optimizing the interface between the sensor and textile substrate using thermoplastic adhesives and breathable encapsulants. Further iterations of the sensor will be subjected to electrical characterization, washability tests, and user trials.

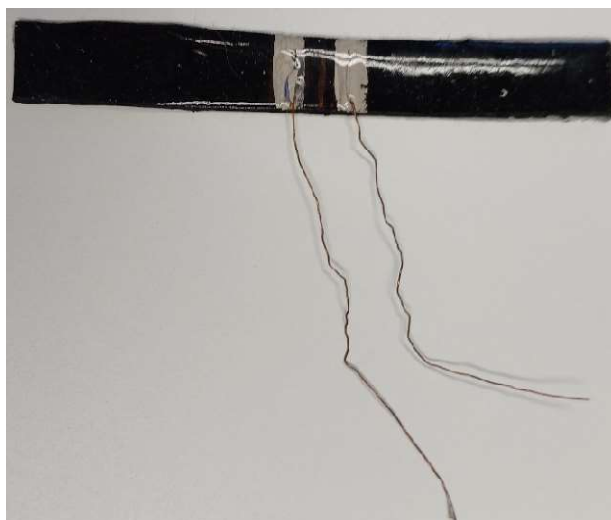


Figure 3. Initial attempt of producing a sensor by mixing carbon nanotubes and reduced graphene oxide in a polydimethylsiloxane matrix.

A further step will be to provide a system vision toward the production of an integrated solution. These studies will help us figure out how well the system works technically and how well it can be used in diverse work situations. Usability studies with workers and occupational health professionals are also foreseen to find out how much they like the product, how comfortable it is, and how it affects their work routine. It will be important to set up common evaluation procedures to make sure that the transition to large-scale deployment goes smoothly.

## 6 CONCLUSION

The integration of sensors in wearables into textiles is a paradigm change in occupational health monitoring. Not only do these technologies enable constant, real-time measurement of physiological parameters but also offer a user-friendly, non-invasive solution for application in numerous diverse industrial workplaces. The application of such systems can significantly reduce the incidence of occupational diseases by identifying early signs of fatigue, heat stress, or physical overloading.

In short, wearable sensors improve worker safety by enabling real-time, continuous monitoring of physiological parameters such as heart rate, respiratory rate, skin temperature, and skin conductance. These

sensors, integrated into textiles, provide unobtrusive data collection without compromising mobility or comfort. Key benefits include the following ones:

- Early Detection of Health Risks: Sensors can identify signs of fatigue, heat stress, or physical overexertion, allowing timely interventions to prevent occupational illnesses or accidents.
- Stress Monitoring: By tracking physiological and environmental data, wearable systems can predict stress levels and adjust workloads, accordingly, reducing psychological strain.
- Thermal Stress Management: Sensors detect temperature variations and heat distribution, helping workers avoid heat-related health issues.
- Enhanced Decision-Making: Data visualization and machine learning algorithms provide insights into worker health trends, enabling occupational health professionals to make informed decisions.

The theoretical model outlined in this paper synthesizes the key conclusions of contemporary literature and plots them into an operational system for use. By combining sensor technology, wireless data transfer, and smart algorithms, the proposed solution addresses both employee comfort and technical viability.

But their achievement depends on the solution of a series of technical and human problems. These are ensuring the durability and washability of sensorized clothing, determining the ideal energy consumption for extended use, protecting privacy and confidentiality of collected data, and creating user acceptance among occupational health professionals and workers.

The continuous collection of physiological data in work environments raises relevant ethical issues. It is essential to ensure that the data belongs to the workers and is only used for the purposes communicated in advance. Compliance with the General Data Protection Regulation (GDPR) must be ensured right from the design of the system, with anonymization and access control measures. Transparency and ethical acceptance will also depend on the involvement of ethics committees and the existence of clear information management policies.

Although prototype tests have not yet been carried out, functional tests in simulated industrial environments are planned, followed by validation in partnership with companies in the textile and metallurgical sectors. These studies will make it possible to assess the technical robustness and adaptability of the system to different work contexts. In addition, we intend to carry out usability studies with workers and occupational health professionals, in order to understand the degree of acceptance, comfort and impact on the work routine. To ensure an effective transition to large-scale implementation, it will be essential to define standardized evaluation guidelines. Future research should also be based on interdisciplinary collaborations between engineers, health professionals and industry representatives, to refine these technologies and ensure their responsible adoption in real industrial environments.

The continuous collection and analysis of workers' physiological data introduces significant ethical and legal challenges. Ensuring compliance with the General Data Protection Regulation (GDPR) is a fundamental requirement. This includes obtaining informed consent, ensuring data anonymization, providing transparency on how the data will be used, and implementing strict access control mechanisms. Additionally, data ownership should reside with the individual, and employers must commit to using the data solely for health and safety purposes, not for productivity surveillance or punitive action. Ethics committee involvement, clear governance policies, and ongoing worker engagement will be integrated into the deployment strategy to uphold ethical standards and build trust in the technology.

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