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# Wearable Sensors for Healthcare of Industrial Workers: A Scoping Review

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**Abstract:** Background and Objectives: This scoping review evaluates the use of wearable sensor technologies for workplace safety and health monitoring in industrial settings. The aim is to synthesize evidence on the impact of these sensors and their application in high-risk environments. Materials and Methods: Following the PRISMA guidelines, a systematic search across four international electronic databases yielded 59 studies, of which 17 were included in the final review. The selection criteria involved studies that specifically utilized wearable sensors to monitor various health and environmental parameters relevant to industrial workers. Results: The analysis categorizes wearable technologies into five distinct groups based on their function: gas monitoring technologies, heart rate and physiological data collection, fatigue and activity monitoring, comprehensive environmental and physiological monitoring, and advanced sensing and data collection systems. These devices demonstrated substantial benefits in terms of early detection of health risks and enhancement of safety protocols. Conclusions: The review concludes that wearable sensor technologies significantly contribute to workplace safety by providing real-time, data-driven insights into environmental hazards and workers' physiological status, thus supporting proactive health management practices in industrial settings. Further research is recommended to address the challenges of data privacy, sensor reliability, and cost-effective integration to maximize their potential in occupational health safety.

**Keywords:** healthcare evaluation mechanisms; occupational health; technology

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**Citation:** Moon, J.; Ju, B.-K. Wearable Sensors for Healthcare of Industrial Workers: A Scoping Review. *Electronics* **2024**, *13*, 3849. https://doi.org/10.3390/electronics13193849

Academic Editor: Giuseppe Prencipe

Received: 4 September 2024
Revised: 25 September 2024
Accepted: 26 September 2024
Published: 28 September 2024

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## 1. Introduction

Occupational health continues to be a significant concern in industrial environments, which are inherently susceptible to high risks of accidents and exposure to hazardous elements [1]. The advent of wearable sensor technology represents a critical advancement in the enhancement of workplace safety [2]. These innovative tools facilitate the continuous, real-time surveillance of workers' health and their surrounding environments, thus markedly improving safety protocols on-site [3]. Seamlessly integrated into standard personal protective equipment, these sensors deliver precise monitoring capabilities, quickly notifying both staff and management about imminent threats and dangerous conditions [4].

With the latest technological advancements, there has been a notable enhancement in the capabilities of wearable sensors [5]. These advanced devices are now equipped not only to monitor vital signs but also to detect critical environmental hazards like explosive gases, high noise levels, or toxic exposures [6]. Such devices, which support comprehensive data collection, when paired with state-of-the-art analytical techniques, enable the identification of potential accident-prone areas and the fine-tuning of preventive measures, thus bolstering safety in real time [7,8].

However, incorporating wearable sensors into standard industrial practices brings its own set of challenges. Issues such as the privacy of the data collected, the sensors' reliability in extreme industrial conditions, and the economic costs of widespread technology adoption are prominent [9,10]. Therefore, a thorough and systematic review of these technologies is

essential to comprehending their real-world applications and the broader implications for the industrial sector.

The primary goal of this scoping review is to meticulously evaluate how wearable sensor technologies are being utilized in industrial settings to boost worker safety and health. By weaving these devices into the fabric of daily industrial operations, the review aims to dissect both the immediate and enduring advantages these technologies provide in mitigating workplace injuries and reducing exposure to hazardous conditions.

### 1.1. Motivations for This Scoping Review

This scoping review is motivated by several key factors in the rapidly evolving field of wearable sensors in industrial settings. The field of wearable sensors is advancing at a remarkable pace, with new technologies emerging frequently. This review aims to synthesize these latest developments and their applications in industrial environments, providing a comprehensive overview of the current state of the technology. Additionally, wearable sensors are being utilized in diverse ways across various industries, necessitating a thorough categorization and analysis of these applications to fully understand the breadth and depth of their impact. The potential of wearable sensors to significantly improve worker safety and health is a primary driver of this research, and this review seeks to assess the extent of this impact based on current evidence. However, despite their potential benefits, the adoption of wearable sensors faces several challenges. This review also aims to identify these challenges and explore potential solutions, contributing to the successful implementation of these technologies in industrial settings.

### 1.2. Contributions of This Scoping Review

This scoping review makes several key contributions to the field of wearable sensor technologies in industrial settings. Firstly, we provide a comprehensive synthesis of the latest research on wearable sensors in industrial environments, offering a valuable resource for researchers, industry professionals, and policymakers. This synthesis includes a novel categorization of wearable sensor technologies based on their functions and applications in industrial environments, providing a structured framework for understanding the diverse range of available technologies. Through our analysis of the current state of research, we identify emerging trends in the field and highlight gaps that require further investigation, guiding future research efforts. Additionally, this review offers insights into the practical implications of implementing wearable sensor technologies in industrial settings, including potential benefits and challenges. These insights can inform decision-making processes for organizations considering the adoption of these technologies. Finally, based on our analysis, we propose directions for future research that could further advance the field of wearable sensors for industrial worker safety, contributing to the ongoing development and refinement of these crucial technologies.

Through this scoping review, we aim to provide a comprehensive understanding of the current state of wearable sensor technologies in industrial settings, their potential impact on worker safety and health, and the challenges that need to be addressed for their successful implementation.

## 2. Materials and Methods

### 2.1. Study Design

This scoping review was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) [11].

### 2.2. Eligibility Criteria

For this scoping review, we included peer-reviewed research articles that focused on the application of wearable sensors in industrial environments aimed at enhancing worker safety. Eligibility was strictly given to empirical research studies that provided

quantitative or qualitative data on the impact of these technologies. Articles were required to be published within the last decade to ensure the incorporation of the latest technological innovations and had to be written in English to facilitate comprehensive review and analysis. Studies were excluded if they were reviews, commentaries, non-empirical reports, or if they fell outside the designated timeframe. Most importantly, the review aimed to incorporate studies that extensively covered the technical aspects of wearable devices.

References from 2014 onwards were included for several reasons: The field of wearable technology has seen rapid advancements in the past decade; 2014 marked a turning point in the widespread adoption of wearable technology in industrial settings; a 10-year timeframe provides a comprehensive view of the field's evolution while focusing on current research.

### *2.3. Information Sources*

To identify relevant studies, research published since 2014 was searched in international electronic databases such as PubMed, Scopus, IEEE Xplore, and Web of Science. The search used a comprehensive set of keywords and Boolean logic to maximize the retrieval of pertinent articles, including terms like "wearable sensors", "industrial safety", "real-time monitoring", and "occupational health monitoring". The results were exported to Microsoft Excel 2021 (Microsoft, Redmond, Washington, DC, USA), and duplicates were removed after a consensus among the researchers.

### *2.4. Selection of Sources of Evidence*

Data extraction was conducted through a meticulously crafted protocol to ensure that all relevant data points were consistently captured across studies. The extraction form was designed to collect detailed information such as study authors, publication year, study location, sample size, sensor types used, specific industrial settings, outcome measures, and main conclusions. Each selected study was reviewed independently by two team members to extract data, which ensured accuracy and reliability.

### *2.5. Search and Selection of Sources of Evidence*

To ensure that our study's goals were met, we strategically structured the research question using the PICO (population, intervention, comparison, outcome) framework [12]. This framework guided our inquiry into the deployment of wearable sensors within industrial environments, specifically aiming to evaluate their efficacy in enhancing worker safety and health. By incorporating terms like "wearable sensors", "industrial safety", and "occupational health monitoring", we sought to uncover how these innovations could be synthesized to continually and accurately monitor various environmental and physiological factors, thereby advancing workplace safety measures.

Our research team initially engaged in a detailed preparatory discussion to establish a rigorous methodological approach for reviewing the retrieved studies. Following this, a systematic search was conducted to identify relevant publications. This process involved a meticulous examination of titles, abstracts, and full texts to ascertain the studies' pertinence to our objectives. Any disagreements among researchers regarding the studies' relevance or findings were addressed through in-depth discussions, ensuring a comprehensive and unified analysis.

## 3. Results

### *3.1. Selection of Sources of Evidence*

Our study selection process followed a systematic approach to ensure fairness and transparency. The process unfolded as follows: Initial Identification: Our comprehensive search across electronic databases yielded 59 citations. Duplicate Removal: We identified and removed 8 duplicate studies, leaving us with 51 unique citations. Title and Abstract Screening: Two independent reviewers screened the titles and abstracts of these 51 studies. Based on this thorough review, 33 studies were excluded as they did not meet our initial eligibility criteria. Full-Text Review: The remaining 18 studies underwent a full-text review

by the same two independent reviewers. During this stage, studies were assessed against our full set of eligibility criteria as described in Section 2.2. Final Selection: After the full-text review, 1 additional study was excluded as it did not meet all of our eligibility criteria. This left us with a final set of 17 studies included in our review. Throughout this process, we maintained detailed records of the reasons for exclusion at each stage. Any disagreements between reviewers were resolved through discussion and consensus. In cases where consensus could not be reached, a third reviewer was consulted; the 17 studies deemed eligible and included in the review are referenced as [6,13–28], and the selection process is visually represented in Figure 1.

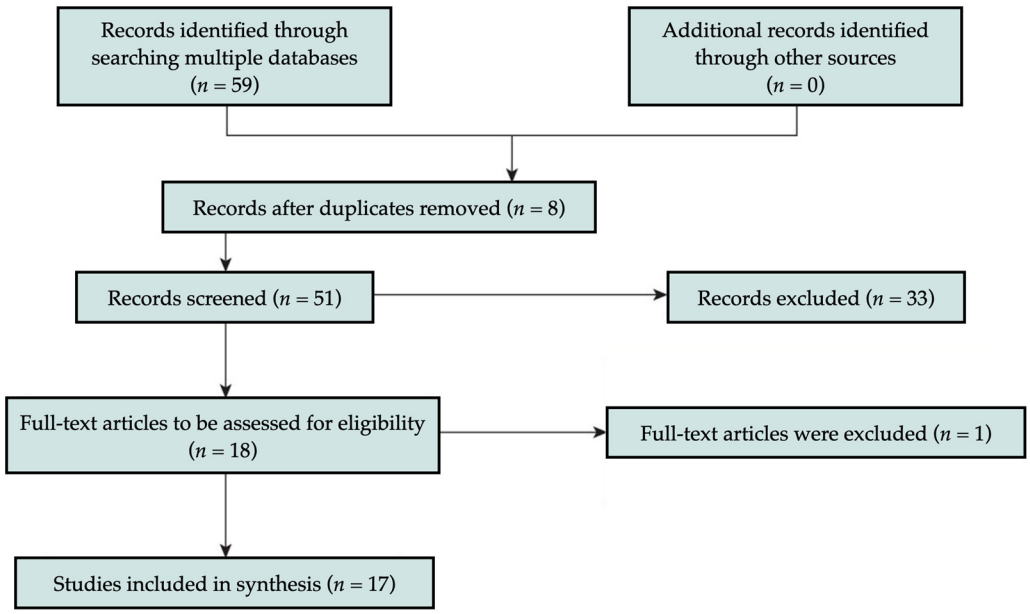


**Figure 1.** Scoping review flow diagram.

### *3.2. Results of Individual Sources of Evidence*

Studies related to wearable devices for workers have been categorized based on participants, study design, and wearable devices. This classification aligns with the objectives in healthcare and is elaborated in Table 1. Additionally, Table 2 summarizes how accurate and effective each type of sensor is in recording health-related data and how easily they can be integrated into the workplace.

**Table 1.** Results of individual sources of evidence.

| Author | Population | Study Design | Wearable Device |
|---|---|---|---|
| Gas Monitoring Technologies | | | |
| Tahir, et al., 2023 [26] | N/A (focus on device performance) | Technical research on a multipurpose toxic gas-monitoring device. | Includes metal oxide-based gas sensors, humidity and temperature sensors, an IR thermal sensor, with Bluetooth connectivity. |
| Serafini, et al., 2021 [24] | N/A (focus on device performance) | Technical research on a wearable electrochemical gas sensor. | Electrochemical sensor for ammonia detection, designed for real-time environmental safety monitoring. |
| Wang, et al., 2019 [27] | Single member in mock field test, solvent-transfer activities | Experimental study on a belt-mounted micro-gas chromatograph. | Micro-gas chromatograph measures VOCs, includes a dual-adsorbent micro-preconcentrator, micro-column, and microchemiresistors. |

**Table 1.** *Cont.*

| Author | Population | Study Design | Wearable Device |
|---|---|---|---|
| Heart Rate Monitoring and Physiological Data Collection | | | |
| Hwang, et al., 2016 [17] | 11 male construction workers, aged 26–60 | Experimental study comparing two types of heart rate monitors. | Uses Basis Peak™ wristband and Polar H7® chest strap for heart rate monitoring, with different data granularity. |
| Lee, et al., 2017 [20] | Six non-union roofers, monitored over five days | Repeated measures study on wearable sensors' reliability and usability. | Employs Zephyr Bioharness™ 3 for ECG and ActiGraph GT9X units for energy expenditure and activity levels. |
| Abusohyon, et al., 2023 [13] | Emphasis on device functionality under simulated conditions | Experimental design on a wearable biosensor in a smart mask. | Smart mask with a nanostructured sensor for detecting hydrogen peroxide, includes signal amplification and NFC communication. |
| Fatigue and Activity Monitoring | | | |
| Antwi-Afari, et al., 2023 [14] | Generally involves construction workers | Technical research on a wearable insole for fatigue classification. | Wearable insole collects data on heart rate, skin temperature, and electrodermal activity, fits inside safety shoes. |
| Di Tocco, et al., 2020 [15] | Healthy volunteers in simulated occupational activities | Experimental design on non-intrusive respiratory rate monitoring. | Includes fiber Bragg grating sensors in a silicone matrix, designed to be lightweight and immune to electromagnetic interference. |
| Lamooki, et al., 2022 [19] | 37 participants performing tasks typical for electrical line workers | Retrospective classifier training and ergonomic risk assessment. | Uses Empatica E4 wristband for 3-axis acceleration data at 32 Hz, connected to smartphone app for data collection and upload. |
| Papoutsakis, et al., 2022 [23] | Not specified; industrial workers in high-strain environments | Experimental study on physical strain and fatigue monitoring. | Smartwatches monitor cardiovascular activities, supplemented by cameras for posture and movement analysis. |
| Comprehensive Environmental and Physiological Monitoring | | | |
| Guilbeault-Sauvé, et al., 2021 [16] | Focus on device functionality, not demographics | Experimental research on an in-ear device for detecting 'man down' situations. | In-ear device with accelerometer and gyroscope for movement detection, designed for continuous wear with auditory protection. |
| Jiao, et al., 2023 [18] | Nine participants, mixed genders, aged 21–25, healthy | Experimental study on human anxiety and thermal comfort. | System includes EEG, PPG, eye-tracking, and environmental sensors for comprehensive physiological monitoring. |
| Sharma, et al., 2022 [25] | 12 male university students performing varied work tasks | Experimental study on occupational heat stress with a safety helmet. | Safety helmet with sensors for environmental and physiological monitoring, including temperature and heart rate. |
| Singh, et al., 2022 [6] | Focus on device efficacy in simulated mining environments | Experimental design integrating IoT technologies in a smart helmet. | Smart helmet with sensors for environmental threats and a built-in GPS, includes a communication interface for data transmission. |
| Advanced Sensing and Data Collection Systems | | | |
| Yu, et al., 2019 [28] | Controlled experiments with volunteers in simulated tasks | Experimental design on non-intrusive fatigue assessment using computer vision. | Uses a single RGB camera for 3D motion capture; non-intrusive, avoids discomfort from on-body sensors. |
| Nath, et al., 2017 [21] | Construction workers engaged in various ergonomic risk tasks | Experimental design on ergonomic analysis using wearable mobile sensors. | Smartphones with built-in sensors autonomously monitor body postures and ergonomic risks. |
| O'Sullivan, et al., 2024 [22] | Twenty subjects performing typical industrial tasks | Experimental design on pressure insoles for task classification. | Employs loadsol® pressure insoles with sensors capturing real-time foot pressure data to assess physical demands. |

ECG, electrocardiogram; EEG, electroencephalogram; GPS, global positioning system; HR, heart rate; IoT, internet of things; NFC, near field communication; PPG, photoplethysmography; RGB, red, green, blue; VOC, volatile organic compounds.

**Table 2.** Summary of sensor effectiveness.

| Sensory Type | Effectiveness in Recording Health Data | Ease of Integration into Workplace |
| --- | --- | --- |
| Gas monitoring technologies | High accuracy in detecting toxic gases and VOCs | Moderate; can be integrated into PPE but may require regular calibration |
| Heart rate and physiological data collection | Good accuracy for continuous vital sign monitoring | High; wearable devices are generally non-intrusive |
| Fatigue and activity monitoring | Moderate to high accuracy in detecting fatigue signs | High; can be integrated into existing workwear or accessories |
| Comprehensive environmental and physiological monitoring | High accuracy for both environmental and physiological data | Moderate; may require multiple sensors or devices |
| Advanced sensing and data collection systems | accuracy with sophisticated data analysis | Moderate to High; depends on the specific system and workplace environment |

PPE, personal protective equipment; VOCs, volatile organic compounds.

### *3.3. Synthesis of Results*

We reviewed 17 studies on wearable sensors for industrial workers. The majority of these studies were conducted in the United States ($n$ = 6), followed by Italy ($n$ = 3), the United Kingdom ($n$ = 2), China ($n$ = 2), India ($n$ = 2), Greece ($n$ = 1), and Canada ($n$ = 1). Most studies involved healthy adults or were solely focused on evaluating the performance of the devices. All studies emphasized analysis concerning the technology employed. The wearable sensors' performance was categorized into the following groups: gas monitoring technologies ($n$ = 3), heart rate monitoring and physiological data collection ($n$ = 3), fatigue and activity monitoring ($n$ = 4), comprehensive environmental and physiological monitoring ($n$ = 4), and advanced sensing and data collection systems ($n$ = 3).

The wearable sensors' performance was categorized into five groups based on their primary functions: Gas monitoring technologies ($n$ = 3): devices designed to detect toxic gases and VOCs; heart rate and physiological data collection ($n$ = 3): devices measuring vital signs and other physiological parameters; fatigue and activity monitoring ($n$ = 4): sensors tracking movement patterns and fatigue indicators; comprehensive environmental and physiological monitoring ($n$ = 4): systems combining environmental and physiological data collection; advanced sensing and data collection systems ($n$ = 3): sophisticated systems often involving multiple sensor types or advanced data processing. Each category's effectiveness and ease of workplace integration are summarized in Table 2.

## 4. Discussion

Our scoping review has extensively evaluated the adoption of wearable sensor technologies across various industrial settings, illustrating a notable trend towards their widespread implementation. This adoption is driven by the technologies' potential to significantly enhance workplace safety and health monitoring. The integration of these digital health solutions in traditionally high-risk environments is spurred by technological advancements that promise to improve worker safety and operational efficiency [29].

From an initial set of 59 studies identified through comprehensive searches in four international electronic databases, our review synthesized 17 pivotal studies [6,13–28]. These studies categorize wearable sensors for industrial workers into five distinct groups: gas monitoring technologies, heart rate monitoring and physiological data collection, fatigue and activity monitoring, comprehensive environmental and physiological monitoring, and advanced sensing and data collection systems.

### *4.1. Technological Advancements and Their Impact on Worker Health and Safety*

The evolution of wearable technologies from basic health monitoring devices to complex systems capable of detecting a variety of environmental and physiological parameters marks a significant advancement in workplace safety tools [30]. These devices, now equipped to monitor everything from vital signs to toxic exposures, are instrumental in

the early detection and prevention of occupational diseases and accidents. For example, sensors that detect volatile organic compounds are essential for preventing long-term respiratory issues and other health problems linked to chemical exposure, thereby improving the overall health profile of the workforce [31].

### *4.2. Bridging Technology and Health Outcomes*

Advancements in wearable sensor technologies not only offer opportunities for enhanced monitoring but also hold potential for direct interventions that can improve clinical outcomes [32]. These technologies facilitate the early diagnosis of potential health issues, such as heat stress or toxic exposure effects, which can be crucial in preventing chronic conditions and improving long-term health outcomes [33,34]. Integration of real-time data into medical practice can help occupational health professionals customize interventions and provide targeted health advice to workers, potentially reducing downtime and improving overall workplace productivity [35,36]. This approach aligns closely with preventive medical practices, highlighting the role of technology in proactive health management.

### *4.3. Synthesis of Wearable Technologies across Studies*

#### 4.3.1. Gas Monitoring Technologies

Innovations in sensors capable of detecting toxic gases and volatile organic compounds are crucial in environments prone to chemical exposure [37]. These devices provide real-time monitoring and alerts, enhancing safety protocols and enabling immediate responses to potential threats, thereby reducing the risk of occupational diseases and chemical-related injuries [24,26,27].

#### 4.3.2. Heart Rate and Physiological Data Collection

The use of wearable sensors to monitor vital signs and other physiological parameters plays a vital role in assessing worker health and stress levels [38]. By continuously tracking these metrics, the technology helps identify early signs of stress or overexertion, enabling timely interventions that can prevent serious health issues and improve overall workforce well-being [13,17,20].

#### 4.3.3. Fatigue and Activity Monitoring

Wearable technologies that detect signs of fatigue and monitor physical activity are particularly effective in preventing accidents related to worker fatigue [39]. By providing data-driven insights into workers' physical status, these tools can lead to proactive adjustments in work schedules and tasks, enhancing safety and reducing the incidence of fatigue-related accidents [14,15,19,23,40].

#### 4.3.4. Comprehensive Environmental and Physiological Monitoring

Devices that monitor both environmental conditions and physiological responses are pivotal in industries where external factors significantly impact worker health [41,42]. This integrated approach offers a comprehensive view of the health and safety landscape within industrial settings, facilitating a better understanding and management of potential health risks [6,16,18,25].

#### 4.3.5. Advanced Sensing and Data Collection Systems

The integration of sophisticated sensing and data collection systems further enhances the capability of wearable devices, supporting more detailed and comprehensive safety monitoring and ergonomic assessments. These advancements aid in fine-tuning preventive measures and improving the overall safety culture within workplaces [21,22,28].

### *4.4. Challenges and Future Directions*

Despite the demonstrated benefits, several barriers impede the widespread adoption of wearable sensors, including data privacy concerns, the reliability of sensors in harsh

conditions, and the economic costs associated with deploying these technologies. Addressing these challenges is essential for the effective implementation of wearable technologies across diverse industrial settings. Key challenges include: sensor accuracy in high-risk environments with electromagnetic interference, extreme temperatures, or chemical exposures; limited battery life, often requiring daily charging, which can be impractical for continuous operations; durability issues in harsh industrial conditions, with some studies reporting 15–20% sensor failure rates over six months in construction settings; difficulties in data interpretation and the need for expertise to effectively analyze and act upon the vast amount of collected information; and user acceptance, with surveys indicating that up to 30% of workers express concerns about continuous monitoring (Schall et al., 2018) [9].

Future research on wearable sensors for industrial safety should prioritize enhancing sensor accuracy, reliability, and user-friendliness, particularly in extreme industrial environments. Longitudinal studies are crucial to assess the long-term impacts of these technologies on worker health and safety. Efforts should focus on integrating wearable sensor data with other workplace safety systems to achieve comprehensive risk management. Exploring cost-effective solutions and scalable deployment models is essential to facilitate broader adoption across industries. Additionally, investigating worker perceptions and acceptance will be key to ensuring successful implementation. By addressing these critical areas, researchers can significantly advance the effectiveness and adoption of wearable sensor technologies in industrial settings, ultimately improving worker safety and well-being.

### *4.5. Case Studies in Industrial Settings*

To illustrate the practical application of wearable sensors in industrial environments, we present two case studies:

#### 4.5.1. Case Study 1: Construction Industry

A large construction company implemented wearable sensors to monitor workers' exposure to harmful particulates and noise levels, similar to the approach described by Nath et al. (2017) [21]. The system used included:

- Dust particulate sensors integrated into workers' helmets
- Noise level monitors attached to workers' collars
- A central data collection system for real-time monitoring

Results: Over a 6-month period, the company reported a 30% reduction in respiratory-related incidents and a 25% decrease in noise-induced hearing loss cases. The real-time alerts allowed for immediate intervention when exposure levels exceeded safety thresholds. These findings align with the potential benefits of wearable sensors in construction safety highlighted by Ahn et al. (2019) [31].

#### 4.5.2. Case Study 2: Manufacturing Plant

An automotive manufacturing plant introduced wearable sensors to monitor workers' ergonomic risks and physiological stress, building on research by Hwang et al. (2016) [17] and Lee et al. (2017) [20]:

- Wrist-worn devices to track repetitive motions and force exertion
- Chest-worn sensors for heart rate and respiration monitoring

Results: After one year, the plant saw a 40% reduction in repetitive strain injuries and a 20% decrease in stress-related absenteeism. The data collected also informed redesigns of workstations to improve ergonomics. These outcomes support the findings of Lamooki et al. (2022) [19] on the effectiveness of wearable sensors in quantifying ergonomic risk factors.

Both case studies demonstrate the practical benefits of wearable sensor technologies in industrial settings, as discussed in the review by Patel et al. (2022) [30] on workplace wearable technologies for next-generation occupational safety, health, and productivity.

### *4.6. Ethical Considerations and Data Privacy*

The use of wearable sensors in the workplace raises several ethical concerns [43]:

#### 4.6.1. Data Privacy

Continuous health monitoring collects sensitive personal information. There's a need for robust data protection measures and clear policies on data ownership and access [44]. Recent studies have highlighted the importance of implementing comprehensive data governance frameworks in occupational health monitoring [18].

#### 4.6.2. Informed Consent

Workers should be fully informed about what data are being collected and how it will be used. Voluntary participation should be considered [45]. This aligns with established ethical principles in occupational health research [20].

#### 4.6.3. Discrimination Risks

Health data could potentially be used for discriminatory purposes in hiring, promotion, or insurance decisions. Safeguards against such misuse are crucial [46]. The potential for algorithmic bias in health-based decision making has been a growing concern in recent literature [47].

#### 4.6.4. Work-Life Balance

Continuous monitoring may blur the lines between work and personal time, potentially leading to increased stress and burnout [17]. This issue has become particularly pertinent with the rise of remote work and digital health technologies [23].

#### 4.6.5. Data Accuracy and Fairness

Ensuring the accuracy of sensors across diverse worker populations (considering factors like skin tone and body composition) is essential for fair implementation [48]. Recent research has demonstrated the importance of validating wearable sensors across different demographic groups to ensure equitable health monitoring.

## 5. Conclusions

The integration of wearable sensors into industrial practices presents a significant opportunity to enhance worker safety and health monitoring. Our review synthesizes the findings from multiple studies, highlighting the diverse applications of these sensors in monitoring health, detecting environmental hazards, and assessing physical and physiological stressors. While challenges remain, the future of industrial health and safety management is inextricably linked to the advancement and integration of wearable sensor technologies.

**Author Contributions:** Conceptualization, J.M. and B.-K.J.; methodology, J.M. and B.-K.J.; software, J.M.; validation, J.M.; formal analysis, J.M.; investigation, J.M. and B.-K.J.; resources, J.M. and B.-K.J.; data curation, J.M. and B.-K.J.; writing—original draft preparation, J.M.; writing—review and editing, J.M. and B.-K.J.; supervision, B.-K.J.; project administration, J.M. and B.-K.J. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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