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Drivers and Barriers to the Use of Wearable Sensing Devices for Real-Time Safety Risk Assessment in Construction

Mehdi Torbat Esfahani[1], Tulio Sulbaran, Ph.D.[1], and Ibukun Awolusi, Ph.D.[1]
[1]The University of Texas at San Antonio

Construction workers face numerous hazards and risks on job sites, necessitating comprehensive risk assessment methods to safeguard their safety and health. Traditional risk assessment approaches in the construction industry often rely on historical data and periodic assessments, potentially overlooking real-time conditions and dynamic environmental changes. This paper addresses this challenge by examining wearable sensing devices (WSDs) integration to provide continuous, real-time data for construction safety risk assessment. This study employs a systematic literature review to synthesize insights from existing academic research on integrating WSDs for safety risk assessment in construction. It aims to elucidate the benefits, challenges, and implementation considerations of incorporating WSDs into established risk management frameworks. Additionally, the study utilizes scientometric analysis to categorize key drivers and barriers to WSD integration while uncovering trends and relationships within the field. The study's results indicate that key drivers, including technological advancements, real-time monitoring, and hazard identification, alongside barriers such as cost, user acceptance, data privacy, training requirements, and integration with existing systems. The scientometric analysis further reveals trends such as real-time hazard detection and worker safety awareness advancements while highlighting challenges like data management and integration across applications. The broader impact is the improvement of risk assessment efficiency and precision, promoting proactive safety risk management strategies, and ensuring personnel safety in construction.

Keywords: Real-Time Monitoring; Risk Assessment; Wearable Sensing Devices.

Introduction

Construction sites are inherently dynamic environments characterized by numerous hazards and potential risks, including falls from heights, exposure to hazardous materials and environmental factors, and accidents involving tools and machinery (Afzal et al., 2021). Effective safety risk assessment methodologies are essential for identifying, evaluating, and mitigating these risks to prevent accidents, injuries, and fatalities (Islam et al., 2017). Traditionally, risk assessments in construction have relied on historical data and periodic evaluations, which may not capture real-time conditions or evolving hazards adequately (Jozi et al., 2015). This approach can lead to gaps in timely hazard identification and implementation of risk mitigation strategies, potentially exposing workers to avoidable dangers.

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Moreover, the dynamic nature of construction sites and the diverse range of hazards underscores the need for more proactive and comprehensive risk assessment practices (Choi et al., 2022). Failure to accurately assess and address construction risks jeopardizes workers' safety and well-being and poses significant financial and reputational risks to construction firms. Therefore, there is a critical need to enhance safety risk assessment practices in the construction industry to address the dynamic nature of construction sites and ensure the timely implementation of proactive safety measures. By improving risk assessment accuracy, timeliness, and comprehensiveness, construction companies can minimize workplace accidents, optimize resource allocation, and enhance overall project efficiency and success (Mahmood et al., 2023; Shi et al., 2019).

Various methods have been employed to address the limitations of traditional risk assessment methods in the construction industry. For instance, researchers have focused on enhancing risk identification, analysis, and evaluation processes by applying advanced, non-deterministic concepts (Lehtiranta et al., 2010). Additionally, integrating real-time data streams and predictive analytics has been explored to facilitate proactive risk management strategies (Carbonari et al., 2011). Furthermore, comparative analyses of traditional risk management approaches with emerging technologies have been conducted to assess their effectiveness in identifying and analyzing risks (Marhavilas et al., 2011). These advancements in risk assessment methodologies have laid the groundwork for integrating innovative technologies, such as wearable sensing devices (WSDs), into construction safety practices. WSDs represent a transformative step toward achieving continuous, real-time monitoring and proactive risk management by bridging the gap between theoretical frameworks and real-world applications.

Real-time monitoring of the physiological, environmental, and positional parameters using WSDs is a pivotal advancement in tracking and assessing construction environment dynamic and evolving hazards (Ahn et al., 2019). WSDs encompass many portable technologies with sensors that monitor physiological, environmental, or behavioral parameters. These devices include but are not limited to, smart wristbands, armbands, chest straps, and body-worn sensors, all designed to collect real-time physiological, environmental, and positional data relevant to worker safety and health (Ahn et al., 2019; Awolusi et al., 2018; Awolusi et al., 2019). By integrating WSDs, construction companies can continuously monitor and analyze environmental factors, worker behavior, and potential risks in real-time (Mahmood et al., 2023). This enables proactive identification of hazards, prompt implementation of appropriate safety measures, and immediate response to emerging risks, thereby significantly enhancing workplace safety and accident prevention efforts (Awolusi et al., 2018; Esfahani et al., 2024). However, to fully leverage WSDs' potential in this field, there is a need to first understand the key drivers and barriers associated with their integration into safety risk assessment systems.

This research paper focuses on exploring and identifying the drivers and barriers to incorporating WSDs to offer ongoing, real-time data for assessing safety risks within construction. A systematic literature review is employed to discover these factors, and a scientometric analysis is further used to identify and categorize key drivers and challenges of WSD integration in real-time safety risk assessment, which were studied in the literature.

Methodology

This study employs a systematic literature review (SLR) methodology to explore the drivers and barriers associated with utilizing WSDs for safety risk management and risk analysis in the construction industry. SLR is a method used to analyze scientific evidence and address specific research questions transparently and systematically. It involves comprehensively gathering all relevant published evidence on a given topic and evaluating the quality of this evidence. SLR has gained prominence in public policy research and health sciences, and proponents suggest their integration into design research (Lame, 2019). The drivers and barriers that impact the integration of WSDs in assessing construction-related risks can be elucidated by systematically searching and synthesizing relevant literature. Figure 1 illustrates the research steps and procedures in this study. It shows the systematic approach adopted in this study, starting with identifying relevant publications using the PRISMA framework. This process includes database selection, keyword identification, and applying inclusion criteria to refine the search. A scientometric analysis was conducted to systematically synthesize drivers and barriers, exploring their correlation.

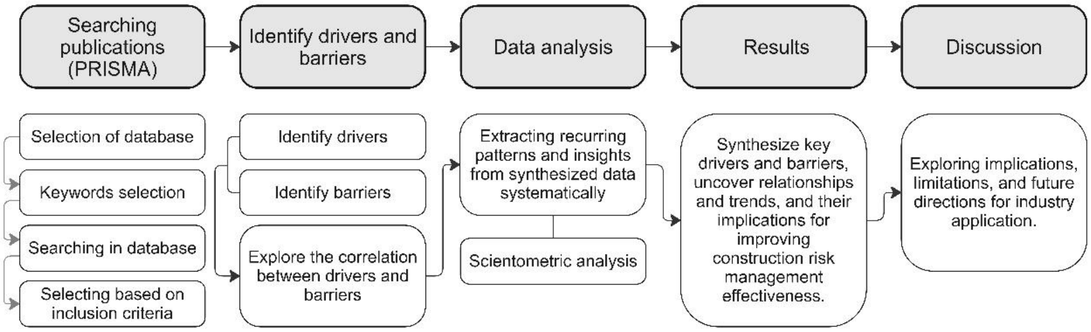

Figure 1. Research steps and procedures

Data Collection and Analysis Process

A systematic search strategy is employed for data collection using two major academic databases: Web of Science and Scopus. These databases provide comprehensive coverage of scholarly literature across various disciplines, offering access to peer-reviewed articles. The search uses predefined keywords relevant to the research topic, detailed in Table 1. These keywords represent essential elements for comprehensive searching and analysis.

Table 1. Keyword combination to search in databases

Combination 1	**Combination 2**	**Combination 3**	**Combination 4**	**Combination 5**	**Combination 6**
Risk Analysis	Risk Assessment	Hazard Analysis	Hazard Assessment	Risk Monitoring	Risk Tracking
Wearable Devices	Wearable Devices	Real-time	Sensors	Monitoring	Technology
Risk Management	Sensors	Technology	Real-time	Data Collection	Integration
Construction	Construction	Construction	Construction	Construction	Construction

A predefined set of search strings was developed using Boolean operators (e.g., AND, OR) to combine identified keywords and ensure a focused and comprehensive search. To refine the results, four specific filters are applied: relevance, requiring materials to address the integration of WSDs in construction risk assessment directly; publication date, limiting the search to literature published after the year 2000; peer-review status, ensuring articles met scholarly rigor and quality standards; and language, including only materials published in English for comprehensive analysis.

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) data collection process. This comprehensive process is depicted in Figure 2. Upon retrieving the initial search results, duplicates will be removed, and the remaining records will undergo a two-stage screening process. The first stage involves screening titles and abstracts to assess relevance to the research topic, while the second stage entails a full-text review of selected articles to determine inclusion based on predefined criteria. Furthermore, to ensure the comprehensiveness and rigor of the literature review, backward and forward citation searching is employed, wherein references of included articles and citing articles are reviewed to identify and add potentially relevant literature that may not have been captured through the initial database search.

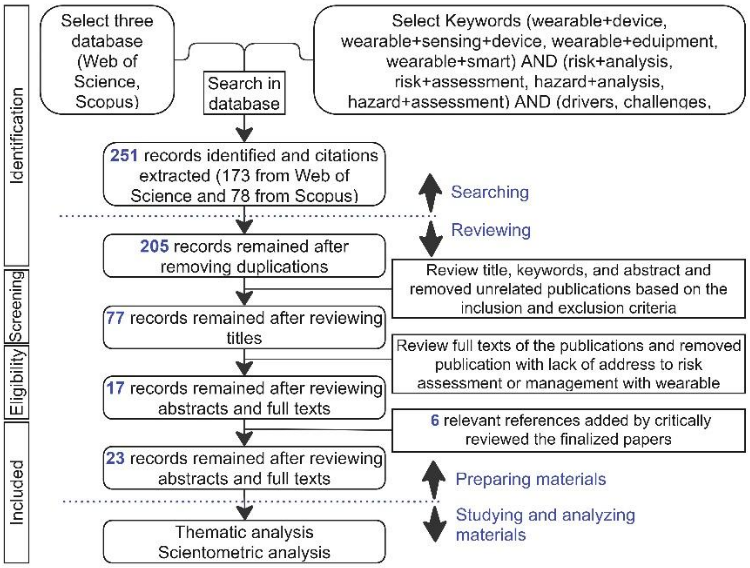

Figure 2. PRISMA data collection process

The review began by searching two primary databases: Web of Science and Scopus, using predefined keywords. The initial search yielded 251 records, including 173 from Web of Science and 78 from Scopus, followed by the removal of duplicates, leaving 205 unique records. These records were then subjected to a title review, reducing the dataset to 77 publications. Subsequently, a comprehensive abstract and full-text review were conducted to identify studies directly addressing risk assessment or management involving wearable devices, further narrowing the dataset to 17 records. To enhance the robustness of the review, six additional relevant references were included through critical evaluation of the finalized papers. Ultimately, 23 publications were identified for thematic analysis, which formed the foundation for synthesizing insights into the drivers and barriers of wearable sensing devices in real-time safety risk assessment.

The data analysis comprised two main stages: systematic extraction of drivers and barriers and scientometric analysis. Initially, the reviewed literature was analyzed to identify factors influencing the adoption of WSDs in real-time safety risk assessment. Key drivers and barriers were extracted and categorized based on recurring themes across the studies. Subsequently, scientometric analysis was conducted to uncover trends, research focus, and collaborations within the field. CiteSpace software (version 6.2.R2) was utilized for the scientometric analysis (Chen et al., 2008). Bibliographic data from the extracted publications were exported in plain text format for compatibility with the software. A 1-year time interval was applied to organize publications chronologically. Cited references and authors were selected as node types for cluster analysis of co-occurring keywords to identify key topics and reference clusters to visualize relationships and track the evolution of research in WSDs integration with construction safety risk assessment.

Results

Drivers for WSDs Adoption in Safety Risk Assessment

One of the primary drivers facilitating the adoption of wearable and sensor technologies is technological advancements (Wei et al., 2024; Bansal et al., 2022; Czekster et al., 2023; Ding & Zhou, 2013; Gao et al., 2024; Liu et al., 2021). These advancements, such as miniaturization, improved sensor accuracy, and wireless connectivity, have made WSDs more accessible, user-friendly, and capable of real-time data collection and transmission. Real-time monitoring capabilities (Bansal et al., 2022; Choi et al., 2022; He et al., 2020; Jiang et al., 2014; Khamraev et al., 2021) offered by wearable and sensor technologies represent another significant driver for their adoption. These technologies allow immediate feedback on workers' health status, environmental conditions, and safety hazards. By providing real-time insights, these devices empower workers and supervisors to make informed decisions to mitigate risks and prevent accidents, enhancing overall safety and productivity. Furthermore, the ability of WSDs to aid in hazard identification (Chenya et al., 2022; Choi et al., 2022; Khamraev et al., 2021; Newaz et al., 2022; Pillet & Waiter, 2023; Wang & Razavi, 2018) is a critical driver for their integration into various industries. These technologies can timely detect potential hazards and unsafe behaviors by continuously monitoring workers' physiological responses, movements, and environmental conditions.

Barriers to WSDs Implementation in Safety Risk Assessment

Despite the numerous benefits of wearable and sensor technologies, several barriers may hinder their widespread adoption and effective implementation. Cost and affordability (Chen et al., 2023; He et al., 2020; Pazienza et al., 2022; Wang & Razavi, 2018) represent a significant barrier, particularly for small businesses or projects with limited budgets. The initial investment required to acquire and implement wearable devices and ongoing maintenance, as well as training costs, may pose financial challenges for organizations (Czekster et al., 2023; Hong & Cho, 2024; Mahmood et al., 2023; Mokhtari et al., 2023; Pillet & Waiter, 2023), and also present a barrier to the widespread adoption of wearable and sensor technologies. Furthermore, some workers may be hesitant to use these devices due to concerns about comfort, privacy, and the perceived intrusiveness of continuous monitoring. Overcoming resistance and gaining user acceptance requires addressing these concerns through education, training, and transparent communication about the benefits of these technologies for personal and collective safety. Therefore, data privacy and security (Czekster et al., 2023; He et al., 2020; Pazienza et al., 2022; Wei et al., 2024) are additional barriers that must be addressed to ensure the successful implementation of wearable and sensor technologies. Collecting and storing sensitive health data raise privacy concerns, necessitating robust data protection measures and compliance with regulations. Moreover, training and skill requirements (Czekster et al., 2023; He et al., 2020; Mokhtari et al., 2023; Pazienza et al., 2022) represent a significant barrier to the effective utilization of wearable and sensor technologies. Adequate training and skill development are essential to ensure workers can use these devices effectively, interpret the data accurately, and respond appropriately to real-time alerts and notifications. Investing in training programs and providing ongoing support is crucial for maximizing the benefits of these technologies and minimizing the risk of misuse or misinterpretation. In addition, integration with existing systems (Czekster et al., 2023; He et al., 2020; Pazienza et al., 2022; Wei et al., 2024) poses technical challenges and complexities that may hinder the seamless adoption of WSDs. Ensuring compatibility and interoperability with existing management systems and workflows requires customization and integration efforts, which may prolong the implementation process and increase associated costs. Table 2 synthesized and organized the aforementioned factors with a brief description. Drivers (D) represent key factors that drive the adoption and utilization of WSDs for safety risk assessment in construction. Conversely, the Barriers (B) highlight obstacles hindering such technologies' widespread implementation and effectiveness.

Table 2. Drivers and Barriers of Wearable and Sensor Technologies for Real-time Risk Assessment

Identifier	Drivers and Barriers	Description	References
D1	Technological Advancements	Advancements such as miniaturization, improved sensor accuracy, and wireless connectivity	Bansal et al., 2022; Wei et al., 2024 Ding & Zhou, 2013
D2	Real-time Monitoring Capabilities	Wearable and sensor technologies enable immediate feedback on workers' health status, environmental conditions, and safety hazards.	Bansal et al., 2022; Choi et al., 2022; He et al., 2020; Jiang et al., 2014; Khamraev et al., 2021
D3	Hazard Identification	Continuous monitoring of workers' physiological responses, movements, and environmental conditions helps detect potential hazards and unsafe behaviors.	Choi et al., 2022; Chenya et al., 2022; Khamraev et al., 2021; Newaz et al., 2022; Pillet & Waiter, 2023
B1	Cost and Affordability	Initial investment, ongoing maintenance, and training costs may pose financial challenges for organizations.	Chen et al., 2023; He et al., 2020; Pazienza et al., 2022; Wang & Razavi, 2018
B2	User Acceptance and Comfort	Some workers may be hesitant to use wearable devices due to concerns about comfort, privacy, and perceived intrusiveness.	Czekster et al., 2023; Hong & Cho, 2024; Mahmood et al., 2023; Mokhtari et al., 2023
B3	Data Privacy and Security	The collection of sensitive health data raises privacy concerns, requiring robust data protection measures.	Czekster et al., 2023; He et al., 2020; Pazienza et al., 2022
B4	Training and Skill Requirements	Training and skill development are essential to ensure the effective use of wearable devices, the interpretation of data, and the appropriate response to real-time alerts.	Czekster et al., 2023; He et al., 2020; Mokhtari et al., 2023; Pazienza et al., 2022
B5	Integration with Existing Systems	Technical challenges and complexities in ensuring compatibility and interoperability with existing management systems and workflows	Czekster et al., 2023; He et al., 2020; Pazienza et al., 2022;

Scientometric Analysis Results

The scientometric analysis summarizes insights from seven major clusters related to wearable sensing devices and construction risk management, as illustrated in Figure 3. This Scientometric analysis visualization highlights key clusters, co-occurring keywords, and thematic trends in adopting WSDs for construction safety risk assessment. The largest cluster (#0) focuses on "Hydropower Construction Sites," emphasizing real-time safety assessments using location systems, with key contributions from studies like Jiang et al. (2014). Cluster #1, labeled "Process Industries," highlights advancements in generative adversarial networks for real-time risk warning, with high connectivity in concepts like convolutional neural networks and data classification. Cluster #2 investigates "By-Equipment Hazard," exploring spatiotemporal models for dynamic risk analysis in construction, while Cluster #3 focuses on the "Construction Workforce," addressing hazard exposure quantification using real-time location data. Smaller clusters, such as #4, center on "Enhancing Individual Worker Risk Awareness," emphasizing personalized safety check systems. Cluster #5 revolves around "Construction Projects," applying systematic literature reviews and artificial intelligence-based risk prediction models. Finally, Cluster #6 explores "Falling Risk," developing wearable frameworks for assessing fall-related risks. The analysis underscores the "Construction Industry" as the most central and significant node, reflecting its broad impact across clusters, followed by critical themes like "Risk Assessment" and "Construction Equipment," with high degrees of connectivity and influence. These findings emphasize the integration of advanced technologies in construction safety and highlight emerging opportunities for applying AI and wearable devices in dynamic risk environments. Moreover, this analysis reveals some barriers to WSD adoption, including user acceptance issues from the 'Enhancing Individual Worker Risk Awareness' cluster, data handling and integration challenges from the 'Construction Projects' cluster, and specialization demands from the 'Falling Risk' cluster.

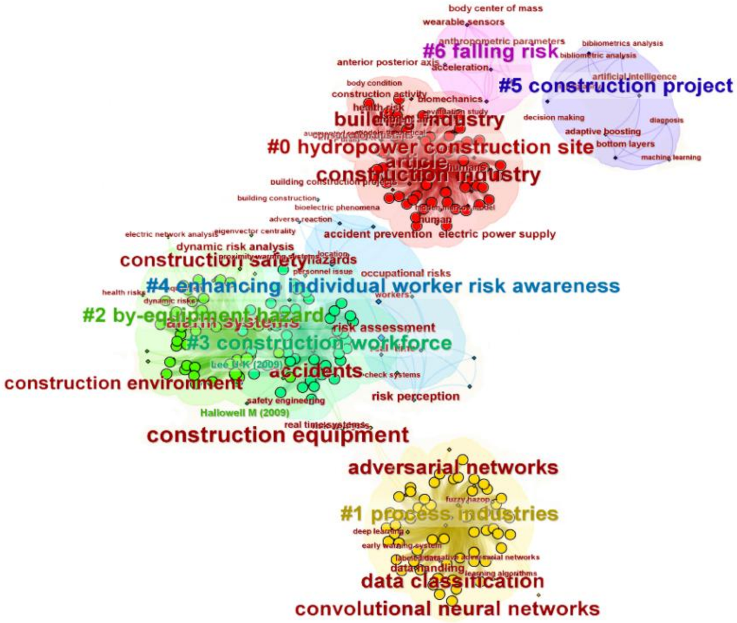

Figure 3. Key clusters in the adoption of WSD for construction safety risk assessment

Discussion

This study highlights several key drivers facilitating the adoption of WSDs in construction risk assessment. Technological advancements, such as miniaturization, improved sensor accuracy, and wireless connectivity, have made WSDs more accessible and capable of real-time data collection and transmission (Wei et al., 2024). These advancements enable continuous monitoring of workers' physiological parameters and environmental conditions, allowing for early detection of risks and timely interventions (Choi et al., 2022; He et al., 2020; Jiang et al., 2014; Khamraev et al., 2021). The scientometric analysis reinforces these findings by identifying clusters focused on real-time safety assessments (Cluster #0) and hazard exposure quantification (Cluster #3), both of which underscore the importance of WSDs in enhancing safety and efficiency. Additionally, the ability of WSDs to provide immediate feedback, as illustrated in Cluster #2, aligns with their capacity to improve hazard identification and empower proactive risk management strategies (Choi et al., 2022; Pillet & Waiter, 2023). Despite these benefits, significant barriers remain that hinder the widespread adoption of WSDs. Cost and affordability represent a significant challenge, particularly for smaller businesses or projects with limited budgets (He et al., 2020; Pazienza et al., 2022). The financial burden of acquiring, maintaining, and training WSDs, as reflected in Cluster #6, limits their accessibility (Czekster et al., 2023; Hong & Cho, 2024; Mahmood et al., 2023). Similarly, user acceptance and comfort are critical barriers, as some workers may resist adopting WSDs due to concerns about privacy, comfort, and perceived intrusiveness (Czekster et al., 2023; Mokhtari et al., 2023; Pillet & Waiter, 2023). These issues are evident in Cluster #4, highlighting personalized safety systems as a focal point for addressing such challenges. Furthermore, data privacy and security concerns, including managing and protecting sensitive health data, require robust safeguards and compliance with regulations (He et al., 2020; Pazienza et al., 2022). Integration with existing systems poses additional technical challenges, as indicated by Cluster #5, necessitating significant customization efforts to achieve compatibility and interoperability (Wei et al., 2024; Czekster et al., 2023; Pazienza et al., 2022).

As demonstrated in Clusters #1 and #5, emerging trends in AI-driven approaches offer promising opportunities to overcome some of these barriers. Advanced techniques like generative adversarial networks and convolutional neural networks enable more accurate hazard prediction and enhanced real-time monitoring capabilities (Czekster et al., 2023; de los Pinos et al., 2024). These innovations align with the scientometric findings, highlighting the centrality of the "Construction Industry" node and reflecting the potential for widespread collaboration and standardization efforts. As emphasized in Cluster #4, personalized safety systems represent an opportunity to design more human-centric technologies that balance usability with effectiveness (Mokhtari et al., 2023; Pillet & Waiter, 2023).

Theoretical and Practical Implications

Integrating wearable and sensor technologies into real-time risk assessment significantly enhances workplace safety across various industries, particularly in high-risk environments like construction. These technologies offer a proactive approach to identifying and mitigating potential hazards by continuously monitoring workers' physical and mental conditions. Through the utilization of sensors, safety professionals have been able to collect real-time data on workers' movements, posture, and physiological responses. This data provides valuable insights into the factors contributing to workplace accidents, enabling the development of proactive safety measures and interventions. In addition, the broader impact of integrating WSDs for real-time safety risk assessment extends beyond individual workplaces to encompass societal well-being and economic prosperity. By reducing the incidence of workplace accidents and injuries, these technologies contribute to the overall health and safety of workers, enhancing their quality of life and productivity. Moreover, implementing proactive safety risk management strategies facilitated by continuous monitoring systems can lead to cost savings, improved project outcomes, and enhanced organizational competitiveness.

Conclusions and Recommendations

Construction sites' dynamic and hazardous nature necessitates innovative approaches to safety risk assessment, as traditional methods that rely on historical data and periodic evaluations often fail to address real-time conditions and evolving risks. Through a systematic literature review, this study identifies key drivers and challenges associated with the integration of WSDs as a transformative solution, offering significant potential to enhance safety risk assessment through technological advancements, real-time monitoring capabilities, and improved hazard identification. However, the findings highlight critical barriers to widespread adoption, including cost, user acceptance, data privacy, training requirements, and integration challenges. Moreover, the analysis reveals notable trends, such as advancements in real-time hazard detection, increased worker safety awareness, and the construction industry's central role in driving technological integration. At the same time, it highlights persistent barriers, including data management complexities, user resistance, and difficulties in system interoperability. Future efforts should focus on addressing these barriers by developing cost-effective and user-friendly solutions, ensuring seamless integration with existing systems, and implementing robust privacy safeguards. Comprehensive training programs and educational initiatives are essential to improve worker proficiency and acceptance. In addition, leveraging AI and machine learning technologies can further enhance the effectiveness of WSDs, while long-term and industry-specific studies are needed to evaluate their scalability and sustained impact. Policymakers should prioritize developing standardized guidelines to facilitate the adoption of WSDs for safety risk assessment.

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