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Trends and Limitations of Construction Safety Technologies

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Abstract

Current literature on construction safety technologies has primarily investigated the technological functionality, feasibility, and benefits of the proposed technologies. The related literature is mainly limited to an individual type of safety technology without the option of a combination of safety technology sets, laboratory, or controlled performance testing of the proposed technology. The primary objective of this paper is to identify the gaps in the literature on construction safety technologies, and to identify common limitations and trends in the proposed technologies. This study contributes to the body of knowledge by dividing construction safety into four phases (*pre-construction phase, workers' safety training phase, safety management, and the construction phase*) based on the impact of proposed safety technology. In addition to identifying four main areas related to the on-site construction phase, technologies trying to improve it (*safety monitoring and proximity sensing, near-miss fall detection, hardhat-wearing monitoring, and workers' emotions*) are discussed. The highlighted common limitations of the proposed technologies concluded in this paper could influence future researchers to cover the mentioned gaps and limitations.

Keywords

Construction Safety, Technologies, Hazard Identification, Near-Miss Fall Detection, Safety Training

1. Introduction

The architecture, engineering, and construction (AEC) industry faces numerous obstacles to achieving goals, such as reducing costs and increasing productivity and safety. To achieve such goals, new practices and strategies—that is, "innovations" are needed. Innovation is defined as the adoption of ideas, systems, policies, programs, processes, products, or services that are new to the adopting organization (Damanpour, 1992). In the context of this research, the focus is on innovations in construction safety technologies. In recent years, the use of new technologies in the AEC industry has been increasing due to market pressure to improve productivity, reduce costs, enhance safety, and increase sustainability (Loosemore 2014). Examples of technology innovations that have been introduced in the AEC industry include building information modeling (BIM), mobile technology, scanning technology, sensor technology, virtual reality, augmented reality, safety monitoring, drones and unmanned aerial vehicles (UAVs), remote-controlled construction equipment, internet of things, and 3D printing (Ko, 2002). Technological innovations in the AEC industry will continue to develop and evolve because the benefits of technologies are well recognized (Maali et al., 2024). However, the adoption of technologies in the industry is typically very slow compared to other industries (Edirisinghe, 2019; Gholizadeh et al., 2018), Which has resulted in the AEC industry not being considered an industry that fosters innovations. Some sources have asserted that the reluctance to adopt innovations is a reason for the decline in the industry's productivity over the previous 50 years (Crew, 2017).

Construction safety plays an important role in the success of construction projects. According to the Occupational Safety and Health Administration (OSHA), the construction industry accounted for 20.5% or 874 worker fatalities in the US (OSHA, 2014). The construction industry accounts for more fatal injuries than any other single service industry. Lower construction safety in a project means a high risk of incidents that lead to injuries and even fatalities, which will dramatically affect the construction process. In any safety-related incident, there are two main cost consequences that will affect the responsible party: direct costs, such as medical expenses, transportation costs, and damaged equipment or materials, and indirect costs, such as loss of productivity, cost of replacement worker, injured worker compensation, and loss of reputation (Al-Bayati et al., 2025). Other consequences are a loss of competitiveness, inability to win bids, increment of insurance, and prequalification issues in future projects.

With such consequences, the industry is now more focused on improving the safety of construction sites in order to reach the ultimate goal of a successful project. With technology diffusion in the AEC industry, researchers have started to utilize new technologies to improve construction safety through multiple innovations.

2. Collection Methodology

Construction is an industry full of safety hazards. In the construction industry, workers are frequently exposed to fatal accidents (Ko and Abdulmajeed, 2022). Even with the implementation of safety regulations and guidelines, construction safety is frequently violated, which exposes workers to incidents of injuries and fatalities (Park et al., 2017). Several types of technologies were proposed and developed to improve safety at construction sites, such as proximity and safety monitoring sensor technologies (Park et al., 2017; Park et al., 2016), detection of near mess falls (Lim et al., 2016; Zhang et al., 2019), detection of hardhats use (Park et al., 2015; Zhang, Yan, et al., 2019), mobile software that improves safety inspection processes at construction sites (Zhang et al. 2017), machine learning software that analyzes videos to identify in real-time whether workers are wearing hard hats at the construction site (Park et al., 2015), eye-tracking technology that would improve safety training for workers (Hasanzadeh et al., 2017), and safety training for construction workers using virtual reality and augmented reality technology (Dawood et al., 2014; Froehlich and Azhar, 2016).

Most of the research on technologies related to construction site safety has focused only on the technological factors and their benefits rather than human and organizational factors that may affect the implementation, diffusion, and adoption of the proposed technology. Some researchers have studied the feasibility and acceptance of wearable safety equipment (Awolusi et al., 2018; Choi et al., 2017).

Previous studies on the topic of construction safety technologies were examined to identify common barriers and limitations of such new technologies. The following aspects of the studies were analyzed to identify gaps and limitations in the body of knowledge: technology type, data collection methods, data samples, and technology performance metrics.

Published articles from 2015 to 2019 were considered for this literature research, as the sponsorship of this project ended in 2020. Articles were collected from various sources, including four leading journals (i.e., *Journal of Construction Engineering and Management*; *Journal of Management Engineering*; *Engineering, Construction, and Architecture Management*; and *Automation in Construction*), international databases (i.e., the American Society of Civil Engineers online library, Emerald Insight online library, and Elsevier online library), and the University of Kansas online libraries. The focus was on collecting articles focused on construction safety technologies. Some of the main keywords used in online searches were *construction safety, innovations in construction safety, safety technologies in the AEC industry, implementation of safety technology*, *adoption of new safety technology*, and *new technology applications for construction safety*. The collected articles were reviewed and filtered so that the literature review included only articles with a focus on new technology applications related to construction safety in the AEC industry. Fifteen articles were selected to be analyzed for this literature review paper. A list of selected papers with some related information is listed in Table 1.

Table 1. Selected papers

#	Author	Journal
1	Awolusi et al., 2018	Automation in Construction
2	Bhandari et al., 2020	Journal of Construction Engineering and Management
3	Choi et al., 2017	Automation in Construction
4	Hasanzadeh et al., 2017	Journal of Management in Engineering
5	Hwang et al., 2018	Journal of Construction Engineering and Management
6	Lim et al., 2016	Journal of Construction Engineering and Management
7	Park et al., 2015	Journal of Construction Engineering and Management
8	Park et al., 2016	Journal of Construction Engineering and Management
9	Park et al., 2017	Journal of Construction Engineering and Management
10	Teo Ai Lin et al., 2017	Engineering, Construction, and Architectural Management
11	Xiong and Tang, 2021	Automation in Construction
12	Zhang et al., 2017	Journal of Management in Engineering
13	Zhang et al., 2019	Journal of Construction Engineering and Management
14	Zhang et al., 2019	Journal of Construction Engineering and Management
15	Zhang et al., 2022	Automation in Construction

3. Gaps in the Literature

The current literature on construction safety technologies has primarily investigated the technological functionality, feasibility, and use benefits. There are several gaps in the literature on safety technologies: first, research designs in the literature are often limited to an individual type of safety improvement using technologies, for example, focusing only on proximity sensing, wearing of hardhats, or near-miss falls. Second, most of the proposed technologies and their performances were mainly tested in laboratories, in addition to a limited number and period of actual site experiments by participants in an actual construction site. Those types of experiments do not perfectly reflect the real use and barriers of such technologies.

Third, most of the literature has focused on developing new technologies or improving previously used technologies; no studies have focused on or experimented with a combination of safety technology sets in order to provide a comprehensive model of construction safety. Finally, the proposed technologies were evaluated while neglecting one of the most important factors, the human “user” factor, such as the acceptance of technology use and adoption.

The objectives of this study are to (1) identify the gaps in the literature on construction safety technologies, (2) identify common limitations and trends in the proposed technologies, and (3) provide future suggestions to cover limitations and gaps.

4. Literature Analysis

The twelve selected articles were analyzed using the following aspects to identify gaps and limitations in the body of knowledge: safety phase, technology type, data collection methods, data samples, and technology performance metrics. After the analysis, the research found that the way to group the safety technology is by the safety phase, which will be mainly impacted by the proposed technology. Safety in construction could be divided into four phases, as presented in Fig 1: (1) the Pre-Construction Phase, (2) the Workers’ Safety Training Phase, (3) Safety Management, and (4) the Construction Phase.

Fig. 1. Construction safety phases

Pre-Construction Phase

This phase is related to safety planning before the start of the construction phase. It is mainly located in the design phase of construction projects. In the context of construction safety technologies, Teo Ai Lin et al. (2017) developed a conceptual framework of intelligent productivity and safety system (IPASS) to improve safety and productivity by using BIM. While the project is submitted for approval, the developed IPASS can point high-risk areas during the design stage, enabling hazard mitigation plans to be applied. The proposed intelligent BIM-based system would allow users to identify and mitigate unsafe designs and their associated risks to increase safety before the start of the project by updating designs accordingly. Also, it will help project managers plan site activities, and safety programmers focus on the higher-risk trades and prioritize hazard mitigation strategies and intervention methods to make effective resource allocation decisions. Some limitations are (1) the proposed system depends solely on the use of BIM and the associated levels of details and (2) the proposed IPASS uses the same BIM models used for submission to the authorities but still may require some manual efforts so that IPASS could be used to its maximum capability (Teo et al., 2017).

Workers Safety Training Phase

Safety technologies that alert workers of safety hazards in day-to-day activities provide an additional layer of protection, but they do not overcome the importance of workers' manual identification of risks and hazards. In this context, Hasanzadeh et al. (2017) studied the eye-tracking technique to measure worker attention to analyze the impacts of safety knowledge (training, work experience, and injury exposure) on workers' attentional allocation. The study performed laboratory experiments on 27 construction workers to record their eye movements while they tried to identify safety hazards presented in 35 construction site images, where each showed multiple hazards. The results showed that tacit safety knowledge acquired from work experience and injury exposure could significantly improve construction workers' hazard detection and their visual search strategies. In other words, practical safety knowledge and judgment on a job site require both interaction and explicit knowledge gained through work experience, injury exposure, and interactive safety training. The study shows that eye tracking can be utilized to improve workers' safety training programs, which will yield a safer working environment.

Safety Management Phase

Site and project management have benefited from new technologies. New project management software has eased expedited activity tracking and execution in construction sites by using smart devices such as tablets and smartphones to interact with site activities. Similarly, Zhang et al. (2017) provided a conceptual application used on smart devices (mobile inspection tools) to improve safety inspection performance and enhance the integration of safety management systems. The study developed and provided a mobile application named *iObserver*. The application is mainly used by safety inspectors who can report safety-related inspection activities easily using the application at the construction site. The developed application has a lot of features similar to existing project management software, such as generating various types of reports, retrieving documents, and manager's accessibility. The application was developed and evaluated by industry practitioners, and it not only resulted in eliminating the redundancy in paper-based systems but also enhanced the coordination and integration of information between safety inspection procedures and other safety management strategies.

The main limitation of the proposed mobile application is related to the functionality and availability of the database for each project. The developed application was a prototype that included only one construction task; hence in order to cope with real-world use, hundreds of tasks need to be added and updated regularly, which will require scientific and automated data-mining approaches, in addition to the need for safety information database to capture results from the analysis of collected inspection data.

Construction Phase

The majority of selected articles are related to new technological innovations in construction safety that deal with ongoing construction activities at the project site. Of the selected twelve articles, six articles discussed technology related to the construction phase. After analyzing the characteristics of the proposed technologies and their use in the field, this research found four main areas of site construction presented in Fig 2 that researchers are trying to improve through the use of new technologies.

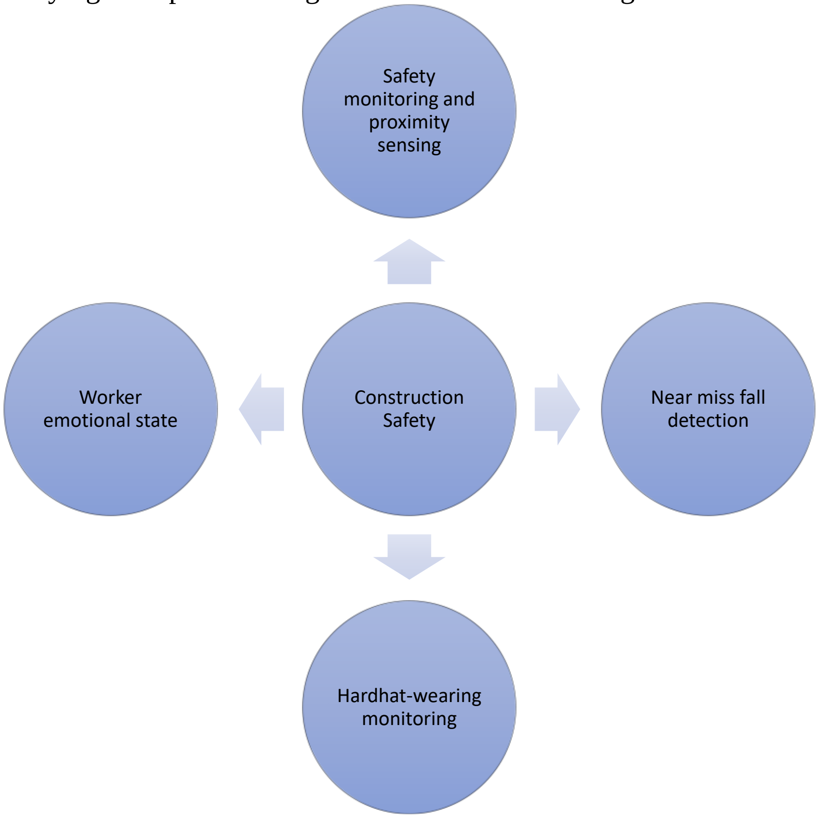

Fig. 2. Technology improvement areas in site safety construction

The four main improvement areas in the literature about on-site safety construction are (1) safety monitoring and proximity sensing, (2) near-miss falls detection, (3) hardhat-wearing monitoring, and (4) workers' emotions. Table 2 lists each improvement area with its related articles from the selected literature for this paper.

Safety Monitoring and Proximity Sensing

Safety technologies can provide workers with a second chance at a safe environment by creating an additional layer of protection for ground workers on construction sites (Teizer et al., 2010). A study by Park et al. (2017) created and evaluated a new low-cost automated safety monitoring system to assist in the construction-safety monitoring process. The system relies on Bluetooth low-energy (BLE) beacons, which are cheap, reliable, and available. Also, it relies on a cloud communication platform, and the main component is BIM -building information model BIM-based hazard identification. The study utilizes automatic identification of hazard areas using BIM-based automatic identification. This means that BIM needs to be fully updated and needs to be in line with construction activities. In addition, some hazards can't be identified using BIM, which means safety inspectors should provide their inputs to cover what the automated BIM identification had missed. The location of workers at the site is located by BLE beacons all around the site and smartphones that connect to those BLE signals. When a worker enters a pre-defined unsafe zone (either by automatic BIM or manual input), the work will get a real-time alert as well as alerts for related safety personnel throughout the cloud. This way of using BIM is superior in identifying hazards due to its indoor capabilities compared to other systems such as ultra-wideband (UWB), global positioning system (GPS), other forms of radio frequency identification (RFID), laser scanning, video camera, magnetic proximity sensing, etc. The limitation of such a system is related to the main component of the proposed system, which is BIM; the need for fully updated BIM with existing site sequences, the reliance on manual efforts to identify potential safety hazards (manual inputs in order to have a full safety layout available on BIM As-built need to be in place) any human error of shortage to result in catastrophic incidents. Another limitation is related to the need for heavy and expensive infrastructure, such as the availability of BIM in the first place, while BIM has still not been fully adopted by the AEC industry.

Table 2. Safety areas and related articles

#	Safety Area	Authors
1	Safety monitoring and proximity sensing	Park et al., 2016 Park et al., 2017 Zhang et al., 2022
2	Near-miss falls detection	Lim et al., 2016 Zhang et al., 2019b
3	Hardhat-wearing monitoring	Park et al., 2015 Xiong and Tang, 2021 Zhang et al., 2019b
4	Workers emotions	Bhandari et al., 2020 Hwang et al., 2018

The second study by Park et al. (2016) developed a new way of proximity sensing using Bluetooth technology regarding the interactions between pedestrian workers and construction equipment that occur in roadway work zones. The proposed system has several advantages compared to other proximity sensing systems, including advantages in lower required infrastructure, lower overall system cost compared to other commercially available systems, good signal continuity, and coverage. For example, a shortage in signals for systems using radiofrequency technology could be impacted by direct contact with metallic objects, while some evaluated systems were incapable of identifying people versus other objects, which included radar and ultrasonic proximity sensing systems (Ko, 2017). Also, proximity sensing strategies using video are incapable of visualizing hazards in low-visibility conditions, such as at night or in dusty environments (Ruff, 2007), and other systems, such as UWB, require sizable infrastructure and are not mobile. The research completed several experiments that were designed to assess the reliability and effectiveness of the Bluetooth proximity detection and alert system and to compare the developed Bluetooth technology with two other commercially available RFID and magnetic field proximity sensing systems, performance evaluation between three systems was based on field experiments (in an open area and normal weather conditions), the evaluation process between the three systems were based on statistical results. Experimental results demonstrate that the created Bluetooth proximity detection and alert system (1) requires minimal infrastructure, (2) provides adequate alerts to equipment operators and pedestrian workers, and (3) provides, through an alert, an additional layer of hazard compared to the other two.

Near-Miss Falls Detection

Zhang et al. (2019) explored the potential use and feasibility of integrating smartphones and artificial neural networks (ANN) to measure near-miss falls, which will help detect near-miss falls and enhance safety monitoring in construction. The paper explored the potential use of a smartphone as a data acquisition tool to detect and identify workers' near-miss falls. The detection of near-miss falls was performed by measuring the variation in the energy released by a worker due to the adjustment of postures during balance loss and the recovery process, which can be measured by triaxial accelerometers embedded in smartphones. The collected data from smartphone sensors are processed through a machine-learning algorithm using an ANN, which can process data with a parallel operation for fast calculation after performing controlled tests the proposed approach demonstrated the feasibility of integrating smartphones and ANN to measure near-miss falls. The proposed system will help detect near-miss fall events and identify hazardous elements and vulnerable workers. In addition, it provides a new perspective for measuring the relationship between near-miss falls and fall accidents quantitatively.

Lim et al. (2016) is similar to Zhang et al. (2019) in that it provided a method for computing information on near-miss events experienced by workers using a triaxial accelerometer embedded in smartphones. The method implements a systematic data processing procedure to measure, collect, and classify data on a worker's motion using a smart ANN-based slip-trip classification method. The success of such a system may encourage more intensive and regular workplace inspections to check workplace factors having the potential to cause injury to employees, i.e., materials, activities, and the environment, to identify safety hazards and recommend corrective action. It encourages preventive and collective actions to reduce construction accidents by identifying the type of near-miss, i.e., slip or trip, and the exact time that it occurs. Future enhancements would be beneficial to integrate a temperature sensor, pressure sensor, light sensor, and camera into the application to extend the proposed system into another version of the construction incident investigation system. The application may be worn by a worker to protect against hazards as part of their personal protective equipment (PPE).

Hardhat-Wearing Monitoring

Park et al. (2015) evaluated if construction workers wearing PPE could be detected with live streaming or time-lapse videos in order to facilitate the work of on-site safety inspectors. Using a novel vision-based method is proposed to automate the monitoring of whether people are wearing hard hats on construction sites. Under the method, human bodies and hardhats are first detected in the video frames captured by on-site construction cameras. Then, the matching between the detected human bodies and hardhats is performed using their geometric and spatial relationship. This way, people who are not wearing hardhats could be automatically identified, and safety alerts could be issued correspondingly. The method has been tested with real site videos, and its high safety alert precision and recall demonstrate its potential to facilitate site safety monitoring work. One of the limitations was that only standing workers could be detected with the current detection template, and workers with other postures (crouching down, bending, and sitting) could not be successfully detected in the videos.

Zhang et al. (2019) studied the implementation of real-time alarming, monitoring, and locating for "Non-Hardhat Use" (NHU) in construction based on sensor, mobile, web, and cloud techniques. A smart hardhat system is developed using an Internet of Things (IoT)-based architecture, including a hard hat with an infrared beam detector and a thermal infrared sensor for nonintrusive NHU detection, RFID triggers for locating NHU with an average detection error of less than 10 cm, a smartphone application for personalized warnings, a web application for data visualization and alarms for managers, and a cloud server for data storage and retrieval. The proposed system enables both workers and managers to take timely actions against NHU. The system performance was evaluated in a laboratory test and validated in a field application by 19 workers. Test results indicated that the proposed system was accurate and reliable, showing the potential to promote safety inspection and supervision in construction in which automatic NHU monitoring plays an essential role. Existing computer vision-based NHU inspection methods, such as those proposed by Park et al. (2015), lack the capability to identify workers and help take real-time action. The previous sensor-based NHU inspection methods required direct skin contact, which would be uncomfortable for workers. In addition, previous sensor-based methods could be deceived by objects other than human heads and could not achieve real-time alarms. Some of the limitations had been noticed during the field test, such as RFID trigger errors and time delays between sensor activation and web or smartphone app alerts, and the possibility of internet unavailability for specific areas in the construction sites.

Workers Emotions

Construction workers' emotional states (pleasure, displeasure, excitement, and relaxation) are known as a critical factor that affects their performance (safety, health, and productivity). To prevent adverse impacts on work performance, measuring emotional states should take precedence to better understand how workers' emotions vary while they are working. Hwang et al. (2018) investigated the feasibility of measuring workers' emotions in the field based on two dimensions of emotions (valence and arousal levels) using a wearable electroencephalogram (EEG) sensor. Previous studies on EEG-based emotion measurement have mostly been conducted in a controlled laboratory; this study performed a real field test that included the participation of ten workers. The results demonstrate the applicability of a wearable EEG sensor for measuring workers' emotions, particularly valence levels, which remain crucial to understanding workers' emotional states. For example, the results showed that unsafe work conditions (on a ladder and in a confined space) and physically demanding working time (working two hours without resting) are likely to make workers fearful, frustrated, and/or depressed with negative valences. The outcome of this study is to enable in-depth studies on how emotions affect work performance, such as safety, health, quality, and productivity. Such efforts will help to better understand which emotional states of workers are the most effective and need to be induced to achieve desired work performances. In summary, the study opens the door for the applicability of analyzing the connected physical and psychological aspects of construction workers to achieve project objectives such as improved safety and productivity.

5. Discussion

The collected articles from the field of construction safety technologies provided a good set of technology innovations and approaches that would improve construction safety. After analyzing the collected articles listed in Table 1, this research found that the proposed safety technology innovations were implemented to improve construction safety in one of the four phases of construction safety (*pre-construction phase, workers' safety training phase, safety management, and at the construction phase*). Also, it was noticed that the majority/trend of the proposed technological innovations in construction safety is related to ongoing construction activities at the project site "*at the construction*" phase and are focusing on four main areas of site construction safety to be improved throughout the use of new technologies (*safety monitoring and proximity sensing, near-miss falls detection, hard hat-wearing monitoring, and workers emotions*).
As one of the objectives of this review paper is to identify the common limitations of the proposed safety technologies, with reference to safety phases, the main limitations of the first three phases (*pre-construction phase, workers' safety training phase, safety management)* lie heavily on the diffusion of other technologies such as the diffusion of BIM, and regulations that may be tied to architectures and engineers, such regulations and laws that force the implementation of safety technologies in order to design a safer construction environment. Limitations of proposed technologies in the fourth phase (*at the construction phase*) are the feasibility of the proposed technology (hardware cost, implementation cost, maintenance

cost, annual costs, etc.), performance and accuracy of the proposed technology, and special projects where some techniques are not available such as internet connections, wi-fi, or even smartphones and cameras.

6. Conclusions

The objectives of this study are to (1) identify the gaps in the literature on construction safety technologies, (2) to identify common limitations and trends in the proposed technologies, and (3) provide future suggestions to cover limitations and gaps. To achieve the study objectives, 15 articles were collected within the context of construction safety technologies.

The main gap related to the literature on construction safety technologies is the limited amount of research that studies the acceptance and barriers to the adoption of safety technologies. Also, rare studies have proposed the integration of two or more safety systems in order to effectively manage the strengths and weaknesses of new or commercially available systems, hence achieving complimentary benefits. Also, there are no studies focused on the organizational change management aspect of adopting safety technologies in the construction industry.

Common limitations of the proposed safety technologies lie in the practicality of the technology, such as the application of that technology. For example, some sensing technologies are designed for open sites while others are for indoor use and ease of use. Some technologies need minimal calibration and require an initial setup, while other technologies need to be moved and relocated as part of the construction or the requirements of manual inputs. Also, some technologies cannot be used in projects where technologies are limited. For example, projects where there is no internet connection or restricted use of technologies such as smartphones, cameras, or GPS.

Limited research has studied the impact of wearable systems on social issues, including privacy, security, and legal issues. For example, wearable devices are vulnerable to security threats, which requires strong security measures to protect data processing and transmission (Awolusi et al., 2018). Also, little is known about user acceptance of safety technologies such as wearable technologies, even with the positive potential and functionality of those technologies (Choi et al., 2017).No research to the authors’ knowledge has studied the implications of the long use of safety technologies, specifically for on-site wearable systems that provide safety warnings. For example, when workers rely heavily on sensing and automated alert systems for an extended period of time, it might lower their attention and judgments regarding unsafe activities or conditions, which means that any delays or issues in automated deduction of unsafe conditions would have higher levels of risk.

This review paper provides a good example of new innovations in construction safety technology. The paper contributed to the literature by dividing construction safety into four phases. Also, this paper highlighted gaps and limitations for the proposed technologies to influence future researchers to cover knowledge gaps. Though the list of articles provides a wide range of construction safety technology innovations, this review paper is limited to the 12 collected articles.

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