How Technolog
OSH MANAGEMENT

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THE CONSTRUCTION INDUSTRY plays a significant role in the prosperity of the economy, reportedly contributing approximately $10 trillion to the global domestic product (GDP; Barbosa et al., 2017). In the U.S., the construction industry's contribution reached more than $892 billion in 2020, which represented about 5% of the total U.S. GDP that year (BEA, 2020). Such a contribution is anticipated to further grow over the next few years, making the construction industry an essential contributor to the economy (Nnaji & Karakhan, 2020). This level of influence is not possible without having a healthy, productive construction workforce. The U.S. construction industry employs more than 72 million individuals with a steadily increased employment rate that is expected to continue growing over the next 10 years (BLS, 2020a). Early in 2020, it was reported that the construction industry in that year would have a monthly average of more than 350,000 job openings and 400,000 hires on a continuous basis, despite the COVID-19 global health crisis (BLS, 2020a).

The challenge is to keep the construction workforce healthy and productive, and to ensure that construction workplaces are as free of hazards as possible. The construction industry is one of the most hazardous industries and has consistently reported high fatal and nonfatal injury rates over the past 10 years. According to the Bureau of Labor Statistics (BLS, 2020b), in the U.S., 1,061 workers died in the construction industry in 2019. These fatalities represent approximately 20% of the overall workplace fatalities in the U.S. that year. This means one in five worker deaths in 2019 was associated with construction operations (BLS, 2020b). One-fifth of U.S. workplace fatalities being associated with construction is an unacceptably high proportion, especially given that construction accounts for only about 5% of the overall U.S. workforce (Abdelhamid & Everett, 2000). According to the International Labor Organization, construction workers are three to four times more likely to encounter a fatal incident at work during their career than in other industries (Gürcanli & Müngen, 2013; ILO, 2020; Jin et al., 2020).

Other industries such as manufacturing typically have safer workplaces than in the construction industry (Karakhan et al., 2019). These safer workplaces positively reflect on the number of workplace incidents, exposing workers to a lower possibility of being severely injured. In 2018, the manufacturing industry reported 343 fatalities versus 1,061 fatalities in the construction industry (BLS, 2020b). One notable difference between these industries is that the manufacturing industry relies heavily on technology in many aspects of its operations, including OSH management (Karakhan et al., 2019).

Several researchers believe that improving technology adoption and application in the construction industry, especially for OSH management, would improve workplace conditions, and lead to improved performance outcomes and reduced numbers of fatal and nonfatal injuries throughout the industry (Al-Saffar, 2020; Skibniewski & Chao, 1992; Zhou et al., 2013). For example, virtual reality (VR) can be integrated into OSH management plans to improve safety training programs and help construction personnel identify and mitigate workplace hazards early in the project life cycle, such as during the design and planning stages (Gheisari & Esmaeili, 2019; Waly & Thabet, 2003). In that regard, Li et al. (2012) developed a multiuser VR tool to train construction workers. The training focuses on safety procedures for tower crane erection and dismantling, which accounts for 10% of all crane fatalities (Li et al., 2012). The tool includes a step-by-step procedure to perform tower crane erection and dismantling safely. The fact that this training is conducted in a VR setting ensures that trainees are exposed to minimal risks, if any, and kept safe throughout the training process (Li et al., 2012).

The goal of the present study is to examine the application of technology for OSH management in construction and identify practical information that could be utilized by construction industry OSH professionals to facilitate and improve technology adoption for OSH management. Such utilization is expected to improve workplace conditions and mitigate worker exposure to hazards on construction jobsites. Keeping this goal in mind, the specific objectives of this article are to: 1. summarize emerging technologies used in practice for OSH management in construction; and 2. describe potential benefits of such technologies in terms of mitigating workplace safety hazards in construction and impact on key performance indicators. Along with these objectives, the authors provide best practices to mitigate workplace safety hazards and improve OSH management in construction in the subsequent section to ensure that the study is practical and of interest to a wide range of safety professionals working in the construction industry.

Literature Review: Technology Applications for OSH Management in Construction

This section describes the result of a review of existing literature on the intersection between safety and technology in the

KEY TAKEAWAYS

● This article explores ways to utilize emerging technology for OSH management in the construction industry.
● It presents a study that identifies emerging technologies used in practice for OSH management in construction and summarizes their potential benefits in terms of mitigating workplace safety hazards in construction and impact on key performance indicators.
● The authors highlight best practice applications of these technologies for OSH management in construction.

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IN CONSTRUCTION

construction industry. In particular, the applications of technology for OSH management in construction are described in the form of industry best practices.

One emerging technology in the construction industry is building information modeling (BIM). Shen and Marks (2015) indicate that BIM can be used to enable field personnel on site to report near-hits, thus enabling managers and supervisors to detect and mitigate potential workplace hazards. Similarly, simulation and visualization can be integrated into a BIM model to facilitate the integration of worker safety and health into the design process, planning and scheduling of a project (Rodrigues et al., 2017). The critical step of creating an effective BIM model is to integrate designers into the project team throughout the project life cycle. Without such an integration, the process may not yield the desired outcomes.

Immersive reality is another emerging technology that has received increased attention in the construction industry. This technology can be linked to a BIM model or used independently. When linked to a BIM model, immersive reality can be used to compare what is being built and what is supposed to be built. Immersive reality can be utilized to support four-dimensional models used in BIM to improve constructability reviews performed during the design stage (Hartmann & Fischer, 2007). When used independently, immersive reality is employed in safety training to provide a real-life, computer-generated, four-dimensional experience, as opposed to traditional trainings that are based on two-dimensional visual aids (Sacks et al., 2013). Providing a real-life, four-dimensional environment when delivering safety training is expected to be associated with improved perception of jobsite hazards (Sacks et al., 2013). Note that the cost of this technology is relatively high. Specifically, the cost of a VR and AR head-mounted unit ranges from $500 to $5,000 (Okpala et al., 2019). The additional cost of supporting hardware (e.g., computer, motion tracker, dedicated space) and game engine software (e.g., Utility 3D) is also encountered (Okpala et al., 2019). The cost of implementation should be considered before deciding whether to adopt a technology.

Wearable sensing devices (WSDs; Figure 1), another emerging technology, can be in the form of oxygen and temperature sensors to facilitate intelligent monitoring of confined spaces on site and send warning signals to safety supervisors in an emergency (Borhani, 2016; Nnaji et al., 2020). WSDs also can be used to perform biometric screening of workers' physical characteristics (e.g., body temperature, repetitive motion) and send real-time data to safety supervisors on site for monitoring (Karakhan & Alsaffar, 2019). Privacy and data security may be

FIGURE 1
## WEARABLE SENSING DEVICES

Wearable sensing devices (WSDs) can be used to monitor various aspects of a worker's safety and health.
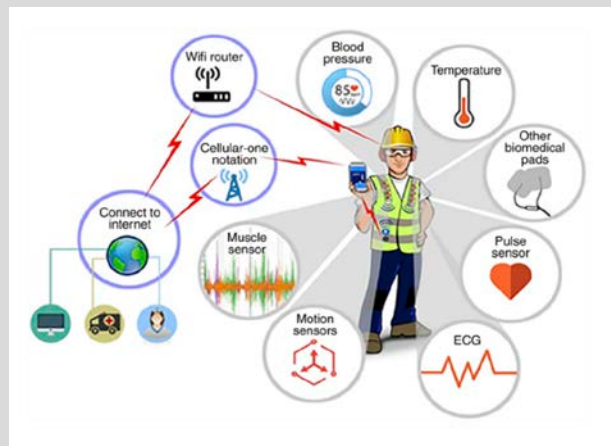
Note. Reprinted from "Digital Skin of the Construction Site: Smart Sensor Technologies Towards the Future of Smart Construction Site," by R. Edirisinghe. Copyright 2021 Emerald Publishing Ltd. Reprinted with permission.

FIGURE 2
UNMANNED AERIAL VEHICLE SCAN

Jobsite screening and scanning using UAVs.
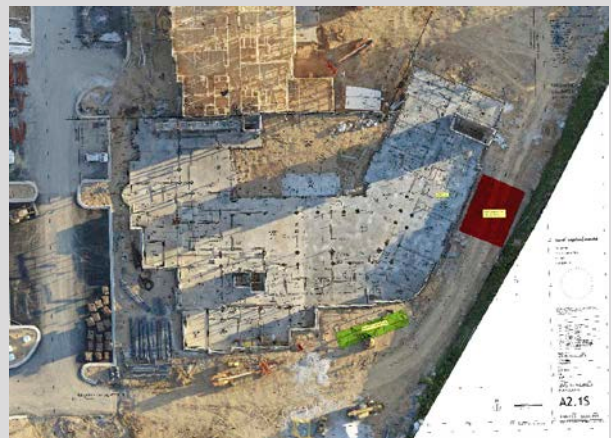
Note. Reprinted from "An Overview of Emerging Construction Technologies," by A. McCoy & A. Yeganeh. Copyright 2021 Harkin Builders, Virginia Tech & Carlos Zuluaga. Reprinted with permission.

a concern when this technology is utilized for OSH management (Okpala et al., 2019).

Similarly, unmanned aerial vehicles (UAVs; Figure 2, p. 19) are an emerging technology frequently used to conduct quality and safety inspections for steel structures at high elevations (Xu & Turkan, 2019), perform reality capture, and take accurate measurements in high-risk or hard-to-reach areas, such as the bottom of a bridge (Şerban et al., 2016). UAVs are appealing to construction stakeholders for many reasons including ease of operation, high-speed data collection and low cost (Okpala et al., 2019).

Recently, researchers and practitioners have been exploring the potential impact of exoskeletons on worker safety. Also called wearable robots, exoskeletons are mechanical systems that provide support and protection for workers by reducing worker fatigue and the physical demand of construction activities (Photos 1 and 2). Exoskeletons can be passive or active systems, and are used to augment the upper or lower body (Zhu et al., 2021).

Other technologies that have existed for some time in the construction industry have only recently been used for the purpose of mitigating workplace hazards and managing OSH. Radio-frequency identification (RFID) tags can be attached to safety gear to support and check on-site compliance with safety procedures (Kelm et al., 2013). RFID tags can be embedded in PPE such as hard hats to identify real-time locations and warn workers when they are near hazards (Borhani, 2016). Single-task robots are sometimes applied to perform welding tasks in high-risk situations (Hashmi, 2016). Using articulated robots that involve little or no human interaction can protect workers and keep them away from workplace incidents.

Photos 1 (left) and 2: An upper-body exoskeleton in use.

Analogously, Skibniewski (2015) reported using a robotic pipe manipulator for concrete pipe laying in trenches.

Table 1 summarizes best practice applications of technology for OSH management in the construction industry, describing the use of 14 categories of these technologies (the "Survey Development" section of this article describes how the categories were identified). The identified best practices can be used by industry professionals and practitioners to mitigate workplace hazards on construction jobsites and protect workers from injury. Such use is expected to improve workplace conditions and reduce jobsite injuries and fatalities throughout the construction industry in hopes that the industry can reach safety levels comparable to the manufacturing industry and other industries known for their excellent safety records.

Research Methodology

To achieve the goal and objectives of the study, a questionnaire survey of industry personnel was carried out. The questionnaire was developed by the authors and approved by institutional review boards at their respective institutions. The survey targeted industry professionals and practitioners focusing on both field and management personnel.

Survey Development

The survey was a questionnaire consisting of three main components. The first focused on collecting demographic information about the survey participants regarding their qualifications and experience. Demographics collected included years of experience in the industry, company size, location of the participants at the time of the study and position of the participants within their organizations.

The second component included questions to determine what type of technologies participants' organizations have been using for OSH management. Participants could select from a predetermined list of potential construction technologies and indicate whether their organizations utilize any of the identified technologies for OSH management. The determination and selection of technologies were conducted through a thorough literature review. Based on the review, 14 categories of technology were identified as being used for OSH management in construction (Awolusi et al., 2018; Guo et al., 2017; Haupt et al., 2020; Karakhan & Alsaffar, 2019; Mihić et al., 2019; NSC, 2020; Nnaji & Karakhan, 2020; Okpala et al., 2019; 2020; SmartMarket Insight, 2019). The identified categories of technology are:
- artificial intelligence (AI),
- BIM,
- smart camera systems,
- digital safety signage,
- exoskeletons,
- immersive reality,
- laser scanning and laser imaging, detection and ranging (LiDAR),
- mobile devices on site,
- photogrammetry,
- quick response (QR) codes,
- RFID,
- single-task robots,
- UAVs, and
- WSDs.

Table 2 (p. 22) summarizes the identified technologies along with their definitions. More details on the review process and its findings can be found in Nnaji and Karakhan (2020).

TABLE 1

APPLICATION OF TECHNOLOGY FOR OSH MANAGEMENT

Category	Application
Building information modelling (BIM)	• Enable field personnel on site to report near-hits, thus enabling managers and supervisors to detect and mitigate potential workplace hazards (Shen & Marks, 2015). • Employ BIM-based tools (e.g., simulation, visualization) to facilitate worker safety integration into the design process, planning and scheduling (Rodrigues et al., 2017).
Wearable sensing devices (WSDs)	• Utilize oxygen and temperature sensors to facilitate intelligent monitoring of confined spaces on site and send warning signals in an emergency (Borhani, 2016). • Perform biometric screening on workers' physical characteristics (e.g., body temperature, repetitive motion) and send real-time data to safety supervisors on site for monitoring (Karakhan & Alsaffar, 2019).
Mobile devices on site	• Provide real-time access to information on required safety precautions and operational procedures for performing specific activities (Nnaji & Karakhan, 2020). • Enable rapid incident and near-miss reporting and support effective safety inspection using preloaded apps (SmartMarket Insight, 2019).
Radio frequency identification (RFID)	• RFID tags embedded in PPE such as a hard hat identify real-time locations and warn workers when they are near hazards (Borhani, 2016). • RFID tags attached to safety gear support and check on-site compliance with safety procedures (Kelm et al., 2013).
Laser scanning and laser imaging, detection and ranging (LiDAR)	• Identify blind spots of a heavy construction equipment on the jobsite using pictorial representations enabled by a 3D laser scanner (Teizer et al., 2010). • Take accurate measurements of heavy construction equipment and the surrounding environment prior to start of work operations to ensure that equipment has room to safely maneuver during work operations (Karakhan & Alsaffar, 2019).
Quick response (QR) codes	• Provide information on required safety precautions and operational procedures for a particular equipment or task (Chu et al., 2012). • Provide a contactless approach for workers and visitors to report health conditions and concerns when checking in at the jobsite, especially during the spread of COVID-19.
Smart camera systems	• Provide detailed information on workers' location and other relevant factors to plan for and avoid the occurrence of work injuries and fatalities, especially those caused by operators' limited vision and awareness of surrounding hazards (Teizer & Vela, 2009). • Provide large coverage of a construction site for monitoring safety performance and controlling site hazards (Zhang et al., 2019).
Digital safety signage	• Provide warnings to alert workers of potential workplace hazards (Karakhan et al., 2019). • Remind workers of necessary safety protection and precautions required to perform a task safely (e.g., COVID-19 guidelines; Karakhan et al., 2019).
Exoskeletons	• Support working postures for bending, static holding of a load or dynamic lifting (and lowering) to protect workers and enhance their health (de Looze et al., 2016). • Constrain worker's body postures within a safe range to prevent the development of work-related musculoskeletal disorders (Cho et al., 2018).
Photogrammetry	• Enable constructing accurate virtual environment to simulate construction operations and ensure safe work operation (Mohammadi et al., 2020). • Enable generating digital elevation models to assess and monitor environmental and other external risks on a construction site (e.g., landslide, avalanches; Calantropio et al., 2018).
Artificial intelligence (AI)	• Provide automatic approaches to predict, assess and mitigate construction hazards such as fall hazards (Adamtey et al., 2018). • Develop an AI-based framework assisted by smart construction objects to monitor, visualize, alert and react to dangerous on-site hazards (Adamtey et al., 2018; Chakkravarthy, 2019; Niu et al., 2019).
Unmanned aerial vehicles (UAVs)	• Conduct quality and safety inspections for steel structures in high elevations (Xu & Turkan, 2019). • Perform reality capture and take accurate measurements in high-risk or hard-to-reach areas such as the bottom of a bridge (Şerban et al., 2016).
Immersive reality	• Use VR in safety training programs rather than photos and other 2D/3D visual aids to improve worker perception of jobsite hazards (Sacks et al., 2013). • Utilize VR supported by 3D/4D models to improve safety constructability reviews conducted during design (Hartmann & Fischer, 2007).
Single-task robots	• Perform welding tasks in high-risk situations using articulated robots (Hashmi, 2016). • Use a pipe manipulator for concrete pipe laying in trenches (Skibniewski, 2015).

TABLE 2

DESCRIPTION OF IDENTIFIED TECHNOLOGIES

Technology	Definition
Artificial intelligence (AI)	The development and use of intelligent machines to perform tasks that require human intelligence.
Building information modelling (BIM)	A virtual process that involves all design and construction elements into a virtual model that all project stakeholders can access and work on.
Smart camera systems	A camera network system with optimal camera placement to achieve maximum coverage of a specific monitoring area of the jobsite.
Digital safety signage	Delivering different forms of safety messages and warnings in a digital format including alerts, signs and lights.
Exoskeletons	A rigid external covering for the body to provide support and protection for workers' tendons and neuromuscular system.
Immersive reality	A virtual environment that provides users an inclusive experience such as images, sound and other stimuli.
Laser scanning and laser imaging, detection and ranging (LiDAR)	An approach that uses laser beams to capture the dimensions of physical objects and information of surfaces in the form of point-cloud data that could be used to generate 3D models.
Mobile devices on site	Mobile safety devices used on site for hazard identification and mitigation.
Photogrammetry	An engineering discipline to obtain information about the properties of surfaces and objects, and to study and analyze such information.
Quick response (QR) codes	Machine-readable two-dimensional barcodes that link to specific websites or applications.
Radio frequency identification (RFID)	The use of electromagnetic fields to identify and track tags attached to objects.
Single-task robots	The design and use of robotics to perform tasks that are normally performed by humans.
Unmanned aerial vehicles (UAVs)	An aircraft that is operated by a ground-based controller, nonhuman pilot or passengers on board.
Wearable sensing devices (WSDs)	A set of electronic devices that can be attached to humans as accessories, embedded in clothing, or through mounting or implanted to human bodies.

TABLE 3

PARTICIPANT DEMOGRAPHICS

Category	Demography	Count	Percent
Organization type	General contractor	92	90.2%
	Subcontractor	4	3.92%
	Designer	5	4.9%
	Consultant	1	0.98%
Job title	Construction manager	62	60.78%
	Project manager	40	39.22%
Professional experience	5 to 10 years	60	58.82%
	11 to 20 years	32	31.38%
	More than 20 years	10	9.8%
Education	High school diploma or equivalent	7	6.86%
	Associate degree or equivalent	26	25.49%
	Bachelor's degree or equivalent	50	49.02%
	Master's degree or equivalent	12	11.76%
	Professional degree or equivalent	4	3.92%
	Doctoral degree or equivalent	3	2.95%

Note. *n* = 102

The third component of the survey focused on identifying the benefits of technologies for OSH management in the construction industry and the impact of these technologies on key performance metrics and indicators. More information about the questionnaire is provided in subsequent sections. Note that, prior to distribution, the questionnaire was pilot tested with four knowledgeable professionals working in the construction industry. The selected professionals have, on average, 12 years of professional experience in the construction industry. This pilot testing ensures that the survey questions are practical and consistent with terminology used in the industry, minimizing potential bias with the survey and verifying that the content and face validity of the survey is achieved. Based on the feedback received, the survey questions were revised and modified prior to distributing them to study participants.

Survey Dissemination

An essential aspect of any questionnaire survey is to select a reliably adequate sample size. This selection includes two important aspects: the sampling method and the sample size. From a statistical standpoint, there are two sampling methods: probability and nonprobability (Leedy & Ormrod, 2016). Probability sampling is generally more adequate, but it involves the selection of a random sample, which is challenging and may not be possible in construction research (Abowitz & Toole, 2010). On the other hand, nonprobability sampling (i.e., purposeful selection of a sample by the researchers) introduces selection bias that may affect the entire research and its findings (Acharya et al., 2013). To avoid such a dilemma, the research team relied on a third-party platform, Qualtrics Panel, to select the survey participants and administer the survey process. Qualtrics Panel is a professional organization that supports researchers in disseminating surveys to a specific target audience and collecting responses within a certain time limit. Previous studies in construction have successfully utilized such third-party platforms to conduct meaningful research (Azeez et al., 2019; Nnaji & Karakhan, 2020).

With respect to the sample size, a sample of 100 data points is often considered adequate from a statistical perspective to provide a high confidence in the survey results and ensure that the sample is representative of the larger population (Lohr, 2008). Accordingly, the research team targeted a sample size involving at least 100 participants. Qualtrics Panel identified a participation pool that included construction managers, project managers and safety personnel who work for general contractors and subcontractors in different states throughout the U.S. Participation was optional and limited to those working in the construction industry. Qualtrics Panel distributed more than 4,000 questionnaires to potential participants across the U.S. construction industry. In the end, 157 participants responded to the questionnaire and provided the requested information as described in subsequent sections.

To ensure that only high-quality responses are included in the study, the research team performed the following two steps. First, all responses from participants with fewer than 5 years of construction-related experience were removed. Second, quality checks were performed on the responses in an effort to eliminate low-quality responses. For example, responses showing signs of straight-lining answers, ambiguous

text, patterns of unanswered questions and abnormally fast response times were removed from the study. Following this process, 102 responses were found to be of high quality and were included in the research.

Participant Demographics

After removing the unacceptable responses and analyzing the collected data, most participants (89.32%) represented general contracting organizations. Approximately 10% of participants represented subcontracting, consulting, engineering and architecture firms combined. Of participants, 62 (60.78%) were construction managers and 40 (39.22%) were project managers. Regarding experience, 60 participants (58.82%) had 5 to 10 years of professional experience, 32 (31.38%) had 11 to 20 years of professional experience, and 10 (9.80%) had more than 20 years of professional experience in the construction industry. Table 3 summarizes the demographic information of the survey participants. Most participants (62%) were in California (23 participants), Florida (21 participants) and New York (21 participants); however, all regions throughout the U.S. (Midwest, Northeast, South and West) were represented in the survey.

Results

After identifying the 14 categories of technology used for OSH management in construction (Table 2), survey participants were asked to indicate whether their organizations use the identified technologies for OSH management. Table 4 summarizes the responses received from participants. The responses indicate that BIM and WSDs are broadly used for OSH management in construction by approximately 86% of the surveyed organizations. Mobile devices on site were reported to be by 84% of the surveyed organizations, which is consistent with results from previous studies (SmartMarket Insight, 2019). Among the 14 technology categories, single-task robots were the least used in practice for OSH management. In particular, 42% of the surveyed organizations indicated that they do not use single-task robots for OSH management. Note that even organizations reported as nonusers of the technologies indicated willingness to utilize these technologies for OSH management in the future. Approximately 20% of surveyed organizations reported as nonusers of technology indicated that they have plans to utilize exoskeletons and UAVs for OSH management in the near future. These plans provide a positive indication of the use of emerging technologies for OSH management in the construction industry.

Regarding the benefits of emerging technologies, a list of potential safety benefits of the identified technologies was compiled from existing literature on the topic (Hallowell et al., 2016; Karakhan & Alsaffar, 2019; Karakhan et al., 2019; Navigant, 2016; Shen & Marks, 2015; SmartMarket Insight, 2019; Wang et al., 2018; Zhang et al., 2019). The list was then given to the study participants to capture their perception of the benefits of these technologies. This exercise identified 12 main benefits of utilizing emerging technologies for OSH management (Table 5). Four benefits were highlighted by more than 50% of study participants. "Improve worker awareness of hazard" received the highest frequency, with 83 participants (81%) selecting this as an apparent benefit of most emerging safety and health technologies. The next most important benefits of safety and health technology identified

are "warn workers of workplace hazards"; "eliminate hazard during design"; and "help visualize workplace hazards." All three of these were selected by 55 participants (54%) as apparent benefits of using safety and health technologies.

As shown in Table 5, these benefits have different purposes; some technologies are used to warn workers about hazards, while others are used to mitigate workplace hazards. The survey results show that BIM and immersive reality are frequently used during planning and design stages to plan for safety and eliminate worker hazards before construction starts. For example, a BIM platform can be developed and used to perform automated safety-rule checking, identify potential workplace hazards and suggest design modifications before actual construction operations start (Jin et al., 2019;

TABLE 4
TECHNOLOGIES USED FOR OSH MANAGEMENT

Technology category	No. (%) using	No. (%) not using
Building information modelling (BIM)	88 (86%)	14 (14%)
Wearable sensing devices (WSDs)	88 (86%)	14 (14%)
Mobile devices on site	86 (84%)	16 (14%)
Radio frequency identification (RFID)	81 (79%)	21 (21%)
Laser scanning and laser imaging, detection and ranging (LiDAR)	76 (75%)	26 (25%)
Quick response (QR) codes	76 (75%)	26 (25%)
Smart camera systems	76 (75%)	26 (25%)
Digital safety signage	75 (74%)	27 (26%)
Exoskeletons	74 (73%)	28 (27%)
Photogrammetry	71 (70%)	31 (30%)
Artificial intelligence (AI)	68 (67%)	34 (33%)
Unmanned aerial vehicles (UAVs)	67 (66%)	35 (34%)
Immersive reality	66 (65%)	36 (35%)
Single-task robots	59 (58%)	43 (42%)

Note. *n* = 102

TABLE 5
BENEFITS OF TECHNOLOGIES USED FOR OSH MANAGEMENT

Safety benefits of technology	No. (%) responses
Improve worker awareness of hazard	83 (81%)
Warn workers of workplace hazards	55 (54%)
Eliminate hazard during design	55 (54%)
Help visualize workplace hazards	55 (54%)
Enhance effectiveness of safety training	40 (39%)
Enhance incident investigation	39 (38%)
Isolate workers from hazard	35 (34%)
Facilitate injury reporting	36 (35%)
Improve safety planning	35 (34%)
Enhance communication between workers	33 (32%)
Improve safety inspections and monitoring	31 (30%)
Enhance near-miss reporting	26 (25%)

Note. *n* = 102

Zhang et al., 2013). Relatedly, study participants indicated that technologies such as WSDs, UAVs, AI and smart camera systems are often used in practice for monitoring and assessing OSH on site, including checking compliance with existing safety rules and regulations. To provide a perspective, WSDs can be used to determine the distance between on-site field workers and send warning signals to both workers and supervisors if social distancing measures are violated. With respect to improving worker awareness of workplace hazards, mobile devices on site and digital safety signage are typically used to ensure that workers are aware and alerted of any potential hazards on the jobsite.

Study participants were asked to indicate to what extent their use of these technologies for OSH has contributed to their project in terms of seven key performance indicators: work quality, client satisfaction, safety culture, project duration, project cost, recordable safety incident and productivity. As shown in Table 6, the participants believe that using technologies for OSH appreciably contributes to achieving a high performance (median rating = 4.00, "High").

Discussion

The study results indicate that most construction organizations sampled already use emerging technologies for OSH management. This is understandable given that on average, participants believe that using these technologies provides significant safety and other benefits. Some technologies such as BIM and WSDs are used by more than 85% of construction organizations to mitigate workplace hazards and manage safety and health management, while other technologies such as single-task robots are used by slightly more than half of the surveyed construction organizations for managing OSH. The level of technology adoption observed is encouraging but higher levels of technology adoption and application especially for OSH management are needed to truly influence workplace conditions and achieve positive safety outcomes. For example, project teams could utilize cameras, UAVs, LiDAR or photogrammetry to obtain on-site data, feed the data into a BIM model, and generate recommendations and safety warnings to field workers and equipment operators. The goal is to help workers and operators identify

workplace hazards and provide recommendations on how to avoid, mitigate or eliminate such hazards. These recommendations and warning signals could be delivered to field workers and equipment operators through wearable devices attached to their bodies. Besides these benefits, the identified technologies can be used for estimating and planning purposes (Mohammed & Ali, 2012). The use of technology with agile construction management would further enhance the construction process (Mohammed & Jasim, 2018), all of which is expected to improve construction outcomes and the experience of construction stakeholders.

However, certain factors could restrain the adoption and use of technology in construction. Study participants identified three main limitations slowing the use and adoption of technology for OSH management in construction: up-front investment costs of technology, cost of continuous use of technology and additional training required for technology to be used effectively. Nnaji et al. (2019) studied the adoption of construction safety technology and found that 26 factors influence the adoption of technology in the construction industry. These factors fall into three main categories: technical (related to the technology itself and the human resources needed to operate the technology); organizational (related to the organization and its policy or budgets regarding the use and adoption of technology); and external (related to the industry, its conditions and regulations). Nnaji et al. (2019) found that technical factors are the most influential in terms of affecting the adoption of technology for OSH management in construction, and that organizational and external factors are of significantly lower influence on adoption rates. This means that if a technology is reliably effective, durable and cost efficient, it would make sense to adopt the technology for OSH management. Such a technology would help contribute to lowering workplace injuries and fatalities in the construction industry. It is expected that, at least in the long run, the benefit of lowering workplace injuries and fatalities would substantially outweigh the costs of technology adoption and implementation.

Conclusion

The goal of the present study was to examine the application of technology for OSH management in construction and provide practical information that could be used by industry professionals and practitioners to improve technology adoption for OSH management. A detailed literature review identified 14 categories of technology used in construction for OSH management. Results from the questionnaire survey indicated that most participants are currently using or intend to use the 14 identified categories of technology for OSH management. Participants believe that using these technologies for OSH improve safety and other key performance metrics. Moreover, a list of potential applications for each technology was provided as a resource for construction professionals and practitioners considering the application of technologies to support OSH management in general and COVID-19 response efforts in particular. Additional research exploring the cost of utilizing construction technology for OSH management is needed to further drive the adoption of these technologies. Researchers and policymakers should focus on developing guidelines and standards for using the identified technologies for OSH management in construction. **PSJ**

TABLE 6
IMPACT OF TECHNOLOGIES ON PERFORMANCE METRICS

Impact of using technologies on organization and project performance metrics.

Performance metrics	Mean	SD
Improved safety culture	4.05	0.92
Improved client satisfaction	4.00	0.97
Increase in productivity	3.99	0.92
Increase in quality	3.97	1.01
Decrease in project duration	3.71	1.04
Reduced recordable incident	3.71	1.09
Decrease in project cost	3.71	1.13

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