WEARABLE SENSING DEVICES
Potential Impact & Current Use for Incident Prevention

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ACCORDING TO BUREAU OF LABOR STATISTICS (BLS, 2020), the construction industry witnessed a period of steady reduction in the number of fatalities and overall incident rate between 1973 and 2010. This reduction was primarily achieved through the introduction of new safety regulations, optimizing safety processes using lagging indicators (Marks, Teizer & Hinze, 2014), and introducing other effective safety practices (Hallowell & Gambatese, 2009). However, recent statistics indicate that the reduction in the number of fatalities has at best flattened over the past several years (CPWR, 2018). Increased construction complexity, escalating job pressure and the aging construction population are plausible antecedents for the observed stagnation. Moreover, Esmaeili and Hallowell (2012) posit that a primary reason for the observed deceleration is the lack of infusion of new safety innovation into construction operations. A study conducted by McGraw Hill Construction (2013) indicated that 43% of contractors do not intend to introduce a new safety innovation (technology or practice).

Given that the industry has reached saturation with respect to traditional incident prevention strategies, researchers have suggested that reducing the number of fatalities in construction will require an increased application of emerging safety technologies across a project's life cycle (Hollnagel, 2014). Studies have shown that technologies such as building information modeling (Zhang, Sulankivi, Kiviniemi, et al., 2015) drones (Şerban, Rus, Vele, et al., 2016), wearable sensing devices (WSDs; Awolusi, Marks & Hallowell, 2018; Cavuoto & Megahed, 2018), virtual reality (Gheisari & Esmaeili, 2019) and exoskeletons (Cho, Kim, Ma, et al., 2018) have the potential to improve construction worker safety.

Of these technologies, WSDs such as proximity sensing devices have been extensively covered in safety research (Awolusi, et al., 2018; Marks & Teizer, 2013). However, there is some hesitancy toward integrating WSDs into construction operations. According to Dodge Data and Analytics (2017), only 13% of contractors use WSDs on projects. Reasons such as the cost of the technologies, privacy, lack of performance-based information and interoperability have been identified as concerns that limit the application of WSDs on construction projects (Awolusi, et al., 2018).

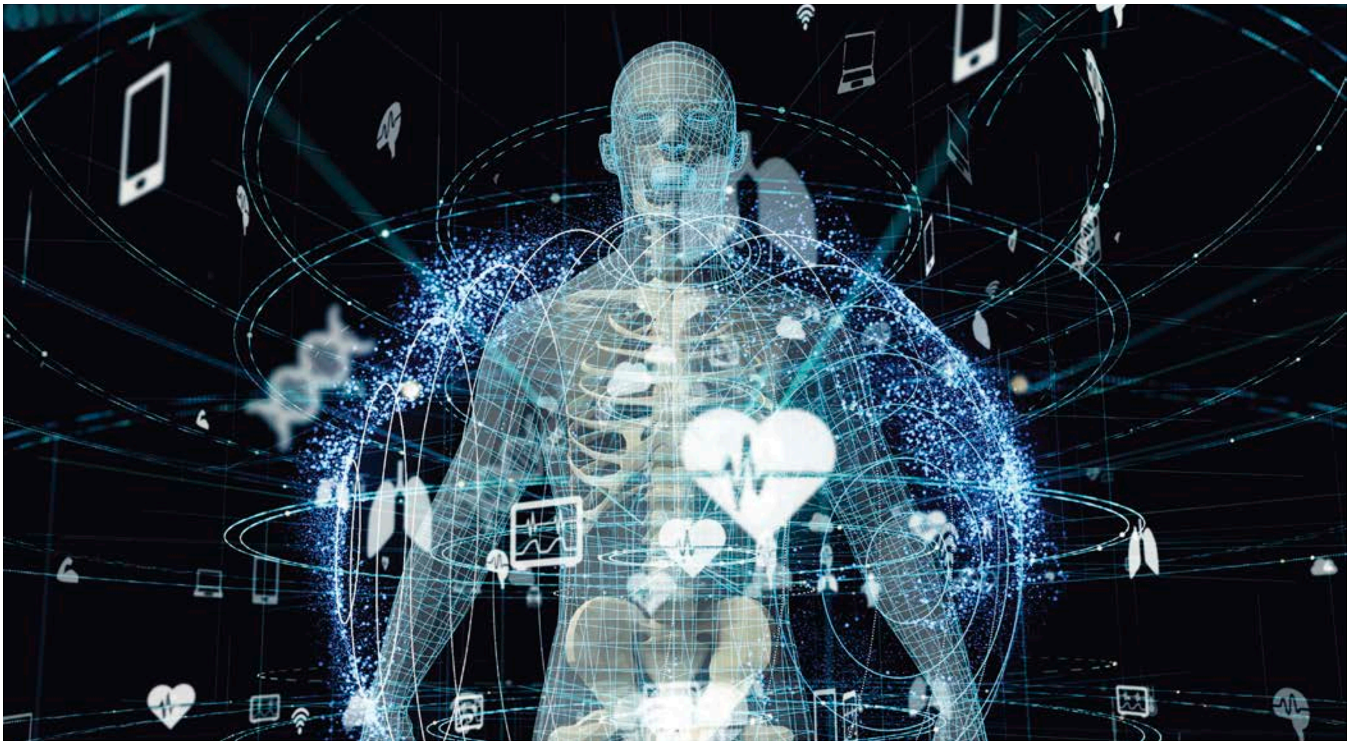
Although the information available on the potential impacts of these technologies is important, no study has investigated the direct causal effect of using WSDs on safety performance. This lack of information could be associated with the time required to empirically evaluate the exact contribution of technology on worker safety and the difficulty in isolating the impact of a single control element. Without information on the impact of WSDs on worker safety, insights on how WSDs could prevent incidents that lead to severe injuries or fatalities could help improve construction stakeholders' perception of WSD utility.

This study aims to investigate the impact of WSDs as a control measure by showing how WSD features could have prevented fatalities using archival data. Also, the present study investigates the perception of top management toward the use of WSDs. It is expected that the information provided in this article will first inform organizations of the intriguing potential of WSDs in construction applications and provide manufacturers with information that could enhance the development of future WSDs.

KEY TAKEAWAYS
- **Studies have shown that emerging technologies have the potential to improve construction worker safety.**
- **Although extensive research is available on wearable sensing devices (WSDs) such as proximity sensing devices, some are hesitant to integrate WSDs into construction operations.**
- **This study investigates the impact of WSDs as a control measure by showing how WSD features could have prevented fatalities using archival data. The study also investigates the perception of top management toward the use of WSDs.**
- **The information provided in this article should inform organizations of the potential WSDs have in construction applications and provide manufacturers with information that could enhance the development of future WSDs.**

Method

The present study adopted multiple methods to adequately meet the aim of the study. First, the researchers conducted a review of existing studies focused on WSDs to identify the different types of WSDs commercially available and highlight key features of WSDs that could reduce the impact of hazards on construction projects. Thereafter, the researchers carried out a detailed archival



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assessment of databases that investigated and recorded construction incidents using an adapted version of a process proposed by Behm (2005). The process involved identifying a database that provides sufficient information on incidents that occurred on a construction jobsite, followed by a systematic and structured analysis of each case using guiding questions and sub-questions.

The researchers reviewed fatality records from the NIOSH Fatality Assessment Control and Evaluation (FACE) program and the fatality and catastrophe investigation summaries within the OSHA archives to gather insights on construction incidents. Although previous studies relied solely on one database (Behm, 2005; Dong, Largay, Wang, et al., 2017; Gibb, Haslam, Hide, et al., 2004), the authors decided to utilize two complementary databases. The OSHA database was included solely to provide additional insight, thereby enhancing the rigor of the process.

The review process relied on the investigation report provided by the fatality investigators. The researchers reviewed each case guided by four primary questions (Figure 1, p. 18). This process was adapted from a previous study that linked construction fatalities to the prevention through design concept (Behm, 2005). First, each fatality case was assessed to identify whether the incident was preventable using a control system that relied on a real-time proactive system (Question 1: Was the incident preventable using a real-time proactive safety control?). In this step, multiple sub-questions (e.g., What was the worker doing?; Were there multiple hazards present in the work environment?; Was the worker knowingly acting unsafely?; Who created the hazard?) were asked and answered. Each question provided an opportunity to critically assess the case study and the context of the incident and extract as much detail as possible. If the assessed conditions suggested that a real-time safety control provided little or no preventive opportunities, the researchers opined that a WSD would have no impact on the safety outcome in that case study.

However, if a real-time safety control could play a role in preventing the incident, the researchers reviewed the case summaries to identify whether a WSD feature (listed in Table 1, p. 18) could have played a significant role in controlling the primary hazard that led to the incident (Question 2: Is there a WSD feature or alert that could have prevented the primary cause of the fatality?). Here, the researchers assessed the potential impact of each WSD feature independently. The researchers also evaluated the different variations of alert produced by the WSD (e.g., visual, haptic, audio) to determine whether any feature or alert type could be effective in the conditions present in each case. This led to more than 10 sub-questions.

Finally, using the Swiss cheese model concept, the researchers reviewed each case to identify whether a latent (referred to as secondary) hazard existed that could have been controlled, thereby preventing the incident (Question 3: Is there a WSD feature or alert that could have prevented a latent hazard associated with the fatality?). In the next step (Question 4), the researchers ascertained the potential role and impact of WSDs. For each case, it was assumed that WSDs could play a major role in preventing the fatality if the answer to Question 2 or 3 was affirmative (Question 4: Could the use of a WSD have prevented the incident?).

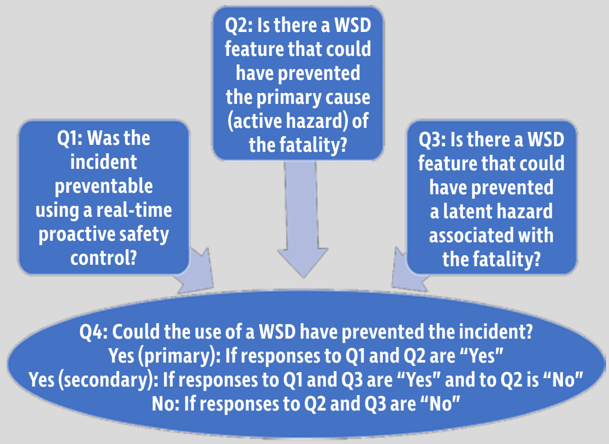
As part of a larger study, the researchers distributed a survey to construction stakeholders to gain additional insight into the use of WSDs in the construction industry. The survey was distributed predominantly to management-level employees to solicit top management perspective on the use of WSDs because, in most cases, technology adoption is initiated by management-level employees (Mitropoulos & Tatum, 1999). Since the survey was intended to investigate the perception of management-level employees toward the use of WSDs in the construction industry, no attempt was made to control conditions or variables (Kelley, Clark, Brown, et al., 2003). The participants were not allocated into groups and no treatment was given to influence their opinion. The survey was designed and distributed via Qualtrics to construction workers across the U.S. The researchers sent e-mails to approximately 2,200 construction workers using the Qualtrics professional database and contacts available to the researchers. A total of 337 responses were received.

Results & Discussion

Review of WSDs & Key Features

As wearable technology gains traction globally and mobile devices become part of everyday life, the number, types and forms of wearable devices have grown astronomically in recent years. A few of these WSDs also exist in the construction industry in the form of smart watches and wristbands, smart hard

FIGURE 1
INVESTIGATION MODEL



Note. Adapted from "Linking Construction Fatalities to the Design for Construction Safety Concept," by M. Behm, 2005, *Safety Science*, *43*(8), 589-611.

TABLE 1
WSDs FUNCTIONS & METRICS FOR CONSTRUCTION SITE HAZARDS

WSD functions	Construction site hazards	Metrics
Physiological monitoring	Dehydration	Skin impedance, blood-water content
	Falls from height	Body posture, gait
	Slips and trips	Body posture, body speed, body rotation and orientation, gait
	Stress	Heart rate, blood pressure, respiratory rate
	Heat or cold	Body temperature
	Fatigue	Muscle state, skin temperature
Environmental sensing	Fire and explosions	Smoke and fire detection
	Noise	Noise level
Proximity detection and location tracking	Caught in or between	Proximity detection
	Cave in	Location tracking
	Struck by object	Proximity detection, location tracking
	Electrocution	Proximity detection, location tracking

Note. Adapted from "Wearable Technology for Personalized Construction Safety Monitoring and Trending: Review of Applicable Devices," by I. Awolusi, E. Marks and M. Hallowell, 2018, *Automation in Construction*, *85*, 96-106.

hats and safety vests, and smart boots, clips and tags. WSDs containing gyroscopes, accelerometers and magnetometers have gradually found practical applications in human motion analysis to improve balance control and reduce falls. These WSDs could help reduce fall-related injuries on construction sites (Awolusi, et al., 2018; Hwang, Jebelli, Choi, et al., 2018; Jebelli, Hwang & Lee, 2017).

However, the trend is moving toward multisensor platforms that incorporate several sensing elements. For example, the standard for the next generation of personalized WSDs appears to be some mix of several sensors such as accelerometer, electrocardiogram (ECG/EKG) sensor, electroencephalography (EEG) sensor, galvanic skin response (GSR) sensor, temperature sensor, heart rate sensor or others. Some of the available construction WSDs (e.g., Spot-r Clips, EquipTags, SmartBoots, Zephyr) combine various functionalities (e.g., physiological monitoring and location tracking) onto a single, compact, power-efficient platform. These WSDs measure slips, trips and falls, worker and equipment location, step count, speed, time spent in work areas, fatigue, heart rate and dehydration risk in the future. Other available WSDs measure heart rate, breathing rate, heart rate variability, posture, body temperature, body acceleration and impact. Table 1 provides the safety metrics for construction site hazards that were used to explore the functions of WSDs for possible prevention of fatalities in cases assessed in this study.

To successfully appraise the cost situation in the industry, the researchers identified trending wearable devices by extensively reviewing literature from Conexpo-Con/Agg (2020) and eSUB (Novotny, 2019). After an in-depth search to determine current market prices, the collated data were categorized in a similar manner to Awolusi, et al. (2018), as shown in Table 2. Some prices of the WSDs were available on manufacturers' websites while others can only be obtained when an actual project is being executed (on a case-by-case basis). Prices from third-party sources were noted as well, where applicable.

As Table 2 shows, many devices are affordable when looking at the unit prices alone. At a project level, the cost-effectiveness can only be determined in relation to the specific project. The researchers did not make further quantitative analysis. In a study conducted by Schall, Sesek and Cavuoto (2018), 117 respondents (who are construction practitioners) indicated that their organization would be willing to spend $63.17 U.S. per person for a wearable device. This suggests that the potential computed costs are not a huge deterrent to future organizational adoption of WSDs.

Archival Analysis

The researchers involved in this study conducted the archival analysis. The researchers have approximately 15 years of practical work experience in safety management, engineering, project control and field worker duties, and 21 years of research experience focused primarily on technology use in the construction industry. Furthermore, a current practitioner vetted the analysis to ensure that the results are in line with what is obtainable in the construction industry. The researchers probed two databases (FACE and OSHA) to identify construction-related incidents. In addition to providing breadth and depth, probing two databases will provide an avenue to compare trends and findings. The parameters for the search are outlined in Table 3.

A total of 251 fatalities, reported between 1982 and 2018, were identified through the FACE program, providing sufficient depth. Twenty-nine studies were identified from the OSHA archives. The researchers limited the OSHA archive probe to 2018 since the primary reason for utilizing a second database was to provide additional insight. A total of 280 cases were reviewed in detail by the researchers.

However, in line with archive-based studies, the researchers had to incorporate some assumptions as part of the archival analysis. First, the researchers assumed that WSDs were not used in the fatality reports reviewed because the use of WSDs is relatively new and is only being employed by a few contractors (Dodge Data & Analytics, 2017). Also, the researchers assumed that the presence of a WSD would prevent the incidents, thereby discounting the impact of limitations such as false alarms and limited reaction

TABLE 2
TRENDING WEARABLE SENSING DEVICES

No.	Technology	Manufacturer	Price	Classification	Features	Source
1	Cooling jacket	Zippkool	$179	Physiological monitoring	Heat or cold	Zippkool, 2019
2	Spot-r	Triax Technologies	Available on case-by-case basis	Physiological monitoring, location tracking	Slips and trips; caught in or between; struck by object	Triax Technologies, 2020
3	Redpoint RTLS system	Redpoint positioning	> $3,500 (third- party source)	Proximity detection and location tracking	Caught in or between; cave in; struck by object; electrocution	Swedberg, 2018
4	XOeye eyewear device (e.g, smartglasses)	XOi Technologies	$500 per unit, with required $99 monthly subscription (third-party source)	Physiological monitoring	Falls from height; slips and trips	Phillips, 2014
5	CAT Detect Personnel	Caterpillar	Available on case-by-case basis	Proximity detection and location tracking	Caught in or between; cave in; struck by object; electrocution	Caterpillar, 2016
6	Smart Helmet + Smart Band	Smart Cap	Available on case-by-case basis	Physiological monitoring	Heat or cold; stress	SmartCap Technologies Pty. Ltd., 2020
7	HoloLens	Microsoft	$3,500 per device	Physiological monitoring, proximity detection and location tracking	Caught in or between; cave in; struck by object; electrocution	Microsoft, 2020
8	Smart Band	Caterpillar	Available on case-by-case basis	Physiological monitoring, proximity detection and location tracking	Stress; heat or cold; caught in or between; cave in	Caterpillar, 2020

time. In a few cases in which information provided was somewhat limited, the researchers relied on their experience and trends observed in previous cases. For example, the researchers assumed that WSDs would have no impact on incidents caused by a worker's clear nonconformance to existing safety protocol (worker behavior related). It could be argued that such a worker could have ignored the prompt received from the WSD as well. Yet, the information in this article was thoroughly vetted to ensure a credible reflection of the potential impact of WSDs.

The complex and dynamic nature of construction environments makes hazard recognition difficult, thus, increasing the likelihood of incidents. As depicted in Figure 2 (p. 20), WSDs could provide an additional layer to protect workers from hazards, whether they are conscious of those hazards or not (Teizer, Allread, Fullerton, et al., 2010). The ability to identify a hazard is influenced by how much knowledge or training the worker has (Guo, Yu & Skitmore, 2017). When a WSD on a worker senses a hazard, a notification or an alert is sent to the worker who either responds to the alert or ignores it. Unwanted incidents could be averted when the worker responds to the alert but when no action is taken in response to the alert, an incident could occur. One possible human factor limitation that can be experienced is workers becoming desensitized to the warning alerts due to the nature of the construction environment (e.g., use of heavy equipment), lack of adequate training on how to respond to notifications and the workers' reluctance to change their behavior. Thus, because construction workers can become desensitized to audible alerts (e.g., backup alarm), WSDs should provide additional alert options (e.g., visual or vibratory alert) to enhance worker response to the warning alerts. Other human factors such as privacy concerns and perceived usefulness could impact the use of WSDs. These factors are currently being investigated by the researchers involved in this study.

Incident Case Analysis

Following are examples of one case in which using WSDs could have prevented the fatality and another case in which using WSDs would likely have a limited impact on the outcome. Additional cases can be found in the support documents.

Case 1

On June 24, 2002, a 21-year-old Hispanic dump truck driver (the victim) died after being caught between the frame and dump body of an off-road dump truck while performing routine lubrication. The victim was working for an excavation contractor at a landfill expansion site on the day of the incident. The victim's foreman drove by the area where the company service truck was set up and stopped to investigate when he heard the air compressor running but not the usual clicking sounds made when workers are greasing their trucks. He found the victim caught between the frame and dump body of the truck. The foreman called out for help and then called 9-1-1 from his cell phone. An excavator operator working nearby responded to the foreman's call for help and climbed into the cab of the truck and raised the bed. Emergency medical services (EMS) and law enforcement personnel responded within 10 minutes. EMS personnel transported the victim by ambulance to a local hospital where he was pronounced dead.

TABLE 3
SEARCH PARAMETERS FOR ARCHIVAL ANALYSIS

Parameters	NIOSH archive	OSHA archive
Incident type	Fatality	Fatality
Data scope	NIOSH FACE reports: Construction	NAICS Code 236220, commercial and institutional building construction
Query start date	1982	Jan. 1, 2018
Query end date	2018	March 11, 2019
No. of cases	251	29
Query data	NIOSH, 2020	OSHA, 2020a

Herein, the proximity detection feature that is part of the proximity detection and location tracking function of a WSD could have alerted the worker to prevent being caught in or between.

Verdict: WSDs could have impacted the outcome.

Case 2

The day before the incident the excavator operator had removed the trench shield used during the sewer installation project to facilitate the removal of broken

FIGURE 2
INCIDENT PROCESS WITH RESPECT TO THE USE OF WSD

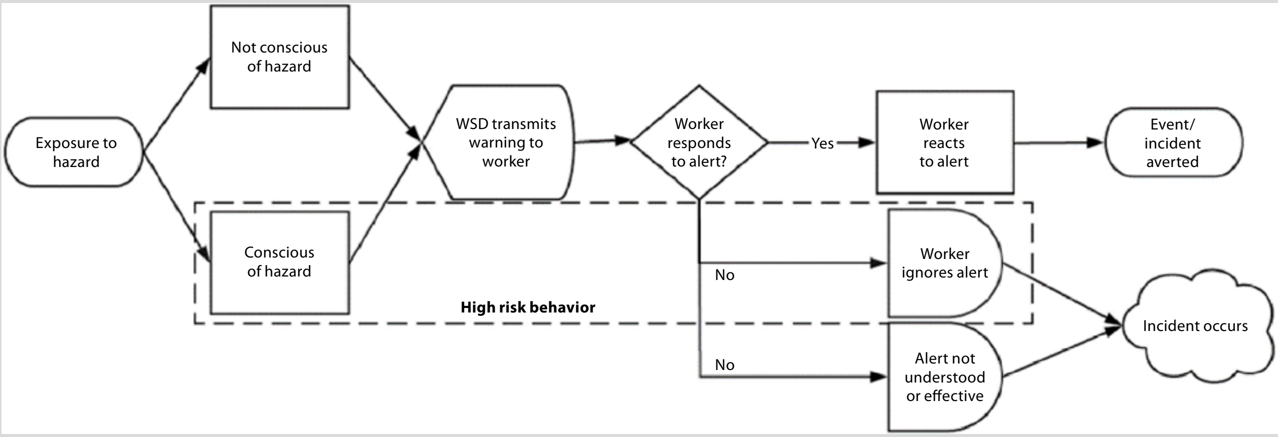


TABLE 4
SUMMARY OF ARCHIVAL ANALYSIS

Summary of archival analysis showing the researchers' assessment of the number of cases in which use of a WSD could have played a role in preventing fatality and the number of cases in which WSDs could have had a secondary impact (associated with latent hazards).

WSD functions	Construction site hazards	NIOSH		OSHA	
		Primary	*Secondary*	*Primary*	*Secondary*
Physiological monitoring	Falls from height	21	0	3	0
	Slips and trips	0	4	0	3
	Stress	1	0	0	0
	Heat or cold	0	1	0	0
Environmental sensing	Fire and explosions	0	0	0	0
	Noise	0	0	0	0
Proximity detection and location tracking	Caught in or between	20	10	0	1
	Cave-in	9	0	0	0
	Struck by object	10	6	6	0
	Electrocution	12	0	1	0
	Total	**73**	**21**	**10**	**4**
	Percent of total cases (*n* = 251; *n* = 29)	**29%**		**34%**	

sewer pipes. When work was resumed the next day, the trench shield was not replaced, and the victim and a coworker (pipe setter) went into the unprotected trench to replace two sections of pipe and to check the grade of the sewer line with a grade pole. While they were placing the grade pole inside the terminal end of the sewer line, a section of the trench wall caved in, striking and burying the victim to his mid-chest and his coworker to his knees.

As noted, incidents like this in which there is a clear nonconformance to standard operating procedure (behavioral safety problem), and incidents with multiple indicators outside of those that could be influenced by WSDs were ignored.

Verdict: WSDs would have had a limited impact on the outcome.

This category of incidents is largely caused by human factors such as unsafe acts/behaviors suggested by researchers to be responsible for most workplace incidents (Abdelhamid & Everett, 2000; Reason, 1995; Sawacha, Naoum & Fong, 1999). Common examples of these incidents in construction include an employee performing work without authorization, operating equipment without proper training or authorization, not wearing appropriate PPE and ignoring warning alerts. These issues can be radically resolved starting from the organizational level to the project level through improved safety climate and culture, including upper management support, employee involvement and evaluation, safety orientation and training, active worker observation, continuous safety audit, and job hazard analysis.

Outcome of Analysis

NIOSH FACE Reports

The researchers determined that using the physiological monitoring and proximity detection component of WSDs, 21 fall-from-height cases could have been prevented had workers received a prompt regarding their body posture and their proximity to a fall hazard. Moreover, the proximity detection and location tracking capability of a WSD could have played an active role in preventing 51 fatalities. Based on the researchers' analysis, the environmental sensing capability of WSDs would have had a limited impact in reversing any outcome since the root cause for most fatalities was worker behavior and work operation. However, a noise meter in WSDs could play a role in preventing hearing loss, which is more of a health concern and is not captured in the evaluated databases. In total, the active hazards present in 73 out of the 251 cases, representing 29% of the fatality cases, could have been prevented using a WSD. In addition, features of WSDs could have provided an alert upstream of the event (secondary) in 21 out of the 73 cases, thereby reducing the worker's exposure to the event that led to a fatality.

The primary reason for most fatalities in cases 190 through 251 was electrocution due to overhead power lines and energized circuits, therefore, the impact of WSDs may have been limited. Also, most NIOSH reports prior to 1990 were not as detailed as those published after 1990. For example, there were no summary sections in cases published before 1990. However, the available data were considered sufficient to make the needed inferences.

OSHA Archives

Out of the 29 cases reviewed by the researchers, 10 cases in which WSDs could have influenced the outcome were identified.

Six out of those 10 cases were related to struck by object, three were connected to falls from height, and the last fatality was associated with the electrocution category. Moreover, WSDs could have had a secondary impact (associated with latent hazards) in four of the 10 fatality cases. These latent hazards were slip and trip (three cases) and caught in between (one case). This finding indicates that WSDs could have played a role in preventing 34% of the deaths recorded in 2018 in the OSHA archives.

Table 4 summarizes the findings from the archival analysis. WSDs could play a critical role in preventing incidents within the Construction Focus Four (i.e., falls from height, caught in or between, struck by object, electrocution). Although this finding reinforces the need for manufacturers to develop sensing technologies that will help prevent or reduce fatalities from these four hazards, it is essential that manufacturers also develop features for other applications. For example, more attention could focus on harnessing the sensing technologies that could reduce fatalities associated with cave-in (fifth largest category).

Current State of WSD Use & Factors Influencing Their Adoption

Although a recent report specifically assessed the level of WSD adoption in the construction industry (Dodge Data & Analytics, 2017), the report does not provide additional insights such as the presence or absence of disparities between general contractors and subcontractors, the types of WSDs used by these contractors, and workers' perceptions on factors that drive the use of WSDs. This information would provide a better picture of the level of awareness and diffusion of WSDs across the industry. Also, an enhanced understanding of factors that may influence the use of WSDs and the key drivers for adopting WSDs would provide essential information to researchers and manufacturers. Hence, the researchers asked participants questions to provide much-needed insight into the aforementioned factors.

A total of 337 responses were received. However, 45 responses were dropped from the study due to missing data (incomplete data), leaving 292 complete responses for further analysis. In terms of spread, at least one response was received from 78% of the states in the U.S. All five regions of the U.S. (Northeast, Southeast, Midwest, Southwest, West) were represented.

Responses were received from general contractors (61%), subcontractors (24%), consultants (6%) and other construction stakeholders such as public agencies (9%). About 63% of the responses were received from management-level employees (e.g., construction manager, safety manager, project manager). Respondents' years of experience ranged from less than 1 year to more than 20 years. However, 60% of the participants had more than 11 years of experience in the construction industry. Most respondents were involved in commercial (34%), residential (28%) and industrial (14%) projects.

First, participants were asked how familiar they were with WSDs: not at all familiar (1); slightly familiar (2); somewhat familiar (3); moderately familiar (4); and extremely familiar (5). Approximately 27% of participants indicated that they were moderately to extremely familiar with WSDs. Of general contractors, 37% were in the moderately to extremely familiar category. Only 9% of subcontractors indicated a similar level of familiarity.

Next, participants were asked to indicate the types of WSDs with which they were familiar (Figure 3). Although most options were associated with PPE, respondents indicated that they were familiar with attachable devices such as Triax Spot-r technologies. The term *general* in Figure 3 (as well as in Figures 4 and 5,

FIGURE 3
FAMILIARITY WITH WSDs

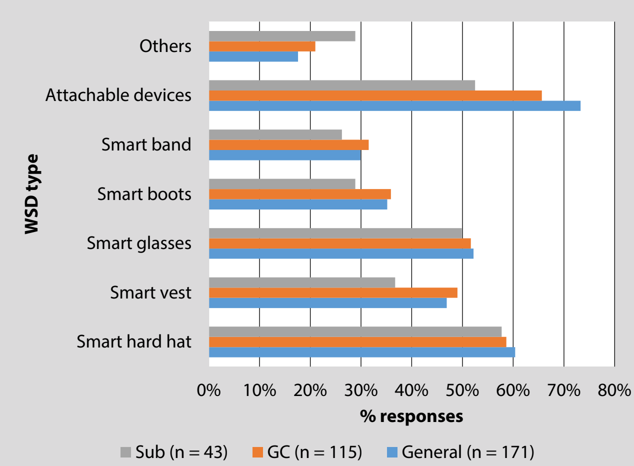


FIGURE 4
CURRENTLY USE WSDs

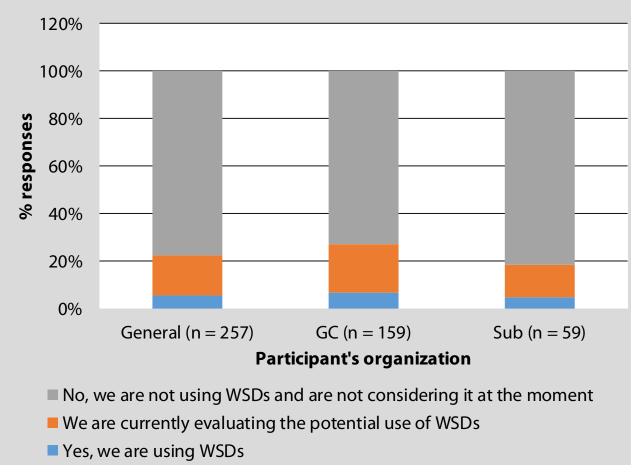


FIGURE 5
FACTORS INFLUENCING WSD USE

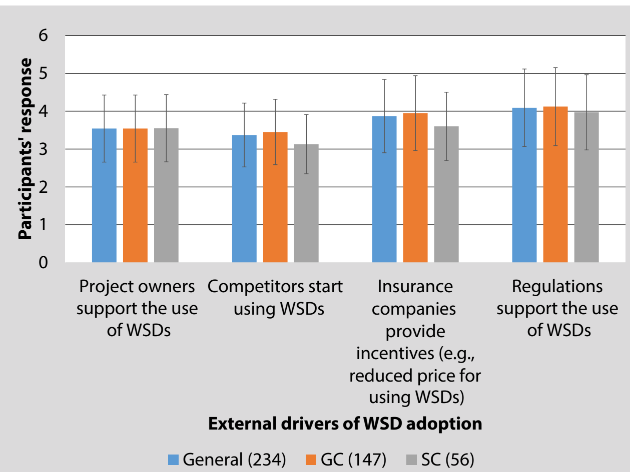


TABLE 5
PARTICIPANTS' PERCEPTIONS OF WSD USE

	Factors	General (234)		GC (147)		Sub (56)	
		Mean	*SD**	*Mean*	*SD**	*Mean*	*SD**
Potential impact of WSDs							
1	Real-time information is needed to optimize worker safety	3.88	0.95	3.95	0.96	3.62	0.90
2	Incident reporting accuracy can be improved using WSDs	3.79	0.93	3.83	0.9	3.75	0.97
3	Application of WSDs enhances my company's safety management program	3.68	0.91	3.76	0.93	3.59	0.88
4	Using analytics from WSDs could optimize workforce efficiency	3.68	0.95	3.73	0.95	3.64	1.01
5	Using WSDs could improve workers' safety	3.64	0.8	3.64	0.79	3.51	0.81
6	Implementing WSDs will enable real-time monitoring of workers	3.63	0.97	3.84	0.9	3.25	0.94
7	Using WSDs could improve workers' perception of organization's safety culture	3.61	0.99	3.73	0.97	3.38	0.99
8	WSDs provides real-time visibility into construction jobsite operations, locations of assets, people, document and materials	3.61	1.00	3.66	1.02	3.5	0.91
9	Using WSDs to monitor my safety would be beneficial for me	3.55	1.01	3.62	1.02	3.38	1.01
Ease of use							
1	It is easy to learn how to use WSDs	3.5	0.98	3.6	0.95	3.27	1.03
2	Field workers will find WSDs easy to use	3.44	1.02	3.61	0.94	3.04	1.16
3	Installing WSDs will be easy	3.21	1.1	3.33	1.08	2.86	1.14
Willingness to use WSDs							
1	I will likely incorporate WSDs into work operations (if it was my decision to make)	3.46	1.03	3.56	0.99	3.3	1.03
2	I will encourage the use of WSDs	3.42	1	3.39	0.98	3.31	1.03
3	I will recommend the use of WSDs to my boss (supervisor) or field worker	3.41	1.05	3.53	1.03	3.13	1.05

Note. ***SD*** **= standard deviation; 1 = strongly disagree/unlikely; 3 = neutral; 5 = strongly agree/likely**

and Table 5) refers to all responses received from construction stakeholders, including general contractors and subcontractors.

Participants were also asked whether they currently use WSDs in their organization as part of the organization's safety management process (Figure 4, p. 21). Only 6% of respondents use WSDs in their organization (GC = 7%; sub = 5%), while 17% said they were currently considering using WSDs in their organization (GC =20%; sub = 14%). Of subcontractors, 81% said they currently have no intention of using WSDs (GC = 73%). The findings (low implementation) are consistent with results reported by Dodge Data and Analytics (2017). These results imply that there is a possibility of broad unanimity between general contractors and subcontractors about their resistance to the implementation of new technology, which reflects what is currently experienced in the construction industry. Thus, a conscious effort should be made to involve general contractors and subcontractors in the design of future WSDs to enhance their adoption and implementation.

Although WSDs have shown some promise, the current adoption rate is a concern. Therefore, it is important to find effective ways to encourage adoption. To gauge factors that could influence the use of WSDs, participants were asked to rate whether certain factors influence the implementation of WSDs (1 = strongly disagree; 3 = neutral; 5 = strongly agree). Respondents indicated that insurance companies could play a key role in increasing the use of WSDs if they introduced an incentive program associated with their use. Also, the introduction of regulations that support the use of WSDs would increase the adoption rate (Figure 5, p. 21).

Finally, participants were asked to assess the potential impact of WSDs on a construction worker, work operation and their organization (Table 5). Individuals who responded to the survey indicated that they are willing to use or encourage the use of WSDs (mean = 3.46 out of 5) given the potential impact of WSD features on workers' safety. For example, participants indicated that the real-time feature provided by WSDs is essential to optimize safety performance (mean = 3.88). These results obviously indicate that top management personnel acknowledge the benefits of WSDs and are aware of the potential positive influence their implementation would have on safety performance as a management tool. This implies that there is a good tendency for smooth integration of WSDs into work processes for safety management if the barriers associated with acceptance and use of the devices by field workers are identified and strategically removed.

Furthermore, some factors recorded relatively high standard deviation (*SD*), which indicates a lack of consensus among responders (Table 5). For example, the subcontractors reported an *SD* of 1.16 when asked if WSDs will be easy for field workers to use. Although previous studies on novel technologies showed a similar trend (Chan, Darko, Olanipekun, et al., 2018; Ozorhon & Karahan, 2017), this divergence in perception of complexity is expected given the resistance observed from some stakeholders regarding the use of WSDs and the lack of empirical evidence on extended effectiveness of WSDs. As more information is provided on the utility of WSDs and workers begin to accept them, the researchers expect less deviation from the mean.

Although valuable insights were gained on the level of adoption and use of WSDs by primarily focusing on top management personnel, this focus involved some limitations relative to the impact on workers because the recorded perception was that of management, not of the workers who are required to use the technology. Future research should involve conducting a more in-depth analysis of worker-level perception to obtain a more holistic understanding of perceptions toward WSD use.

Barriers to WSD Adoption

Previous studies identified factors such as privacy concerns, limited interoperability with existing systems, need for Internet of Things (IOT) infrastructure, security of information, lack of standardization, safety of acquired data and cost as key concerns that create a barrier to WSD adoption (Awolusi, et al., 2018; Haghi, Thurow, Habil, et al., 2017). Furthermore, the authors believe that when considering privacy concerns, the novelty of collating data (especially vitals) can raise apprehension among the workers considering that it is perceived that they do not have total control over the end use of the data. This concern could be reduced by developing a personalized device that only transmits critical information. Moreover, workers are hesitant to give up information about their location at every moment. Limited interoperability with existing systems and the need for information technology infrastructure are perceived as factors that limit an organization's interest in deploying WSDs (Masum, Lackman & Bartleson, 2013). In addition, liability concerns (e.g., legal access to stored safety data if a lawsuit is filed), capital and maintenance costs, and lack of incentive and support from external stakeholders (e.g., client, government, safety regulation agencies, insurance companies) could impact the use of WSDs. According to Okpala, Nnaji and Awolusi (2019), no standard exists supporting the use of WSDs in the construction industry. A well-implemented standardized platform will foster interoperability and, thus, reduce barriers to the diffusion of WSDs (Okpala, et al., 2019). To maximize the potential of WSDs, researchers and manufacturers must work closely with the industry to identify key roadblocks and develop innovative approaches that would reduce the barriers currently observed in the industry.

Implications to Safety Research & Practice

This study makes two primary contributions to research. First, it details a reproducible model for retrospectively assessing the impact of safety technology. Using the information provided in this study, researchers working on use cases can better analyze the potential link between using WSDs or other safety technologies as a safety measure and incident reduction. Also, this study provides a structure that could be used to develop a framework for WSD cost-benefit analysis. In addition to research implications, this study provides additional practical suggestions. Given the limited availability of project or organization use cases on WSDs, this study provides much-needed insights on the potential impact of WSDs to worker safety. It also identifies key features and combinations of features of WSDs that could impact safety outcomes. Moreover, the study identifies some drivers of WSD adoption. This information could provide the impetus required to foster productive discussions between construction stakeholders, such as insurance companies, project owners and contractors on workers' compensation adjustments, which is mutually beneficial. Additionally, this study has brought to light the importance of conducting an inclusive investigation on worker-level perception to ensure a profound knowledge of perceptions toward WSD adoption in the construction industry.

Conclusion

The researchers conducted a study to explore the potential impact of WSDs on worker safety. They also assessed the level of awareness and use of WSDs among general contractors and subcontractors. The authors provide practical insight to technology manufacturers and practitioners on ways to improve the adoption and implementation of WSDs. Results from the archival analysis indicate that WSDs could play a significant role in reducing fatalities in the construction industry.

As WSDs evolve and the use of IOT becomes more ubiquitous, WSDs such as smart fall protection systems and smart soles could be used to prevent falls associated with improper tie-off and predict and detect potential slips and trips using advanced machine learning algorithms. These expected advancements are expected to increase the utility of WSDs, thereby making their use more pervasive. As this class of technology evolves, it is expected that the advantages will outpace the disadvantages. **PSJ**

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