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Sensing and Warning Based Technology Applications to Improve Occupational Health and Safety in the Construction Industry: A Literature Review

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Abstract

Purpose – Sensing and warning-based technologies are widely used in the construction industry for occupational health and safety (OHS) monitoring and management. A comprehensive understanding of the different types and specific research topics related to the application of sensing and warning-based technologies is essential to improve OHS in the construction industry. This review aimed to examine the current trends, different types and research topics related to the applications of sensing and warning-based technology for improving OHS through the analysis of articles published between 1996 and 2017 (years inclusive).

Design/methodology/approach – A standardized three-step screening and data extraction method was used. A total of 87 articles met the inclusion criteria.

Findings – The annual publication trends and relative contributions of individual journals were discussed. Additionally, this review discusses the current trends of different types of sensing and warning-based technology applications for improving OHS in the industry, six relevant research topics, four major research gaps and future research directions.

Originality/value – Overall, this review may serve as a spur for researchers and practitioners to extend sensing and warning-based technology applications to improve OHS in the construction industry.

Keywords: Construction; Health; Occupational; Safety; Sensing; Technology.

Introduction

Enhancing occupational health and safety (OHS) is a major issue across global construction industries (Zhou *et al.,* 2012). The construction industry is one of the industry sectors with severe occupational injuries and fatality risks, making it both a unique and challenging sector (Umer *et al.,* 2017a). For example, in Hong Kong Special Administrative Region (HKSAR), there were 3,332 injuries and 37 fatalities in the construction industry in 2013, which accounted for 19.68% of fatalities across all industries (HKOSH, 2014). In USA, 36% of fatalities (1231 of 3419) were related to fall injuries in the construction industry from 2011 to 2014 (Bureau of Labor Statistics, 2016a). In Australia, there were 35 out of 182 fatalities in the construction industry in 2016, which accounted for 3.3 fatality rate (fatalities per 100,000 workers) across all industries (Safety Work Australia, 2017). In addition, occupational injuries can lead to project delays, increased project costs, medical burden and disabilities (Umer *et al.,* 2017a). In order to improve OHS in the construction industry, there is the need to develop and provide pragmatic solutions to prevent occupational injuries and fatalities.

With the development of sensing and warning-based technology, a growing number of researchers and practitioners have realized that their applications could provide effective solutions to improve OHS in the construction industry. Heng *et al.* (2016) developed a behavior-based safety (BBS) with proactive construction management system (PCMS) for intrusion warning and assessment method in reducing incidents and enhancing workplace site safety. Yi *et al.* (2016) developed a global system mobile communication (GSM) based on environmental sensors for warning site worker in hot and humid environments. These findings indicate that the applications of sensing and warning-based technology can be a feasible way to eventually minimize fatal and non-fatal occupational injuries in the construction industry. Antwi-Afari *et al.* (2017b) and Umer *et al*. (2017b) evaluated the effect of biomechanical risk factors such as awkward working postures based on self-reported discomfort and spinal biomechanics (muscle activity and spinal kinematics) by using surface electromyography (sEMG) and inertial measurement units (IMUs) sensors. Based on the proposed methods of using sensing and warning-based technologies, the findings of these studies demonstrated that the suggested interventions (e.g., team lifting, adjustable lift equipment, and domestic stool) have a great potential in reducing work-related musculoskeletal disorders (WMSDs) risks in construction workers. Therefore, there is the need for innovative sensing and warning-based technology applications to improve OHS in the construction industry globally.

Generally, advanced information-based technologies (e.g., Video Range Imaging, Virtual Reality (VR), 4D Computer Aided Design (4D CAD), Building Information Modelling (BIM), sensing and warning-based technology) have received significant attention and have been widely applied to detect, model and track moving construction resources like workforce, equipment or materials within the construction workplace (Bai *et al.,* 2015; Yi *et al.,* 2016; Zhou and Ding, 2017). The applications of sensing and warning-based technology offer many advantages and have been used in various civil engineering applications such as structural health monitoring (SHM) (Wang and Yim, 2010; Bai *et al.,* 2015; Song *et al.,* 2017). While these applications can effectively collect, identify and process information from workers during the construction phase, they can also be used in the operation phase of a project to monitor the safety of users. Specifically, the quality of a structure, as well as the safety issues are related to the livelihood of users, which may be important OHS issues during the operation phase. Undoubtedly, structural failures/damages can result in severe injuries of workers during construction and fatalities of users during operation

(Acikgoz *et al.,* 2017; Song *et al.,* 2017). For instance, Lee *et al.* (2014) developed and validated a curing temperature management system based on wireless sensor network (WSN) that enabled direct, real-time and continuous monitoring of the internal temperature of concrete and curing process at real construction sites. Similarly, fiber optic sensors (FOSs) used in SHM of OHS research not only improve workers' safety during construction phase but also help users to take corrective steps to avoid further damages (e.g., cracks, deformation) of concrete structures (e.g., bridges, dams) during the operation phase (Afzal *et al.*, 2012). Continuous monitoring of temperature, deformation, and displacement should be considered in the total life cycle approach of a construction project. As such, SHM can be considered as an important part of OHS in construction.

Within the construction industry, key stakeholders including construction managers, safety officers, and researchers, could benefit from an overall understanding of the current types and applications of sensing and warning-based technology for improving OHS. In order to share innovative research findings, access future research directions, suggest potential safety interventions, and prevent occupational injuries and fatalities, construction safety practitioners and researchers need a critical review of previous studies on sensing and warning-based technology. Such a review can summarize various types of sensing and warning-based technology, and their key applications areas to improve OHS. The results can allow researchers and practitioners to recognize the research gaps and opportunities between construction safety research and construction safety practice. Taken together, there is an essential need to conduct a comprehensive literature review on the applications of sensing and warning-based technology to improve OHS in the construction industry.

With the goal of fostering and directing further research on the application of sensing and warning-based technology for OHS in construction, this review article focuses on several streams. First, this review summarized the current trend of sensing and warning-based technology in leading peer-reviewed journal publications from different database sources. Second, various state-of-the-art sensing and warning-based technology and key research areas of OHS were discussed to provide directions for researchers in planning their future studies and in introducing new sensing and warning-based technology to improve construction workplace safety performance. In short, the current review study aimed to summarize existing sensing and warning-based technology, identify research gap, and discuss future directions through answering the following research questions:

1. What were the annual publication trends of sensing and warning-based technology applications for OHS in the construction industry from 1996 to 2017 (years inclusive)?
2. What were the relative contributions of different journals to the field of sensing and warning-based technology applications during that period?
3. What are the current trends of different types of sensing and warning-based technology applications for OHS in the construction industry?
4. What are the key and specific research topics/areas related to the application of sensing and warning-based technology for OHS in the construction industry?
5. What are the research gaps and future research directions in using sensing and warning-based technology for OHS in the construction industry?

The remaining part of this review is structured as follows. Section 2 reports a three-step method to identify and summarize relevant articles. Section 3 presents results and discussion on the annual publication trends, contributions of journal publications, and the current trends of different types of sensing and warning-based technology applications for OHS. In the fourth section, the key research topics covered were discussed. Section 5 summarizes the research gaps and directions for future studies. Finally, the conclusions of this review are presented in section six.

Methods

The current review methods comprise three major steps: (1) literature search; (2) literature selection; and (3) literature coding. The three-step method was adopted from a similar review (Zhou *et al.,* 2013) of applying advanced technology to improve safety management in the construction industry.

Step 1: Literature search

With regards to the diversity of the aforementioned research questions on this research topic, the literature search was conducted across disciplines and included several databases. As a result, a systematic search was conducted to obtain relevant articles on sensing and warning-based technology applications for OHS in the construction industry through searching eleven electronic databases: Academic Search Premier, ASCE Library, CINAHL Complete, Emerald Management e-Journals, Health and Safety Abstract, Medline, PsycINFO, Science Direct, Scopus, Web of Science, and Wiley Online Library. In addition, other relevant information sources were identified by manually checking references to include seven relevant articles.

In this review, keywords search and free-text words were adopted to select relevant articles on sensing and warning-based technology applications for OHS. A systematic and extensive search was conducted under the 'article title/abstract/keyword' field in the databases. Although there are different codes among the eleven selected databases, the search string consisted of three parts. The first part comprised keywords related to 'wearable sensors' or 'sensing technology' or 'warning technology'. The second part comprised 'occupational' or 'health' or 'safety' or 'accident' or 'incident' or 'work-related musculoskeletal disorders' (WMSDs). The final part covered 'construction industry' or 'construction sector' or 'construction workers'. As such, these three components of keyword searches were used in this review article to retrieve relevant articles on the topic of sensing and warning-based technology applications to improve OHS in the construction industry.

The total search terms and results (number of included relevant articles) are shown in Figure 1. For instance, the full search code for Science Direct database was: TITTLE-ABS-KEY ((“wearable sensors” OR “sensing technology” OR “warning technology”) AND (“occupational” OR “health” OR “safety” OR “accident” OR “incident” OR work-related musculoskeletal disorders”) AND (“construction” OR construction industry” OR “construction sector” OR “construction workers”)). All citations identified from the systematic searches from the selected databases were exported into EndNote X7 (Thompson Reuters, New York, USA). A total of 1,608 references were identified through the 11 databases.

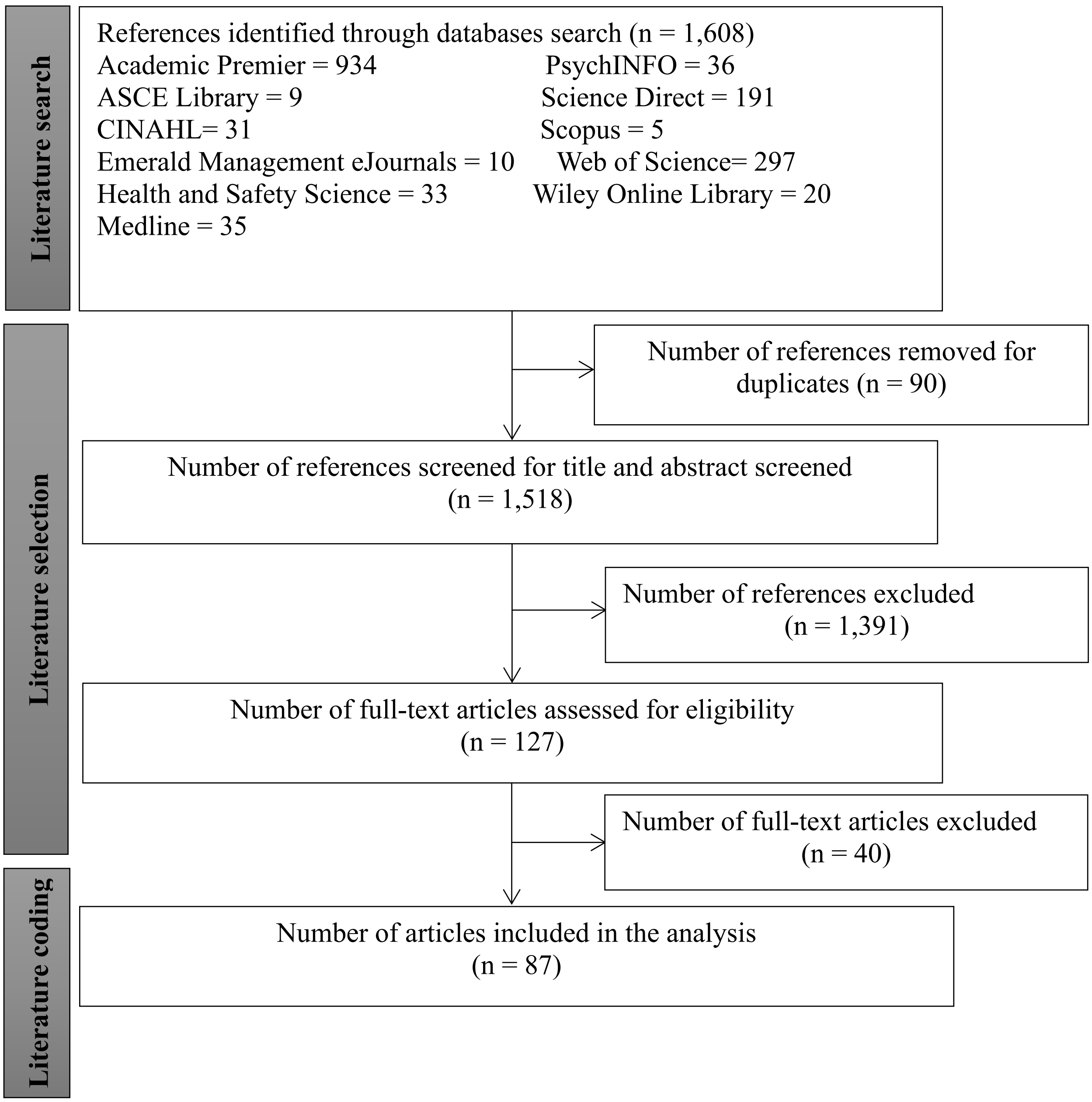

Figure 1. Flowchart depicting a three-step method to identify relevant included articles

Step 2: Literature selection

A total of 1,518 articles were identified after removing the duplicates. A two-stage screening process was then conducted. At the first stage, titles and abstract were screened by two independent authors (MA and TO). Citations related to book reviews, company directory, editorials, editor's notes, generics, letters to editors, news items, and patents were excluded. Any disagreements between the two reviewers were resolved by consensus among all authors. For instance, articles that just mentioned some keywords in their titles or abstracts, but irrelevant to the research topic were excluded by consensus. Potential citations were then retrieved for full-text screening. The number of included full-text articles was 127. The second stage screening involved the selection of relevant full-text articles that met the following inclusion criteria:

1. The article was empirical with a substantive focus on sensing and warning-based technology for OHS.
2. The contents involved construction related resources (i.e., personnel/worker, equipment, and material), construction-related OHS (e.g., building, tunnel, bridge etc.), and different types of OHS fatalities, unsafe behaviors, and injuries (e.g., crane collapse, cracks, scaffold collapse, slips, trips, falls, WMSDs etc.). For example, Zhou and Ding (2017) established a hazard energy monitoring system and the use of Internet-of-Things (IoTs) technologies to provide safety barrier strategies and scenarios for avoiding unsafe behaviors and unsafe status of construction equipment and workers' environment on underground construction sites such as Yangtze River-crossing Metro Tunnel.
3. The article was published in a refereed journal.
4. The article was published between January 1996 to December 2017 (years inclusive).
5. The article was written in English.
6. The article was available online.
7. The article focused on using sensing and warning-based technology for OHS applications as well as other applications for construction management research. For example, based on case-

based reasoning, Liu *et al.* (2013) provided solutions to three key issues such as index selection, accident cause association analysis, and warning degree forecast implementation, through the use of association rule mining, support vector machine classifiers, and variable fuzzy qualitative and quantitative change criterion modes, which also penetrate the whole process of safety management.

A total number of 87 articles met the selection criteria and were included for analyses. A full list of the 87 articles is presented in a reference database.

Step 3: Literature coding

In this review, title, keywords, and abstract were the main sources for coding an article. Moreover, the full-text article reading was used for further coding and data extraction. The literature coding was mainly focused on the sections of research method and conclusions. In order to provide data analysis to discuss the aforementioned research questions, each of the included articles was coded. In the process of coding an article, the following key data were extracted from each article and formatted in our database (see an example in Table 1):

1. Title of the article
2. Researcher/Author name
3. Research institution of each author
4. Country or origin of where the study was conducted
5. Publication year
6. Published journal
7. Type of sensing and warning-based technology adopted
8. Key research topic or application area

Following the literature coding and data extraction from the included studies (i.e., 87 articles), data analysis was carried out to summarize and discuss the applications of different types of sensing and warning-based technology in improving OHS in the construction industry. Further, various research gaps and future research direction were discussed. To identify the annual publication trend and the relative contributions of various journals of the included articles, the publication year and names of journals were analyzed, respectively.

Table 1. An example of article literature coding in a reference database

Item	Title of the article	Researcher/ Author name	Research institution	Country or origin	Public ation year	Journal publication	Type of sensing and warning-based technology	Key research topic or application area
1.	Range Imaging as Emerging Optical Three-Dimension Measurement Technology	Jochen Teizer Timo Kahlmann	Georgia Institute of Technology Swiss Federal Institute of Technology	USA Switzerland	2007	Transportation Research Record: Journal of the Transportation Research Board	Remote-Sensing techniques (3D video range imaging camera)	Construction site safety management and monitoring

Note: The order of researcher/author names, research institutions and countries were maintained according to each article. A complete list of included studies (i.e., 87) is available upon request from the corresponding for our interested readers.

Results and discussion

Annual publication trend on sensing and warning-based technology articles

Figure 2 presents the annual publication trend of the included articles on sensing and warning-based technology during the studied period. There was no published article on sensing and warning-based technology between 1996 and 2006 (Figure 2). The first 2 relevant articles were published in 2007 (Figure 2). Since then the numbers of relevant articles published annually increased from 2 articles in 2008 to 9 articles in 2013. Following the decline in research outputs to 6 articles in both 2014 and 2015, 23 relevant articles were published in 2016 (Figure 2). Similarly, 24 articles were published in 2017 (i.e., peak year) (Figure 2). The current review revealed that sensing and warning-based technology did not play a significant role in OHS until 2007. The exponential increases in number of relevant articles showed that researchers and practitioners had recognized sensing and warning-based technologies as effective measures to provide potential OHS interventions in the construction industry in recent years.

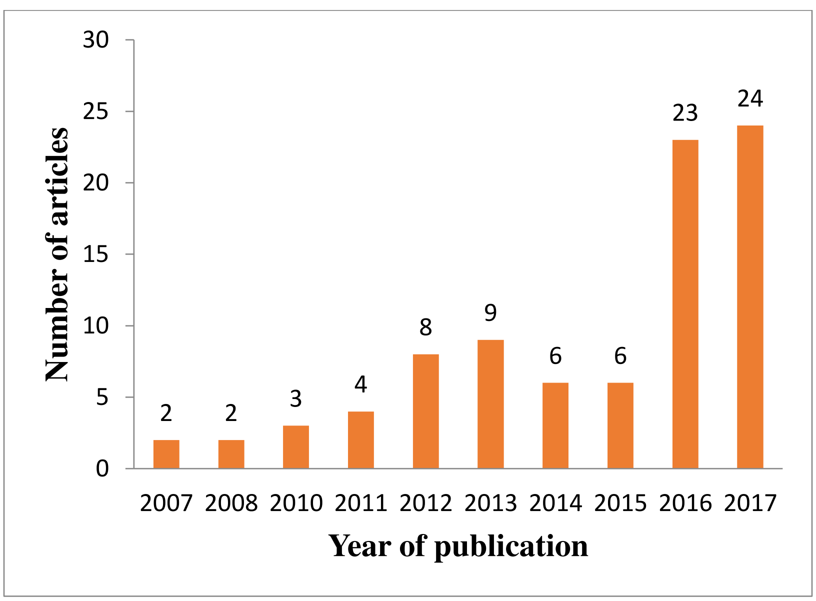

Figure 2. Annual trend of sensing and warning-based technology research articles from 1996 to 2017 (years inclusive)

Contribution of journal publications

Table 2 presents the contribution of journal publications with the corresponding number of relevant articles during the studied period. In this review article, a total of 34 peer-reviewed journal publications were included for the analysis during 1996 to 2017 (years inclusive) (Table 2). A majority of the journals only published a single article, representing 27.6% of all included studies (Table 2). Each of the 3 journals, namely: *Structural Control and Health Monitoring, Journal of Civil Engineering and Management*, and *Construction Innovation: Information, Process, Management* had published 2 relevant articles during the studied period (Table 2). In addition, a total of 3 relevant articles were published in either *Transportation Research Record: Journal of the Transportation Research Board* or *Applied Ergonomics* during the studied period (Table 2). Four relevant articles were found in *Advanced Engineering Informatics* (Table 2). Whilst 5 relevant articles were published in either *Safety Science* or *Journal of Construction Engineering and Management*, a total of 7 relevant articles were found published in *Journal of Computing in Civil Engineering*, representing 8% of all included articles (Table 2). Ultimately, there were 30 relevant articles published in *Automation in Construction*, representing 34% of all articles (Table 2). The finding of this result indicates the significant contribution of *Automation in Construction* in the domain of applying sensing and warning-based technology to improve OHS in the construction industry.

Table 2. Names of journal publication with the corresponding number of relevant articles during 1996 to 2017 (years inclusive).

Item	Journal publication	Number of articles
1.	Automation in Construction	30
2.	Journal of Computing in Civil Engineering	7
3.	Journal of Construction Engineering and Management	5
4.	Safety Science	5
5.	Advanced Engineering Informatics	4
6.	Applied Ergonomics	3
7.	Transportation Research Record: Journal of the Transportation Research Board	3
8.	Construction Innovation: Information, Process, Management	2
9.	Journal of Civil Engineering and Management	2
10.	Structural Control and Health Monitoring	2
11.	Annals of Work Exposures and Health	1
12.	Applied Mechanics and Materials	1
13.	BMC Musculoskeletal Disorders	1
14.	Computer-Aided Civil and Infrastructure Engineering	1
15.	Computer Vision and Image Understanding	1
16.	Engineering Geology	1
17.	Future Generation Computer Systems	1
18.	Information Fusion	1
19.	Instrumentation Science & Technology	1
20.	International Journal of Building Pathology and Adaption	1
21.	Journal of Architectural Engineering	1
22.	Journal of Information Technology in Construction	1
23.	Journal of Occupational and Environmental Hygiene	1
24.	Journal of Rehabilitation Research and Development	1
25.	Mechanical Systems and Signal Processing	1
26.	Optik-International Journal for Light and Electron Optics	1
27.	Practice Periodical on Structural Design and Construction	1
28.	Professional Safety	1
29.	Shock and Vibration	1
30.	Smart Structures and Systems	1
31.	Sustainability	1
32.	The Computer Journal	1
33.	The Egyptian Journal of Remote Sensing and Space Sciences	1
34.	The Scientific World Journal	1
	Total	**87**

Current trend of different types of sensing and warning-based technology

Table 3 presents the different types of sensing and warning-based technologies covered for OHS in the included studies. As shown in Table 3, there are 10 different types of sensing and warning-based technologies. It should be noted that about 11 articles integrated different types of sensing and warning-based technology. As such, the corresponding total number of articles of the different types sensing and warning-based technologies was more than the total number of included articles. It was revealed that direct measurement sensors such as sEMG, force sensors, IMUs, and physiological status monitors (PSMs) were mostly applied in 44 included articles (Table 3). Other included sensing and warning-based technologies were remote-sensing techniques (14 articles), real-time location system (RTLS) based radio-frequency identification (RFID) (12 articles), global positioning system/geographical information systems (GPS/GIS) (6 articles), and RTLS based on ultra-wide band (UWB) (6 articles) (Table 3). The application of the other sensing and warning-based technologies was below 6 articles during the studied period (Table 3). Generally, sensing and warning-based technology applications are constantly changing with the development and integration of new sensors to improve OHS in the construction industry.

Table 3. Types of sensing and warning-based technologies covered by the included articles

Item	Sensing and warning-based technology	Number of articles
1.	Direct measurement sensors	44
2.	Remote-Sensing techniques	14
3.	RTLS based on Radio Frequency Identification (RFID)	12
4.	Global positioning system/Geographical information systems (GPS/GIS)	6
5.	RTLS based on Ultra-wide Band (UWB)	6
6.	Fiber Optic Sensors (FOSs)	5
7.	RTLS based on Bluetooth Sensing Technology	4
8.	Wireless Sensor Networks/Wireless local Area Network/ Internet of things (WSN/WLAN/IoT)	4
9.	Behavior-Based Safety (BBS) with Proactive Construction Management Systems (PCMS)	2
10.	Safety Early Warnings based on Case-Based Reasoning and Variable Fuzzy Sets	1

Note: RTLS = Real-time location system

Figure 3 provides the trends of different types of sensing and warning-based technology applications of the included studies during the studied period. In order to depict the trend more clearly and comprehensively, the time span from 1996 to 2017 (years inclusive) was divided into 3 periods. Since no published articles were found in the first decade (i.e., 1996 to 2006), the included studies started from the second decade (i.e., 2007 to 2017). Each division contains 4 years except the last period, which spans from 2015 to 2017 (years inclusive).

From Figure 3, sensing and warning-based technology applications were distributed as discrete and individualized (i.e., using only one type of sensing and warning-based technology), because there were not many different types of sensing and warning-based technology used to improve OHS during 2007 to 2010 (years inclusive). Some of the individualized studies on the types of sensing and warning-based technologies used within these periods were: direct measurement sensor (Wang and Yim, 2010); RFID technology (Domdouzis *et al.,* 2007; Ko, 2010; Teizer *et al.,* 2010); remote-sensing techniques (Teizer and Kahlmann, 2007); UWB (Teizer *et al.,* 2008). Only a single study (Behzadan *et al.,* 2008) integrated two different types of sensing and warning-based technology (wireless local area network (WLAN) and GPS) during 2007 to 2010 (years inclusive).

During the period from 2011 to 2014 (years inclusive) (Figure 3), the trend of applying sensing and warning-based technology had gradually become more complicated. Despite the fact that some studies only applied a single type of sensing and warning-based technology, other included studies were more diversified and integrated sensing and warning-based technologies for OHS in the construction industry, particularly in the year 2013. The number of included articles that applied a single type of sensing and warning-based technology during 2011 to 2014 (years inclusive) was: direct measurement sensors (11 articles); RFID (4 articles); remote-sensing techniques (3 articles); UWB (4 articles); FOSs (1 article); and case-based reasoning and variable fuzzy sets (1 article). Conversely, the majority of the included articles integrated two or more sensing and warning-based technologies during this same period. For instance, the integration of RFID and micro-electromechanical sensors and systems (MEMS) based temperature and humidity sensors from a laboratory study as well as a small-scale field study (Ceylan *et al.,* 2013). The integration of FOSs and RFID based labor tracking system was used to prevent accidents and to improve safety management in underground construction (Ding *et al.,* 2013). Taken together, publications during this period focused on the integration of different types of sensing and warning-based technology to complement each other in improving OHS in the construction industry.

Interestingly, during the period from 2015 to 2017 (years inclusive), the trend of integrating different types of sensing and warning-based technologies to improve OHS increased (Figure 3). The number of articles that integrated two or more different types of sensing and warning-based technologies during this period were: direct measurement sensors and remote-sensing techniques (2 articles), direct measurement sensors and GPS (3 articles), RFID and remote-sensing techniques (1 article), and RFID and IoTs (1 article). On the other hand, many included studies only investigated the use of a single sensing and warning-based technology. These include: direct measurement techniques (25 articles); remote-sensing techniques (7 articles); RTLS based on Bluetooth sensing technology (4 articles); FOSs (3 articles); BBS with PCMS (2 articles); GPS/GIS (2 articles); WSN, WLAN, IoTs (2 articles); and RFID (1 article). One potential explanation for this massive increase was that more attention has been given to the use of sensing and warning based technologies as essential tools and pragmatic methods to improve OHS in recent years.

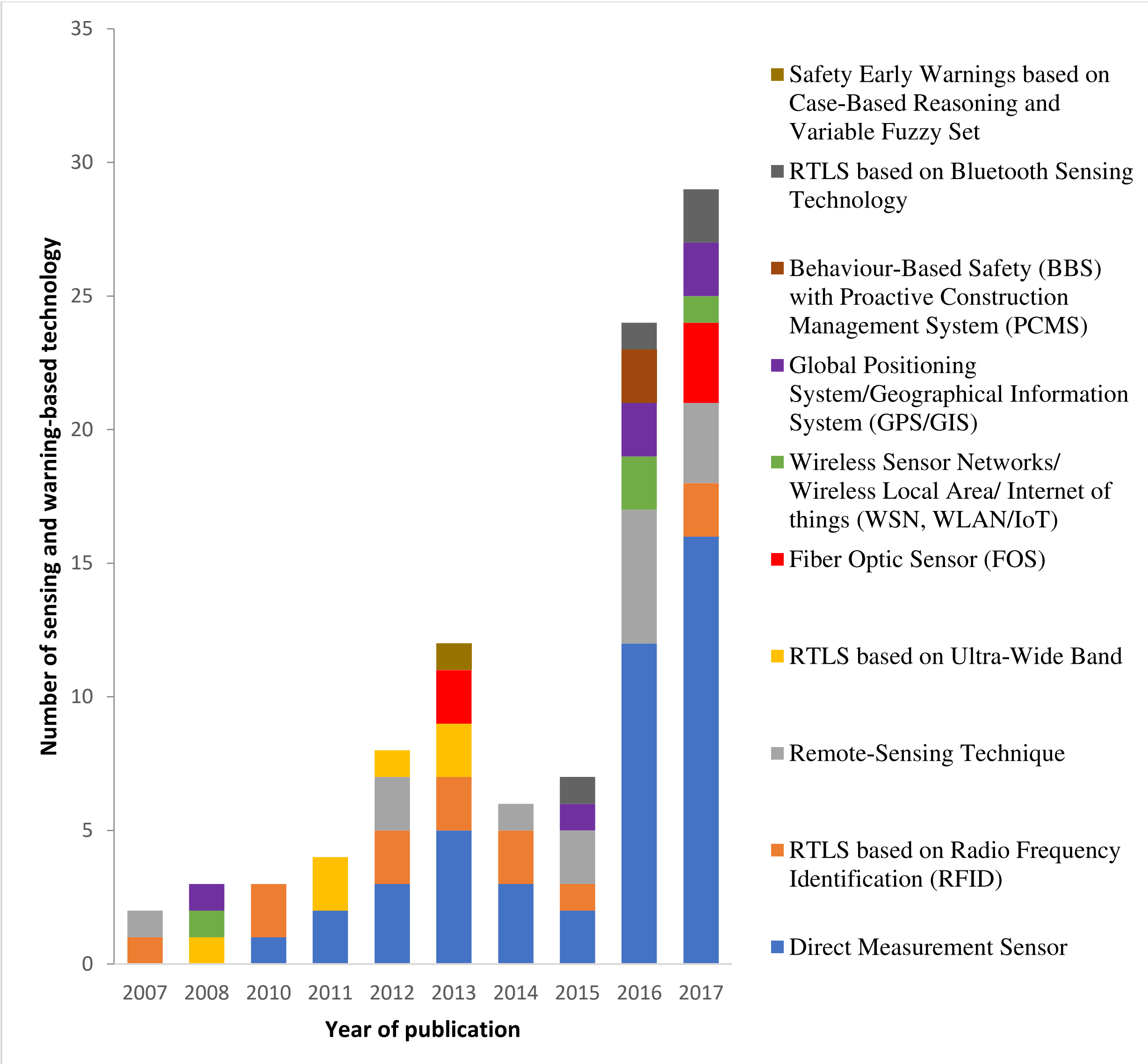

Figure 3. Current trend of sensing and warning-based technology applications

Key and specific OHS research topics covered

In this review article, each included article was categorized according to the main research topic, although some articles may contain more than one research topic. Table 4 summarizes the key research topics covered by sensing and warning-based technology applications for OHS during the studied period. Our results found six main research topics (Table 4). As depicted in Table 4, the first research topic covered was construction site safety management and monitoring. This key research topic had a total number of 21 articles, representing 24.1% of included articles during the studied period (Table 4). The second and third relevant research topics covered were safety risk identification and assessment (18 articles) and intrusion warnings and proximity detection (16 articles), respectively (Table 4). The awareness percentage of the first three research topics was 63.2% of included articles during the studied period. The remaining three research topics covered had not more than 15 included articles in each area (Table 4).

Table 4. Key and specific occupational health and safety (OHS) research topics covered

Item	Research topic	Number of articles	Percentage of articles
1.	Construction site safety management and monitoring	21	24.1%
2.	Safety risk identification and assessment	18	20.7%
3.	Intrusion warnings and proximity detection	16	18.4%
4.	Physiological status monitoring	14	16.1%
5.	Activity recognition and classification accuracy	9	10.3%
6.	Structural health monitoring	9	10.3%
	Total	**87**	**100%**

Construction site safety management and monitoring

In the research application of construction site safety management and monitoring, different types of sensing and warning-based technology such as RTLS based on RFID, UWB, GPS/GIS, Bluetooth technology, and WLAN were mostly prominent. Unlike intrusion warnings and proximity detection, the focus of the included studies related to construction site safety management and monitoring applications was only based on using sensing and warning-based technologies such as RTLS tracking technologies to identify the location and tracking of resources (e.g., worker, material and equipment) for safety management and monitoring during the planning, designing, and execution phases of a construction project. By using an UWB technology, Cheng *et al.* (2011) showed that real-time location tracking has potential construction applications in assisting the safety management of job sites and other areas requiring monitoring and control. In particular, safety and efficient site resource allocation would be of help to any site manager in charge of planning and control work activities (Cheng *et al.,* 2012). Several sub-topics applications of GPS/GIS technology were applied (1) to improve the management level and safety quality in different project phases; (2) in the studies of urban rail transit safety management and information integration; (3) to shield construction schedule information; (4) for construction safety risk information; (5) for construction site video information (Bai *et al.,* 2015). Taken together, the included articles of construction site safety management and monitoring showed that real-time location tracking has potential construction applications in assisting the safety management of job sites and other areas requiring monitoring and control.

Safety risk identification and assessment

In the current review article, sensing and warning-based technology applications were predominantly covered in areas of safety risk identification and assessment. Even though the included articles which focused on safety risk identification and assessment used similar types of sensing and warning-based technology, their research provided evidence-based prevention of WMSDs and fall injuries about the level of physical exposure of the human body (e.g., back, shoulders) during specific work tasks in the construction (Seo *et al.*, 2015; Jebelli *et al.*, 2016; Antwi-Afari *et al.,* 2017a; 2017b). Other included articles also suggested potential information on how to implement participatory interventions aiming at reducing excessive physical workload (Brandt *et al*., 2015; Umer *et al.,* 2017b). Jebelli *et al.* (2016) demonstrated the feasibility of utilizing IMU sensor data for workers' posture and motion analysis to provide insights into understanding and characterizing the levels of fall risks of construction workers. Umer *et al.* (2017b) developed a simple ergonomic solution by attaching a low height domestic stool to the pants of rebar workers, which has a great potential in reducing WMSDs among Asian rebar workers. Ultimately, the included articles covered for safety risk identification and assessment provided the real-time monitoring of for workers' posture and motion analysis during construction tasks to enhance the understanding of the gap between physical work demands and workers' capability, and offer a firm foundation for the improvement of workers' safety and health in construction.

Intrusion warnings and proximity detection

Another relevant category of research topic covered from the application of using sensing and warning-based technology for OHS was intrusion warnings and proximity detection. In this category, the identified sensing and warning-based technologies were capable of detecting and providing warning alerts to construction workers, equipment operators, and pedestrians in real-time during hazardous proximity situations. For instance, Yi *et al.* (2016) developed a GSM based on environmental sensors to warn site workers in a hot and humid environment. The early-warning system involves: (1) collecting timely information and undertaking risk assessments of heat stress; (2) generating an accurate and timely warning to trigger prompt health and safety intervention; and (3) disseminating heat strain assessments and symptoms of heat illness to site supervisor/foreman. These authors also reported that the GSM system has other functions to support risk analysis, warning sign, and response capability. Heng *et al.* (2016) developed a BBS with PCMS for intrusion warning and assessment method in reducing incidents, enhancing site safety, and improving personal behavior. Although their study was exploratory on safety behavior in construction works, the reported research could inspire further research in safety behavior studies at petroleum, manufacturing, traffic management, and nuclear power industries. Based on IoTs technologies such as meter-level of RFID-based location and tracking technology, centimeter-level of ultrasonic detection technology, and infrared access technology, Zhou and Ding (2017) established a hazard energy monitoring system to provide safety barrier strategies and scenarios for avoiding unsafe behaviors and unsafe status of construction equipment and workers' environment on underground construction sites such as Yangtze River-crossing Metro Tunnel. Overall, the included articles covered for intrusion warnings and proximity detection in hazardous zones may not only provide supervisory staff and safety professionals with a surveillance method to safeguard the health and safety of frontline workers when working on construction sites but can also indirectly lower investment costs by guiding safety input benefit maximization.

Physiological status monitoring

The fourth research topic covered on OHS based on sensing and warning-based technology applications was physiological status monitoring. In this research application category, the included studies mostly used innovative direct measurement sensors called PSMs that can simultaneously monitor heart rate, breathing rate and other physiological parameters. Yan *et al.* (2013) developed an equivital life monitor (EQ02) which was a multi-parameter body-worn system capable of logging and transmitting physiological data describing a wearer's cardiorespiratory and thermal status. Another study combined UWB technology with PSM to automatically identify and localize the ergonomic related unsafe working behaviors (Cheng *et al.,* 2013). This study reported a new approach for automating remote monitoring of construction workers safety performance by fusing data on their location and physical strain. Zhao *et al.* (2017) developed a cooling vest to alleviate physiological and perceptual strain in hot and humid environment during two experimental conditions (i.e., cooling vest vs. no cooling vest). Their results indicated that the designed cooling vest can significantly alleviate heat strain and improve thermal comfort, based on the decrease in body temperature, heart rate, and subjective perceptions of the participants. Overall, the included studies covered for physiological status monitoring demonstrated that PSMs can have a positive impact on workers' safety, productivity, and long-term well-being.

Activity recognition and classification accuracy

The fifth key research topics covered on the application of sensing and warning-based technology for OHS was activity recognition and classification accuracy. Generally, this category of research application mostly used direct measurement sensors such as IMUs (Joshua and Varghese, 2013; Akhavian and Behzadan, 2016; Lim *et al.*, 2016) and remote-sensing techniques such as Kinect (Khosrowpour *et al.,* 2014; Ho *et al.,* 2016) to provide insight into the accuracy of recognizing construction workers' activities by analyzing collected data using different machine learning algorithms (e.g., decision tree, artificial neural networks (ANN), support vector machine, etc.). Lim *et al.* (2016) demonstrated the feasibility of using triaxial accelerometer embedded in a smartphone for ANN-based near-miss classifiers to detect the type of near-miss event (slip or trip) and identification of the worker involved in real time. They concluded that information on a worker's motion was reliable and could be used for corrective and injury preventive measures. Alternatively, Ho *et al.* (2016) used Kinect data-driven framework to classify workers postures and differentiate between correctly and incorrectly performed the movement in the same context.

By integrating R-GBD camera with IMUs sensors, Chen *et al.* (2017) proposed an efficient motion tensor decomposition approach to compress and reorganize two sample activities composed of sequential awkward postures in construction activities. The results revealed that the proposed approach is able to provide sufficient recognition accuracy with less computation power and memory. Ultimately, sensing and warning-based technology applications for activity recognition and classification accuracy help to measure and control safety, productivity, and quality in construction sites.

Structural health monitoring (SHM)

The final key research application area of OHS based on sensing and warning-based technology applications was SHM. SHM is an all-inclusive comprehensive process of monitoring the various types of damages and problems in different fields and areas of engineering (Afzal *et al.,* 2012). Concrete structures are one of the most important filed in civil engineering and currently being widely used application in construction works. Generally, SHM as an application area of OHS is important to observe, monitor, and evaluate the conditions of mainly concrete structures (e.g., bridge, road highways, dams) in real-time to avoid any kind of occupational accidents (e.g., construction, mining) and tasks that may lead to structural failure (e.g., extension of existing bridges or buildings) (Wang and Yim, 2010; Ceylan *et al.*, 2013; Acikgoz *et al.,* 2017; Song *et al.,* 2017). For example, FOSs in SHM of concrete structures are used to detect deflections in the embankment dams, and to detect cracks in roller-compacted concrete dams (Afzal *et al.,* 2012). Song *et al.* (2017) integrated FOSs such as Raman optical time-domain reflectometry (ROTDR), Brillouin optical time-domain analysis (BOTDA) and fiber Bragg grating (FBG) to monitor the temperature and the stress/stain variations of a reinforced concrete pound lock structure during the construction process. The findings indicated that the proposed approach have a great potential in performance monitoring of hydraulic structures.

Research gaps and future studies

In this review article, different types of sensing and warning-based technologies were applied for OHS in the construction industry. This section highlights four main research gaps that are worth for directions in future studies.

Application of sensing and warning-based technologies in the total life cycle of a construction project

The applications of sensing and warning-based technologies need to cover pre-construction, construction, and post-construction phases of a construction project. Until recently, the use of FOSs for SHM mostly focused on the post-construction phase (i.e., operation and maintenance phases) to monitor concrete structures in order to prevent cracks and collapse of existing structures. However, many fatalities during the construction phase were due to falls from height of temporary structures such as scaffolds, ladders, hoists and tower cranes. According to the Bureau of Labor Statistics (BLS) in the USA, fatal injuries caused by falls from heights remain to be the leading cause of fatalities on construction sites (Bureau of Labor Statistics, 2016b). Future studies should investigate the effectiveness of using FOSs and other sensing and warning-based technologies to detect failure of temporary structures during the construction phase. Further, future research is warranted to develop a decision support tool to assist practitioners to incorporate construction risks monitoring and site safety management during the pre-construction phase. In short, more attention should be paid to the total life cycle of construction projects so that researchers and industry practitioners can explore the collective use of the identified sensing and warning-based technologies to optimize productivity and safety.

Hardware and software design of sensing and warning-based technologies

The size, weight, and data processing and transmission are examples of important attributes that need to be considered when designing sensing and warning-based technologies. The size and weight of sensing and warning-based technologies, particularly for direct measurement sensors, can cause workers' discomfort and interference of monitored activities due to the attached sensors on skin (Antwi-Afari *et al*., 2018a). In order to achieve non-invasive and unobtrusive monitoring of workers' activities on site, future research should develop small and lightweight wireless sensors. Such new sensors may improve workers' acceptance of using wearable sensing technologies. However, it is noteworthy that data transmission procedures of direct measurement sensors are often influenced by motion artefacts (i.e., noise), which affect measurement accuracy. Also, depending on the type of sensing and warning-based technologies, the collected data may need to be processed in multiple stages, which may delay the time to alert workers regarding hazardous zones, to detect unsafe behaviors or to identify specific hazard on construction sites. Future studies should also develop sensing and warning-based technologies that are less sensitive to motion artefacts and provide non-localized processing of output data.

Application of sensing and warning-based technologies from research to practice

In this review article, the research topics or the application areas of the identified sensing and warning-based technologies were mostly limited to academic research of simulated activities in a laboratory setting. Moreover, most of the laboratory experiments were conducted by novice volunteers. As a result, the identified sensing and warning-based technologies and the proposed methods have not been validated in real construction environments. Researchers and practitioners should focus more on sensing and warning-based technologies transition from construction safety research to construction safety practice (i.e., using real construction workers on sites). In addition, a robust cost-benefit analysis and validation of the identified sensing and warning-based technologies will be significant to both researcher and construction practitioners. Future research should give more attention to address these areas, in order to provide a holistic view.

Integration of sensing and warning-based technologies and other advanced information technologies

In this review article, different types of sensing and warning-based technologies used in OHS of the construction industry is listed in Table 3. As such, there is a great potential for future research to evaluate the strengths and weaknesses of each sensing and warning-based technology in order to integrate different types of sensing and warning-based technologies for multi-sensor platforms and multi-parameter monitoring. For instance, remote-sensing techniques would complement the limited number of attachable tracking devices by providing clear site and object information regarding the size of heavy equipment and the boundary information of dangerous areas. Also, the integration of GPS and UWB tracking technologies and remote-sensing techniques could address the research gap on the performance of object identification and tracking with more accurate 3D spatial information. While the focus of this review article was on sensing and warning-based technologies, other advanced information technologies can be incorporated in future. Future research studies could integrate sensing and warning-based technologies with visualization and other information technologies such as 4D CAD, VR, and BIM to: (1) automatically identify and recognize potential safety hazards on construction sites; (2) collect and analyze the trajectories of workers with respect to potential hazards; and (3) enable safety managers or construction managers to continuously monitor construction resources against identified potential hazards in order to mitigate site accidents.

Like other reviews, the current review has some limitations. Firstly, although a comprehensive search strategy was used in the current review, some relevant studies may have been missed. As such, future review studies should consider adding conference proceedings and special issues articles to broaden the scope of the study. Secondly, while there are other advanced information technologies and digital design for OHS in the construction industry, the present review only focused on articles related to sensing and warning-based technologies for improving OHS published from 1996 to 2017 (years inclusive). Future reviews may consider more recent articles on sensing and warning-based technology for improving OHS and digital designs in order to provide updated overview in the construction industry.

Conclusions

The current review has summarized the trends in the applications of sensing and warning-based technology for OHS in the construction industry from 1996 to 2017 (years inclusive). A three-step approach was used to identify relevant articles for data analysis and discussion. Our findings indicated an increasing annual publication trend on sensing and warning-based technology for the construction industry in the recent years. While most of the included articles (34.5%) were published in *Automation in Construction*, other journals have started to publish papers relevant to this topic. Of 10 different types of major sensing and warning-based technologies, direct measurement sensors were most commonly used for the investigation of OHS in the construction industry. Other commonly investigated technologies include remote-sensing techniques and RTLS based on RFID technologies. These sensing and warning-based technology applications can closely complement each other to improve OHS, particularly with sensing networks of on-site safety management. This review also identify six key research topics in the applications of sensing and warning-based technology for OHS in the construction industry: construction site safety management and monitoring; safety risk identification and assessment; intrusion warnings and proximity detection; physiological status monitoring; activity recognition and classification accuracy; and structural health monitoring. Finally, four major research gaps and future directions were identified and discussed including: (1) application of sensing and warning-based technologies in the total life cycle of a construction project; (2) hardware and software design of sensing and warning-based technologies; (3) application of sensing and warning-based technologies from research to practice; and (4) integration of sensing and warning-based technologies and other advanced information technologies. Future researchers and practitioners can conduct more relevant studies and propose pragmatic interventions based on the identified research gaps, to improve the performance and applicability of sensing and warning-based technology for OHS in the construction industry.

Declarations of interest

None

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