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Applications of existing and emerging construction safety technologies

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ABSTRACT

Safety is one of the most important success factors in construction projects. Many advanced technologies, such as Artificial Intelligence, construction robotics, and digital technologies, have been increasingly implemented to support safety activities on construction sites and improve workers' health. The objective of this paper is to investigate applications of existing and emerging construction safety technologies across different construction safety areas. A systematic review methodology was conducted to analyze 129 journal articles published from 2018 to 2023 related to construction safety technologies. The results of this study include a detailed categorization of advanced technologies in four construction safety categories: prevention through design, safety management, safety culture and awareness, and computing in construction safety. Additionally, a checklist of recommended technologies for specific construction safety improvement areas was developed. This study contributes to the body of knowledge by systematically categorizing and specifying the commonly used advanced technologies to address various construction safety problems.

1. Introduction

Construction is a hazardous and physically demanding industry where workers' health and safety always require critical attention from both practitioners and academic researchers worldwide [1]. Construction activities are often performed in a clumsy environment containing numerous safety risks, such as falling, tripping, slipping, heavy lifting, and unhealthy working conditions [2]. Poor construction safety practices increase the risk of worksite injuries and fatalities, dramatically impacting the construction process and burdening the project owner with direct costs (e.g., medical expenses and transportation costs) and indirect costs (e.g., loss of productivity, injured worker compensation, and loss of reputation) [3]. Although a variety of safety regulations, guidelines, and protocols have been mandatorily executed on construction sites, the rates of injuries and fatalities of workers remain very high [4]. For example, according to a recent report from the Occupational Safety and Health Administration (OSHA), construction workers' fatalities represent nearly half of all fatal occupational injuries in the States [5]. Falling from heights, tripping hazards, unguarded machinery and moving machinery parts, and electrical hazards have been cited as the common causes of injuries and fatalities in construction [6,7]. There is a need to implement robust safety risk prevention and to utilize advanced technologies to improve construction workers' health and safety.

Various technologies, such as Artificial Intelligence, unmanned aerial vehicles (UAVs) or drones, and 3D modeling (e.g., Building Information Modeling – BIM), have been implemented in the construction industry to improve workers' health and safety [8–13]. These technologies have been used in various construction safety domains to provide a lasting solution for various problems related to construction workers' injuries and fatalities [14–17]. Due to their ability to provide real-time responses and monitoring of safety, advanced technologies have been increasingly used to improve construction safety management. For example, Zhang et al. [18] explored the potential feasibility of integrating smartphones and artificial neural networks (ANN) to detect and measure near-miss falls to enhance safety monitoring in construction. The fall detection was performed based on data acquired by triaxial accelerometers embedded in a smartphone carried by the worker, measuring the variation in the energy released by the worker due to posture adjustment during balance loss and recovery. Emerging construction safety technologies, such as wearable sensors, construction robotics (e.g., exoskeletons), augmented reality (A.R.) and virtual reality

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(V.R.), and Internet-of-Things (IoT), have also been implemented together to enhance the capability of providing a lasting solution for various safety-related problems on the construction site [19–24]. For instance, Park et al. [19] developed a new approach for proximity sensing using Bluetooth technology to track interactions between workers on foot and construction equipment occurring in roadway work zones. The Bluetooth-integrated system showed several advantages over the other commercially available proximity sensing systems, including reduced infrastructure requirements and lower overall implementation cost, good signal continuity, and wide coverage. Park et al. [20] developed a system using live streaming and time-lapse videos to detect workers' correct use of personal protective equipment (PPE), making it easier for on-site safety officers to do their jobs. A computer vision technique was developed to automate the oversight of correct hardhat use on construction sites.

The current literature shows an increasingly adopted rate of advanced technologies in the construction safety area, creating a foundation for developing proactive strategies to reduce accidents, injuries, and fatalities on the construction job sites and promote the continuous improvement of workers' health and safety [8,21]. The growing adaptation of various technologies, such as sensing technologies, digital technologies, immersive technologies, and Artificial Intelligence, to the construction safety domain, has initiated the need of systematically investigating and deepening the understanding of the mechanisms and applicability of these technologies [1]. Most literature review studies on the topic of construction safety technologies have concentrated on one or two specific types of commonly used technologies in the industry. For instance, Dobrucali et al. [3] focused on providing key applications of digital technologies to support construction safety management practices. Hou et al. [13] specifically explored the use of virtual and visualization technologies to develop extensive safety management plans in the planning and design processes. Akinosho et al. [9] concentrated on introducing the use of advanced Artificial Intelligence algorithms to address monitoring and predicting problems in construction site safety. However, the wide range of adaptation and implementation of multiple types of advanced technologies across different safety categories in the construction industry have generated challenges in the selection of appropriate construction safety technologies. A research gap exists regarding a thorough investigation and categorization of various existing and emerging technologies that have been used for construction safety improvements, especially through different safety phases of a construction project. By deepening the understanding of how advanced technologies are categorized for specific safety application areas, practitioners can utilize appropriate technologies to improve construction safety, and academic researchers can conduct further investigations to improve the applicability of advanced safety technologies in the construction industry.

The objective of this paper is to systematically investigate the existing and emerging applications of safety technologies in the construction industry across different safety categories, including prevention through design, safety management, safety culture and awareness, and computing in construction safety. In addition, this study focused on state-of-the-art applications, including Artificial Intelligence, construction means and robotics, sensing technologies, and digital technologies, to support construction safety improvements and future research directions. The findings of this study are expected to benefit academic researchers and industry practitioners in terms of categorizing construction safety technologies and selecting appropriate advanced applications for specific safety purposes. The structure of this paper is as follows: (1) Background contains a brief summary of previous studies investigating existing and emerging technologies in the construction safety area; (2) Systematic Literature Review Methodology describes the research methods of this study; (3) Results show key findings of this study in terms of categorization of construction safety technologies; and (4) Discussion provides a list of recommended technologies for specific construction safety improvement areas.

2. Literature review

The current literature shows a variety of studies that explore and analyze the use of advanced technologies, such as Artificial Intelligence [3,10,22,25–33], automation and robotics [4,14,34–42], sensing technologies [1,6,17,43–50], and digital technologies [51–57], in construction safety, focusing on minimizing safety risks on the job sites and improving safety behaviors of construction workers [58–60]. Table 1 provides a summary of previous literature review studies on the applications of advanced technologies in the construction safety domain.

Dobrucali et al. [3] provided a comprehensive search and review of 209 papers regarding digital technologies used for construction health and safety published from 1986 to 2021. Similarly, Guo et al. [28] studied 153 published articles from 1997 to 2019 with a concentration on computer vision technologies for construction safety management. Zhang et al. [32] also focused on the use of vision-based applications to monitor construction workers' health and safety. Hou et al. [13] reviewed 89 publications on Digital Twins in construction safety from 2010 to 2020, discussing the use of virtual construction simulation and

Table 1
Previous literature reviews regarding advanced technologies in construction safety.

Reference	Journal	Paper Title	Review Periods	Number of Reviewed Papers
Dobrucali et al. [3]	*Engineering, Construction and Architectural Management*	A bibliometric analysis of digital technologies use in construction health and safety	1986–2021	209
Hou et al. [13]	*Applied Sciences*	Literature review of Digital Twins applications in construction workforce safety	2010–2020	89
Akinosho et al. [9]	*Journal of Building Engineering*	Deep learning in the construction industry: A review of present status and future innovations	2012–2020	45
Akinlolu et al. [1]	*International Journal of Construction Management*	A bibliometric review of the status and emerging research trends in construction safety management technologies	2009–2019	240
Ahn et al. [8]	*Journal of Construction Engineering and Management*	Wearable sensing technology applications in construction safety and health.	2000–2019	77
Guo et al. [28]	*Safety Science*	Computer vision technologies for safety science and management in construction: A critical review and future research directions	1997–2019	153
Zhang et al. [32]	*Safety Science*	A critical review of vision-based occupational health and safety monitoring of construction site workers	2000–2019	117

visualization technologies and sensing technology in constructions safety. Concentrating more on wearable sensors, Ahn et al. [8] explored the practices in implementing wearable sensors, such as kinematic-measurement, cardiac activity–measurement, skin response–measurement, muscle engagement–measurement, eye movement–measurement, and brain activity–measurement sensors, in construction safety. One of their reviewed paper, Hwang et al. [61], investigated the feasibility of measuring workers' emotions in the field based on two dimensions of emotions (e.g., valence and arousal levels) using a wearable Electroencephalography (EEG) sensor. Their findings show that it is possible to evaluate workers' emotions with a wearable EEG sensor, especially valence levels, which are still essential for comprehending workers' emotional states. For example, the findings demonstrated that unsafe conditions for workers (such as being on a ladder or in a small area) and physically challenging working conditions (such as working two hours straight without rest) are likely to lead to employees experiencing negative emotions such as fear, annoyance, and depression. Aiming to Artificial Intelligence applications in construction safety, Akinosho et al. [9] investigated the use of deep learning techniques in construction safety problems by reviewing 45 research studies published from 2012 to 2020. As an example of Artificial Intelligence applications, Lim et al. [24] developed a technique used to calculate near misses encountered by workers using the triaxial acceleration sensors found in smartphones using an intelligent ANN-based slip-trip classification method to construct a systematic data processing mechanism to gather, categorize and evaluate data on a worker's mobility. Akinlolu et al. [1] conducted a bibliometric review of 240 published papers from 2009 to 2019, focusing on the emerging trends of using advanced technologies, such as visualization and image processing, digital technologies, IoT, and automation and robotic systems, in construction safety management. For example, Zhang et al. [59] developed an automated hazard inference process using construction scene graphs and a semantic approach where multiple construction scenes can be captured using cameras for safety regulations. Each construction scene graph consists of entities, attributes, and interactions. Using five scenes to validate the performance of their method, Zhang et al. [59] found that 97.82% accuracy of hazard identification can be derived using their approach. However, capturing proper construction scene graphs could be difficult due to the complex interaction between multiple entities and attributes.

The existing literature shows a large number of advanced technologies that have been widely used in the construction safety domain to prevent workers' injuries and fatalities as well as improve their health and safety behaviors. Different technologies, such as computer visions [26], sensing technologies [46], and automation and robotics [39], have been used during the construction process to accommodate the safety needs of construction job sites while other technologies, such as BIM [55], A.R/V.R. [62], and IoT [17], have been mainly implemented during the preconstruction phase. Comprehensive investigations and categorizations of existing and emerging safety technologies in the construction industry are needed to thoroughly exploit the capability and applicability of these existing and emerging means to improve construction safety management practices. This study aims to enlarge the existing construction safety literature with an integrated categorization of advanced technologies in construction safety and recommendations for selecting suitable technologies to improve safety practices in construction projects.

3. Systematic literature review methodology

This study included a systematic literature review methodology with content analysis for collecting, organizing, and analyzing articles published in high-quality journals presenting applications of existing and emerging safety technologies in the construction industry. This systematic literature review methodology utilizes the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach proposed by Moher et al. [63] to develop a comprehensive body of knowledge on the reviewed subject and follows guidelines suggested by Fellows et al. [64] to avoid biased selections of the relevant publications. The applied methodology includes four steps: (1) background, (2) systematic literature review methodology, (3) results, and (4) discussion, as shown in Fig. 1. First, the current state of practices in utilizing advanced safety technologies in the construction industry is presented in the background summary. Second, a comprehensive literature review was performed with three stages: identifying potential construction safety publications via electronic libraries and databases, screening the papers to exclude duplicates and unrelated papers, and including relevant papers for final review and analysis. Third, a content analysis was conducted to categorize the collected papers into applicable groups of safety technologies for construction projects. Finally, this study recommends the implementation of appropriate technologies for specific safety improvement areas in construction projects.

3.1. Selection of journals and papers

Construction safety technologies-related papers were searched in terms of title, abstract, keywords, and paper content. Table 2 shows the criteria for the inclusion and exclusion of safety technologies-related articles to produce a list of selected papers for the final review and content analysis. For inclusive papers, the criteria included (1) the relevant keywords, (2) high-quality journals in the construction safety community, (3) and regular publications in English from 2018 to 2023. Specifically, the title, abstract, and keyword categories of the selected papers had to have at least one of the following terms: construction safety, advanced technologies, safety monitoring, automation and robotics, Artificial Intelligence, computer visions, sensing technologies, wearable sensors, exoskeletons, UAVs and drones, 3-D printing, modular construction, digital technologies, BIM, V.R./A.R., and IoT. For exclusive papers, the threshold was determined regarding whether or not the papers are complete journal articles, mention construction safety technologies, and specify the implementation of existing and emerging technologies in construction safety.

The systematic literature review search was conducted using multiple online libraries and databases, including Science Direct, Elsevier, Emerald Insight, Wiley Online, SpringerLink, American Society of Civil Engineers (ASCE), IEEE Xplore, Google Scholar, and Taylor & Francis Group as shown in Table 3, to select highly ranked journals in the construction safety domain. The top three databases contributing to the final list of papers for subsequent analysis included Elsevier (n = 35), Science Direct (n = 34), and ASCE (n = 24). By utilizing multiple databases, the literature search can maximize the coverage of the selected publications related to various applications of safety technologies in the construction industry.

After excluding unrelated papers and duplicates, a list of 129 journal articles from 39 high-quality journals in the construction safety research community was compiled for the subsequent content analysis. Fig. 2 shows a list of 42 journals included in this study. The journals with the most selected articles in this study consist of Automation in Construction (34 papers), Safety Science (16 papers), Sensors (8 papers), Journal of Building Engineering (5 papers), ASCE Journal of Construction Engineering and Management (7 papers), Engineering, Construction and Architectural Management (4 papers), Buildings (4 papers), American Journal of Industrial Medicine (4 papers), International Journal of Construction Management (2 papers), ASCE Journal of Computing in Civil Engineering (2 papers), International Journal of Environmental Research and Public Health (2 papers), Applied Sciences (2 papers), IEEE Access (2 papers), and Advanced Engineering Informatics (2 papers).

3.2. Content analysis

After determining the final list of 129 selected papers, a formal content analysis was used to explore the current practices of existing and

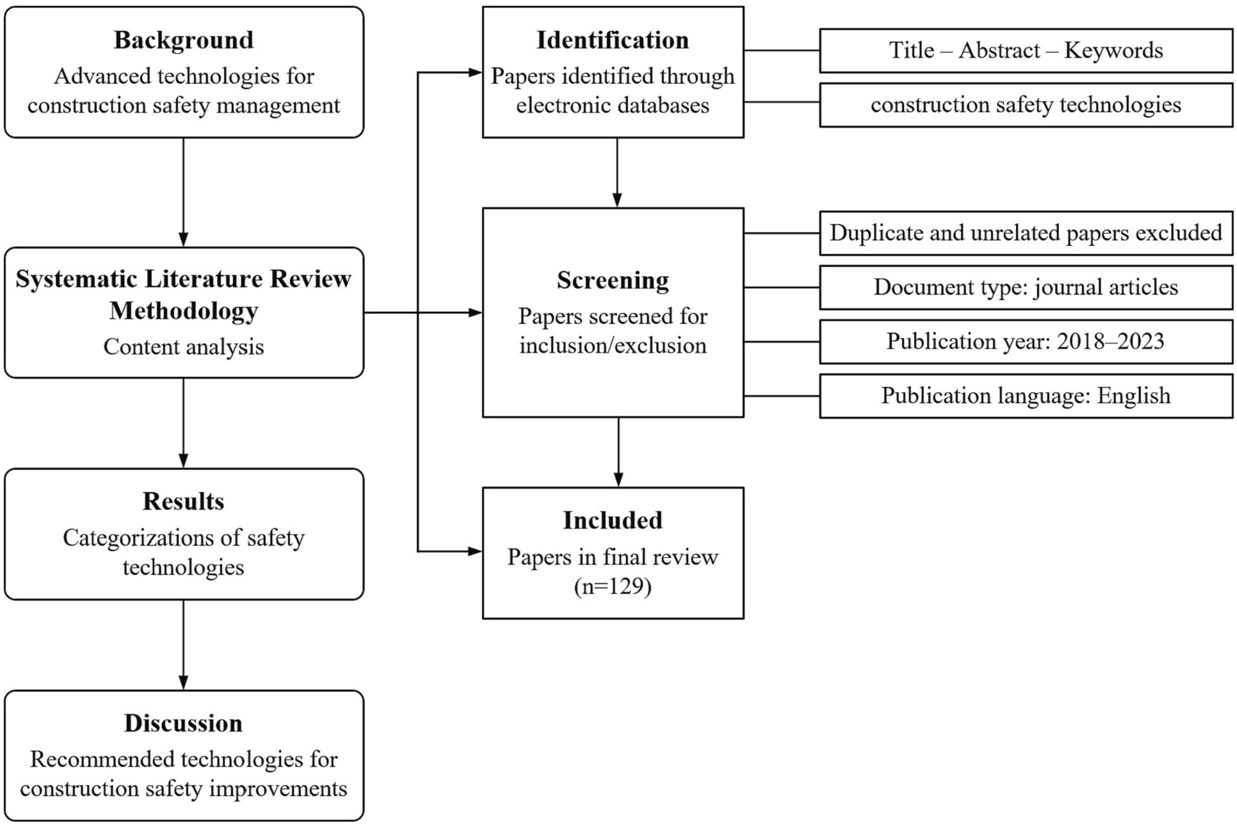

Fig. 1. Systematic literature review methodology.

Table 2
Search criteria for selected papers.

Search criteria for inclusive papers	Criteria for exclusive papers
Papers including "construction safety", "advanced technologies", "safety monitoring", "automation and robotics", "artificial intelligence", "computer visions", "sensing technologies", "wearable sensors", "exoskeletons", "UAVs and drones", "digital technologies", "BIM", "V.R./A.R.", "IoT", "3-D printing", "modular construction" in their TITLE-ABS-KEY category.	Papers that do not mention construction safety technologies at all.
Papers from high-quality journals in construction safety that had more than two (three or more) publications explicating safety technologies.	Papers that do not specify the implementation of advanced technologies in construction safety.
Papers written in English language.	Papers that lack detailed information (e.g., including only abstracts, workshop presentations, and presentation slides).
Papers regularly published (e.g., weekly, bi-weekly, monthly) from 2018 to 2023.	Any grey literature.

Table 3
Selected online libraries and databases for searching relevant safety technologies.

Search Database	Number of Papers Found with Keywords	Selected Papers for Final Review
Elsevier	6252	35
Science Direct	9380	34
American Society of Civil Engineers	1174	24
Emerald Insight	2501	11
Taylor & Francis Online	12,534	10
SpringerLink	9013	7
Wiley Online Library	15,604	6
IEEE Xplore	73	2
Total	56,531	129

emerging technologies in construction safety research in terms of categorizations, implementation trends, and conclusions regarding the applicability of the technologies to improve specific construction safety areas. The content analysis method was used to organize and assess the dominant aspects and contents of the selected papers to identify the major facets and determine possible inferences from the collected information. There are qualitative and quantitative approaches to the content analysis method. While the qualitative content analysis focuses on identifying the meaningful conceptions of the collected information by grouping data into several categories based on the contents, the quantitative content analysis leverages the outcomes of the qualitative approach by adding numerical values to the categorization process in terms of rankings and ratings to calculate the frequencies of a relevant topic across the collected data and information. This study utilized both qualitative and quantitative approaches to conduct the content analysis of 129 papers. First, relevant information of the selected papers, including (a) safety application areas, (b) research problem, (c) research objective, (d) construction safety technologies used, (e) reason to implement the technologies in construction safety, and (f) evaluations of the applicability of the safety technologies if applicable, were extracted. Next, the dominant safety technologies were categorized in terms of construction safety phases based on application area, type of technologies, year of publication, and journal. Finally, the categorized technologies were reviewed and discussed in terms of their applicability and recommendations for specific construction safety improvement areas.

Construction safety applications can be classified using different

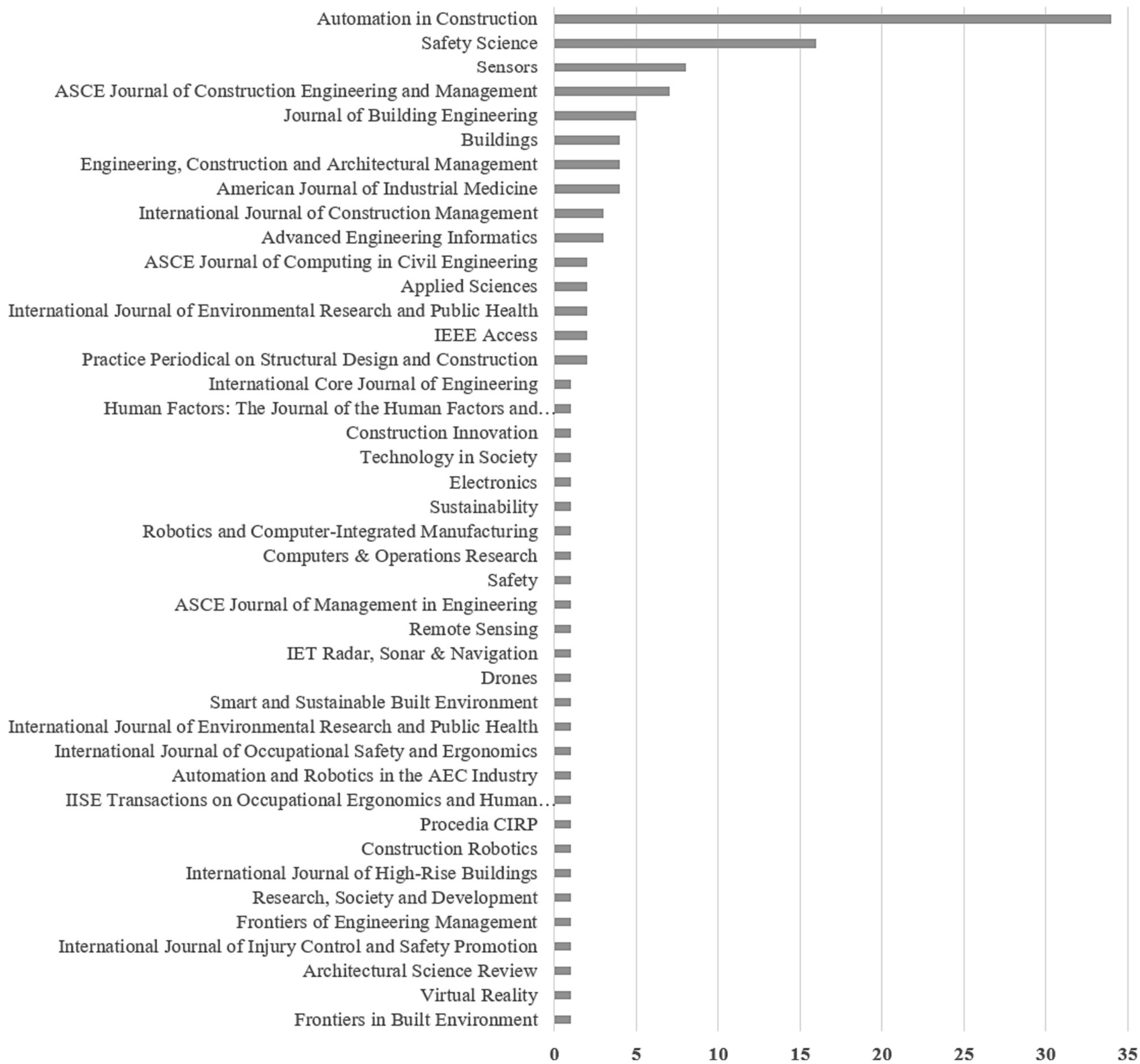

Fig. 2. List of journals ($n = 42$).

approaches, such as project stages, safety purposes, and major safety practices [1,26,32]. In this study, construction safety practices were clustered into major safety applications in construction projects, including (1) prevention through design, (2) safety management, (3) safety culture and awareness, and (4) computing in construction safety, as shown in Fig. 3. The prevention through design category includes applications that aim to reduce and eliminate injuries and fatalities on construction job sites by thoroughly incorporating prevention considerations in all designs that impact workers. The safety management category consists of safety applications related to hazard identification, healthy workplace, and safety equipment (e.g., PPE) that are often implemented during the construction phase to prevent accidents and enhance construction productivity and performance. The safety culture and awareness category focuses on improving workers' understanding of safety risks and hazards and advising their safety behaviors through construction safety education and training, mental health, operational excellence, and continuous improvements in safety practices. The computing in the construction safety category includes advanced algorithms and optimization methods to increase the accuracy of safety-related assessments and augment real-time monitoring for construction safety management. The classified safety applications in this study are highly interconnected to improve construction safety practices. For instance, a thorough analysis of the designs that impact workers can enhance the safety management of the construction job sites. The positive outcomes of safety management can increase the safety culture and awareness of workers to enhance their mental health and productivity. In addition, utilizing state-of-the-art computing means and algorithms can help produce better safety-enhanced designs and foster safety management practices. The classification was established using feedback from the advisory board at the Craig and Diane Martin National Center for Construction Safety, University of Kansas, USA.

4. Categorization of advanced technologies in construction safety

The results of the content analysis provide the categorization of construction safety technologies in 129 selected papers in terms of four main groups: prevention through design, safety management, safety culture and awareness, and computing in construction safety. Table 4 shows that, across the four construction safety categories, the main

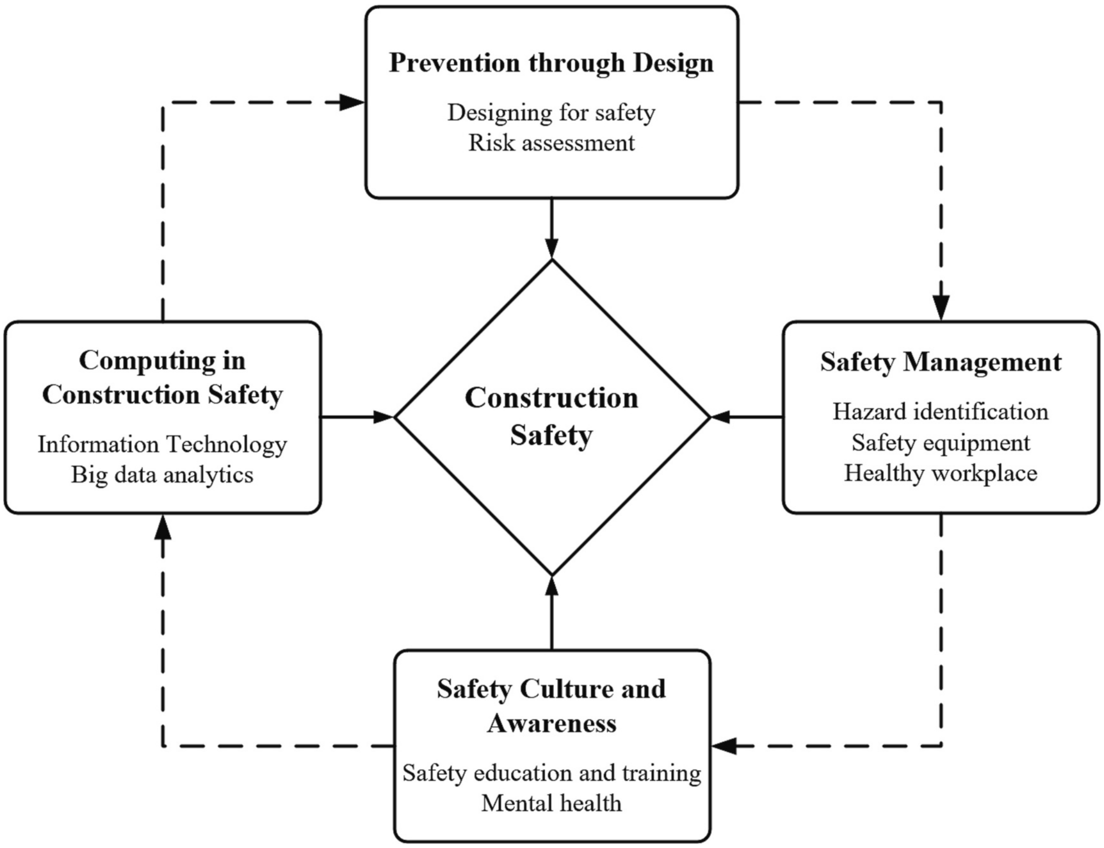

Fig. 3. Construction safety applications.

Table 4
Summary of advanced technologies across construction safety categories ($n = 129$).

Construction Safety Category	Advanced Technologies				
	Artificial Intelligence	Construction Means and Robotics	Sensing Technologies	Digital Technologies	Total Percent (%)
1. Prevention through design	1	10	3	7	16.3
2. Safety management	19	27	26	10	63.6
3. Safety culture and awareness	3	6	8	4	16.2
4. Computing in construction safety	5	0	0	0	3.9
Total Percent (%)	21.7	33.3	28.7	16.3	100

technology applications include Artificial Intelligence (21.7%), construction means and robotics (33.3%), sensing technologies (28.7%), and digital technologies (16.3%). Specifically, out of 129 selected papers, the computing in construction safety category was found with the least technology applications (3.9%) with Artificial Intelligence applications (5 papers). The safety culture and awareness category was identified with 16.2% of the implemented technologies, including Artificial Intelligence (3 papers), construction means and robotics (6 papers), sensing technologies (8 papers), and digital technologies (4 papers). The prevention through design category was found with 16.3% of the implemented technologies, including Artificial Intelligence (1 paper), construction means and robotics (10 papers), sensing technologies (3 papers), and digital technologies (7 papers). The safety management category was found with the largest number of the implemented technologies, including Artificial Intelligence (19 papers), construction means and robotics (27 papers), sensing technologies (26 papers), and digital technologies (10 papers).

The following sections provide detailed results of each advanced technology across four construction safety categories. Relevant papers with each category were also discussed to show why and how the technologies have been applied to support construction safety practices. A paper was selected for detailed discussion if it (1) implemented one or more advanced technologies in one construction safety category, (2) utilized multiple advanced technologies across different construction safety categories, and (3) satisfied the criteria in (1) and (2) and was recently published.

4.1. Artificial intelligence

Implementing Artificial Intelligence for construction safety involves using computer vision applications to detect and analyze potential safety hazards and risks on construction sites [65] and developing machine learning, deep learning, and reinforcement learning algorithms to predict and monitor safety practices for construction job sites [9]. Applications of Artificial Intelligence are capable of enhancing safety measures, mitigating safety risks, and monitoring job site security [66,67]. The implementation of Artificial Intelligence in the construction safety domain requires a combination of hardware, including computer stations, cameras, and sensors, and relevant machine learning, deep learning, and reinforcement learning algorithms for analyzing image and video data to identify potential safety violations, hazards, and abnormal safety behavior patterns of workers [68]. In addition, computer visions, a subset of Artificial Intelligence, are often integrated with the construction company's safety protocols to ensure the efficient adoption and effective utilization of safety management activities [26].

The content analysis results of this study show that applications of Artificial Intelligence represent a fifth of the technologies (21.7%) implemented in the construction safety domain. Artificial Intelligence is often utilized to improve safety management [3,28,69–71], manage the use of PPE [22,29,30], monitor construction equipment safety [27], ensure site safety compliance [9,10,72], and prevent falling accidents [7,73,74]. Specifically, computer visions can analyze video feeds or images from cameras placed strategically across the construction site to provide real-time monitoring of the compliance of workers in wearing the required safety gear, such as hard hats, high-visibility vests, safety goggles, and protective footwear [30]. In addition, Artificial Intelligence-based computer vision systems can be trained to detect potential falls by analyzing the movement patterns of workers to identify risky behaviors and abnormal motions, such as a worker approaching an unprotected edge and provide appropriate interventions and prevention of the accidents before they occur [75]. Applications from computer visions can also be used to identify potential hazards on construction sites by recording videos and images that can help the safety personnel recognize any construction materials and equipment that are improperly placed, obstructing pathways, and potentially causing tripping accidents [69]. Artificial Intelligence applications can assist construction supervisors in monitoring the operation of heavy machinery and equipment to make sure that the existing safety protocols are properly followed [27]. If any deviations from safety guidelines occur, the implemented Artificial Intelligence algorithms can trigger alerts to the safety personnel to conduct prompt actions to prevent any potential accidents [27]. Another application of Artificial Intelligence-based computer vision is to detect and track unauthorized individuals entering the site outside of designated hours to identify any potential intruders and minimize the risk of theft and property damage [66]. For construction site analysis and planning in the pre-construction phase, computer vision systems can also help construction supervisors analyze site layouts and plans to identify potential safety risks and take proper safety actions for optimizing safety measures [69]. Table 5 presents selected papers for applications of Artificial Intelligence in construction safety.

Table 5
Papers selected for applications of Artificial Intelligence in construction safety.

Construction Safety Category	Year	Reference	Application Area	Journal
Safety Management	2022	Li et al. [29]	PPE	Safety Science
Safety Management	2022	Otgonbold et al. [30]	PPE	Sensors
Safety Management	2022	Cheng et al. [10]	Site safety compliance	Automation in Construction
Computing in Construction Safety	2022	Meng et al. [121]	Safety data analytics	Buildings
Safety Management	2021	Golovina et al. [27]	Construction equipment safety	Automation in Construction
Safety Culture and Awareness	2021	Guo et al. [28]	Safety education	Safety Science
Safety Culture and Awareness	2021	Liu et al. [76]	Workers' safety behaviors	Buildings
Prevention through Design	2021	Mostafa & Hegazy [69]	Designing for safety	Automation in Construction
Computing in Construction Safety	2021	Paneru & Jeelani [70]	Safety management	Automation in Construction
Computing in Construction Safety	2021	Soares Júnior et al. [71]	Safety management	Research, Society and Development
Computing in Construction Safety	2021	Wang & Wang [57]	Safety data analytics	Safety Science
Computing in Construction Safety	2020	Akinosho et al. [9]	Site safety compliance	Journal of Building Engineering
Safety Management	2020	Delhi et al. [72]	Site safety compliance	Frontiers in Built Environment
Safety Management	2020a	Fang et al. [26]	Construction safety assurance	Automation in Construction
Safety Culture and Awareness	2020b	Fang et al. [65]	Site safety compliance	Advanced Engineering Informatics
Safety Management	2020	Nath et al. [66]	Site safety compliance	Automation in Construction
Safety Management	2020	Tang et al. [31]	Safety monitoring	ASCE Journal of Computing in Civil Engineering
Safety Management	2020a	Zhang et al. [32]	Safety monitoring	Safety Science
Safety Management	2019	Mneymneh et al. [77]	PPE	ASCE Journal of Computing in Civil Engineering
Safety Management	2019	Ren & Peng [73]	Fall prevention	IEEE Access
Safety Management	2019	Wu et al. [75]	PPE	Automation in Construction
Safety Management	2018	Mneymneh et al. [78]	Indoor construction safety	Frontiers of Engineering Management
Safety Management	2018a	Fang et al. [7]	Falling prevention	Automation in Construction
Safety Management	2018b	Fang et al. [74]	Site safety compliance	Automation in Construction
Safety Management	2018c	Fang et al. [79]	Falling prevention	Automation in Construction

4.2. Construction means and robotics

The category of construction means and robotics consists of two major applications: advanced construction methods and construction robotics. Applications of robotics in construction safety include exoskeletons, exosuits, UVAs, and drones have been increasingly used in the construction industry and providing a range of benefits to both workers and employers. Construction robotics applications have the potential to enhance construction safety by improving worker well-being and increasing labor productivity [4]. Exoskeletons are wearable devices designed to provide physical support for workers and reduce the risk of musculoskeletal injuries and the likelihood of work-related accidents [80]. Although exoskeletons offer some great benefits to construction safety, the use of this technology requires proper training and education to ensure that workers understand how to effectively and safely use exoskeletons in practice [81]. In addition, construction practitioners are recommended to conduct regular ergonomic assessments to identify tasks where exoskeletons can have the most significant impact to improve the applicability of this technology on site [82]. The maintenance and durability of the exoskeletons and exosuits are also crucial to keep this application for long-term use and create safer working environments [83]. Other applications of construction robotics consist of UAVs and drones, which have been increasingly used in the construction industry due to their versatility and capability to provide valuable data and insights into construction-related problems, such as safety management, site planning and inspections, and labor productivity [113]. By using the power of this aerial technology, safety personnel can proactively identify and address safety concerns, minimize site hazards, and create a safe working environment. However, to maximize the use of UAVs and drones for construction safety, proper training processes and certification for operators need to be carefully considered [116]. Advanced construction means to improve safety practices of the construction job sites include additive manufacturing (i.e., 3-D printing) and modular/prefabrication construction methods [130,135,137]. The utilization of 3-D printing is to produce components off-site, reduce the need for workers to be in hazardous environments and help minimize the risk of repetitive stress injuries due to performing labor-intensive tasks [129,131]. By implementing modular construction, prefabricated components are assembled quickly on-site, reducing the need for extensive labor and minimizing the risk of on-site accidents [133,134]. Modular construction also helps streamline the construction process, leading to fewer accidents caused by human errors. It incorporates safety features, such as fall protection systems and fire-resistant materials, into the prefabricated components [132].

The content analysis results of this study show that applications of construction means (e.g., 3-D printing and modular construction) and robotics (e.g., exoskeletons, UAVs, and drones) represent a third of the technologies (33.3%) implemented in the construction safety domain. UAVs and drones are utilized in various safety practices, such as safety assessment [12], emergency responses and search [114], environmental monitoring [16], and surveillance and security [115]. Exoskeletons are often used to improve safety management [4,35,39,40,84], support manual material handling [14,38,85], monitor construction operations [86], mitigate safety risks [87,88], and assist highway construction safety [89]. A major benefit of using construction robotics is to augment ergonomic support for construction workers and prevent common workplace-related injuries, such as strains, sprains, and back problems [90]. For example, exoskeletons and exosuits can provide mechanical assistance to reduce the strain on the musculoskeletal system and reduce the risk of overexertion when workers perform repetitive tasks, such as heavy lifting, carrying, and working in awkward positions [80]. The application of exoskeletons equipped with strength-enhancing mechanisms can be used to provide load assistance in lifting heavy objects and decrease the strain on the worker's body to prevent the frequency of carrying and transporting heavy loads [91]. Applications of construction robotics are also used to aid in facilitating the rehabilitation process of construction workers who have suffered injuries [40]. Nnaji et al. [40] found that using exoskeleton wearable devices allows injured workers to return to their jobs more quickly and safely. The adaptability of construction robotics in construction safety has been increased because of

Table 6
Papers selected for applications of construction means and robotics in construction safety.

Construction Safety Category	Year	Reference	Application Area	Journal
Safety Management	2023	Bennett et al. [84]	Safety management	Buildings
Safety Management	2023	Cai et al. [35]	Safety management	Safety Science
Safety Management	2023	Golabchi et al. [38]	Manual material handling	Construction Robotics
Safety Culture and Awareness	2023	Gonsalves et al. [4]	Safety education	ASCE Journal of Construction Engineering and Management
Safety Culture and Awareness	2023	Liang and Cheng [39]	Safety education	International Journal of Environmental Research and Public Health
Safety Culture and Awareness	2023	Nnaji et al. [40]	Safety education	Safety Science
Safety Management	2023	Okpala et al. [86]	Construction operation safety	ASCE Journal of Construction Engineering and Management
Prevention through Design	2023	Chourasia et al. [133]	Designing for safety	Practice Periodical on Structural Design and Construction
Safety Management	2022	Mahmud et al. [83]	Safety management	Sensors
Safety Management	2022b	Okpala et al. [81]	Safety management	Automation and Robotics in the Architecture, Engineering, and Construction Industry
Safety Management	2022	Guan et al. [109]	Safety management	Drones
Safety Management	2022	Liang & Seo [110]	PPE	Remote Sensing
Safety Culture and Awareness	2022	Liu et al. [111]	Workers' safety behaviors	Advanced Engineering Informatics
Safety Management	2022	Zhu et al. [115]	Road construction safety	Sensors
Prevention through Design	2022	Chatzimichailidou and Ma [132]	Safety risk assessment	Safety Science
Prevention through Design	2022	Wasim et al. [135]	Designing for safety	International Journal of Construction Management
Safety Management	2021	Antwi-Afari et al. [14]	Manual material handling	Safety Science
Safety Management	2021	Ogunseiju et al. [85]	Manual material handling	Engineering, Construction and Architectural Management
Safety Culture and Awareness	2021	Svertoka et al. [82]	Safety training	Sensors
Safety Management	2021	Zhu et al. [42]	Manual material handling	Automation in Construction
Safety Management	2021	Elghaish et al. [52]	Safety management	Smart and Sustainable Built Environment
Safety Management	2021	Jeelani & Gheisari [16]	Safety management	Safety Science
Safety Management	2021	Umar [112]	Safety inspection	Engineering, Construction and Architectural Management
Prevention through Design	2021	Besklubova et al. [130]	Designing for safety	Journal of Construction Engineering and Management
Safety Management	2020	Balzan et al. [88]	Construction site safety	International Journal of High-Rise Buildings
Safety Management	2020	Howard et al. [91]	Safety management	American Journal of Industrial Medicine
Safety Management	2020	Ippolito et al. [80]	Safety management	Procedia CIRP
Safety Management	2020	Nnaji et al. [89]	Highway construction safety	ASCE Practice Periodical on Structural Design and Construction
Safety Management	2020	Alizadehsalehi et al. [51]	Construction site safety	International Journal of Occupational Safety and Ergonomics
Prevention through Design	2020	Martinez et al. [125]	Safety planning and monitoring	ASCE Journal of Management in Engineering
Prevention through Design	2020	Ahn et al. [129]	Safety risk assessment	Journal of Construction Engineering and Management
Prevention through Design	2020	Zheng et al. [137]	Designing for safety	Automation in Construction
Safety Culture and Awareness	2019	Davila Delgado et al. [90]	Safety education and training	Journal of Building Engineering
Safety Management	2019	Lowe et al. [92]	Safety management	IISE Transactions on Occupational Ergonomics and Human Factors
Safety Management	2019	Gheisari & Esmaeili [12]	Safety management	Safety Science
Safety Management	2019	Li & Liu [113]	Safety management	International Journal of Construction Management
Safety Management	2018	Howard et al. [114]	Safety management	American Journal of Industrial Medicine
Safety Management	2018	Jordan et al. [116]	Safety monitoring	IET Radar, Sonar & Navigation
Prevention through Design	2018	Delgado Camacho et al. [131]	Designing for safety	Automation in Construction
Prevention through Design	2018	Fard et al. [134]	Safety risk assessment	International Journal of Injury Control and Safety Promotion
Prevention through Design	2018	Wu et al. [136]	Designing for safety	Architectural Science Review

its flexibility in customization for specific construction tasks and workers [38]. For example, as construction tasks change throughout a project, exoskeletons can be adapted to accommodate different work scenarios, ensuring optimal safety and performance [38]. Table 6 presents selected papers for applications of construction means and robotics in construction safety.

4.3. Sensing technologies

Sensing technologies, such as wearable sensors and IoT devices, have been widely implemented in the construction industry as a valuable tool to improve construction safety by providing real-time data and insights about worker health and safety behaviors [48]. Wearable sensors can be used as standalone devices and/or integrated into PPE to monitor the vital signs of construction workers, detect potential hazards on site, and support construction supervisors to monitor workers' safety behaviors [93]. In addition, data from wearable sensors can be integrated with advanced data analytics platforms and connected to a central monitoring system to produce meaningful insights regarding workers' safety measures [94]. IoT sensors can be deployed across construction sites to monitor various safety parameters in real-time to manage hazardous gas levels, monitor environmental conditions, measure noise levels, and track worker movements [123]. To implement sensing technologies, especially wearables in construction projects, practitioners need to establish relevant policies and guidelines to protect workers' privacy and clarify how their physiological and biological data will be collected, stored, and used [68].

The content analysis results of this study show that applications of sensing technologies represent more than a quarter of the technologies (28.7%) implemented in the construction safety domain. Sensing technologies are often utilized to improve fall protection [6,95,96], improve safety management [1,44,97], monitor workers' safety behaviors [45,46,49,98], improve construction site safety [43,99,100], support manual material handling activities [47], and facilitate safety training [101]. Sensing technologies are capable of providing real-time health monitoring by tracking and collecting vital signs of workers, such as heart rate, body temperature, respiration rate, and fatigue levels [23]. The collected physiological and biological sensory data can provide insights into workers' well-being and identify potential signs of physical stress, dehydration, and exhaustion [8]. Using real-time information of workers' physiological conditions, safety personnel and supervisors can be alerted promptly whether any worker's health is compromised to prevent health-related incidents. Wearable sensors can also support environmental monitoring by providing workers with immediate feedback on extreme working conditions, such as heat stress, noise levels, humidity, and air quality, so that they can take necessary precautions [50]. In addition, wearable sensors have been widely utilized to support ergonomic analysis by detecting workers' movements and postures and providing insights into ergonomic risks and potential musculoskeletal injuries [47]. During the construction phase, using wearable sensors equipped with accelerometers and gyroscopes can detect sudden movements, changes in orientation, and the absence of movement of workers to prevent falls from height [96]. Specifically, when a potential fall is detected, the sensor can automatically alert the safety personnel to provide immediate response and medical assistance. Sensing technologies are often used in safety training by providing real-time feedback to workers and promoting safer behaviors [100]. The integration of IoT sensors and big data analytics in construction safety has the potential to accurately provide real-time monitoring, predictive analysis, and actionable insights into safety-related problems [121,122]. IoT is capable of interconnecting digital devices and sensors to collect and exchange data that can be used to monitor construction safety activities [17], while big data analytics contributes by processing and analyzing a large volume of signal data to extract meaningful information [57]. The implementation of IoT and big data analytics in the construction safety domain requires considerations to protect the confidentiality of the collected data and privacy concerns [57,124]. Table 7 presents selected papers for applications of sensing technologies in construction safety. The selection of the inclusive papers was made based on (a) the relevant safety technology keywords, (b) high-quality journals in the construction safety community, and (c) regular publications in English from 2018 to 2023. Specifically, at least one of the following keywords: "construction safety technologies," "sensing technology," "wearable sensors," and "Internet-of-Things," are included in the paper's title, abstract, and keyword categories.

4.4. Digital technologies

The content analysis results show that applications of digital technologies, including A.R., V.R., and BIM represent around 16.3% of the technologies implemented in the construction safety domain. Digital technologies have been mainly incorporated with the Artificial Intelligence category and widely implemented in various safety areas, including safety planning and monitoring [109], PPE [110], safety compliance [111], accidents' prevention [17], and safety inspection [112].

Digital technologies hold great potential for enhancing construction safety with their ability to provide immersive training experiences, improve real-time hazard awareness, and enhance communication between workers and supervisors [117]. The content analysis results show that the implementation of digital technologies, such as A.R. and V.R., requires an integration of spatial mapping, real-time data collection, and user-friendly interfaces [118]. The use of V.R. can immerse users in a fully simulated digital environment to oversee and monitor safety-related problems, while A.R. is capable of overlaying virtual information onto the real world to help safety personnel actively address specific safety challenges [54]. V.R. applications also allow construction workers, supervisors, and safety personnel to virtually explore and navigate a construction site before physical work begins [2]. A.R. applications can be integrated into PPE to help workers receive real-time notifications and reminders about safety regulations [117]. Another well-known application of digital technologies – BIM, with the ability to create a virtual model of the building and incorporate various data and information throughout its lifecycle, have extensively used in various construction domains, such as safety, project planning, project delivery, and operation and maintenance [55]. BIM can be used to improve construction safety by enabling clash detection, improving proactive safety risk assessment, and providing effective communication of safety protocols between project stakeholders [15]. Specifically, construction safety considerations can be thoroughly considered in a virtual model to simulate different work scenarios for minimizing safety risks and preventing accidents [119]. The visualization of the construction sequence, including the chronological order of construction activities, can be conducted using BIM to identify and evaluate potential safety risks and hazards at each stage of construction [120]. Table 8 presents selected papers for applications of digital technologies in construction safety.

5. Discussion

A variety of technologies have been used to accommodate different construction safety issues and concerns. The diversity of technologies applied across various construction safety categories lead to difficulties in evaluating and comparing the performance outcomes, accuracy, and reliability of the safety technologies. A guideline is needed regarding the common use of specific technologies to handle specific construction safety areas. The content analysis results from 129 selected papers show multiple improvement areas across the construction safety categories: (1) prevention through design, (2) safety management, (3) safety culture and awareness, and (4) computing in construction safety. In this study, the safety improvement areas associated with each construction safety category were compiled using feedback from the industry advisory board at the Craig and Diane Martin National Center for Construction

Table 7
Papers selected for applications of sensing technologies in construction safety.

Construction Safety Category	Year	Reference	Application Area	Journal
Safety Management	2023	Choo et al. [6]	Fall prevention	Automation in Construction
Safety Management	2022	Akinlolu et al. [1]	Safety management	International Journal of Construction Management
Safety Culture and Awareness	2022	Choi et al. [44]	Safety education	Robotics and Computer-Integrated Manufacturing
Safety Management	2022	Lee et al. [46]	Healthy workplace	Engineering, Construction and Architectural Management
Safety Culture and Awareness	2022a	Okpala et al. [49]	Workers' safety behaviors	Construction Innovation
Safety Managment	2022	Rao et al. [99]	Construction site safety	Automation in Construction
Safety Management	2022	Khan et al. [17]	Fall prevention	Automation in Construction
Safety Management	2021	Bangaru et al. [43]	Scaffold builder activity	Automation in Construction
Safety Management	2021	Jeon and Cai [45]	Workers' safety behaviors	Automation in Construction
Safety Culture and Awareness	2021	Ke et al. [98]	Mental health	Automation in Construction
Safety Management	2021	Kim et al. [93]	PPE	Sustainability
Safety Culture and Awareness	2021	Lee et al. [23]	Safety education and training	Journal of Building Engineering
Safety Management	2021	Mudiyanselage et al. [47]	Manual material handling	Electronics
Safety Management	2021a	Nnaji et al. [102]	Safety management	Technology in Society
Prevention through Design	2021	Shakerian et al. [50]	Heat stress	Safety Science
Safety Management	2021	Liu [68]	Safety management	International Core Journal of Engineering
Prevention through Design	2021b	Nnaji et al. [87]	Safety risk management	Sensors
Safety Management	2021	Zhao et al. [122]	Safety management	Computers & Operations Research
Safety Management	2020	Asadzadeh et al. [97]	Safety management	Automation in Construction
Safety Management	2020	Li et al. [103]	Workers' safety behaviors	Automation in Construction
Safety Management	2020	Menolotto et al. [104]	Workers' safety behaviors	Sensors
Safety Management	2020	Singh et al. [95]	Fall prevention	IEEE Access
Safety Management	2020	Yang et al. [124]	PPE	Journal of Building Engineering
Safety Culture and Awareness	2019	Ahn et al. [8]	Safety education and training	ASCE Journal of Construction Engineering and Management
Safety Management	2019	Awolusi et al. [21]	Safety monitoring	ASCE Computing in Civil Engineering
Safety Culture and Awareness	2019	Choi et al. [11]	Safety education and training	Safety Science
Prevention through Design	2019	Jeelani et al. [105]	Safety risk assessment	ASCE Journal of Construction Engineering and Management
Safety Management	2019	Li et al. [106]	Workers' safety behaviors	Automation in Construction
Safety Management	2018	Antwi-Afari et al. [107]	Workers' safety behaviors	Automation in Construction
Safety Management	2018	Awolusi et al. [100]	Safety monitoring	Automation in Construction
Safety Management	2018	Hasanzadeh et al. [96]	Fall and tripping prevention	ASCE Journal of Construction Engineering and Management
Safety Culture and Awareness	2018	Jeelani et al. [101]	Safety training	Automation in Construction
Safety Management	2018	Kanan et al. [94]	Workers' safety behaviors	Automation in Construction
Safety Culture and Awareness	2018	Schall et al. [108]	Safety education	Human Factors: The Journal of the Human Factors and Ergonomics Society
Safety Management	2018	Wu et al. [123]	Safety monitoring	Sensors

Table 8
Papers selected for applications of digital technologies in construction safety.

Construction Safety Category	Year	Reference	Application Area	Journal
Safety Management	2023	Dobrucali et al. [3]	Safety management	Engineering, Construction and Architectural Management
Safety Management	2023	Gómez-de-Gabriel et al. [22]	PPE	Safety Science
Safety Culture and Awareness	2022	Prabhakaran et al. [140]	Safety education	Automation in Construction
Safety Culture and Awareness	2022	Zhang et al. [141]	Safety training	Automation in Construction
Prevention through Design	2021	Opoku et al. [127]	Designing for safety	Journal of Building Engineering
Prevention through Design	2021	Lu et al. [56]	Safety risk assessment	Automation in Construction
Safety Management	2021	Gao et al. [138]	Safety risk identification	Virtual Reality
Safety Management	2021	Han et al. [139]	Hazard identification	Advanced Engineering Informatics
Safety Culture and Awareness	2020b	Zhang et al. [118]	Safety education	Automation in Construction
Prevention through Design	2020	Getuli et al. [15]	Construction planning	Automation in Construction
Prevention through Design	2020	Fargnoli & Lombardi [55]	Designing for safety	Buildings
Prevention through Design	2020	Hou et al. [13]	Designing for safety	Applied Sciences
Safety Management	2019	Moore & Gheisari [117]	Safety management	Safety
Safety Management	2019	Shi et al. [2]	Fall prevention	Automation in Construction
Prevention through Design	2019	Akram et al. [120]	Designing for safety	Safety Science
Safety Culture and Awareness	2018	Eiris et al. [126]	Safety training	International Journal of Environmental Research and Public Health
Safety Management	2018	Li et al. [54]	Safety management	Automation in Construction
Safety Management	2018	Cheung et al. [119]	Safety monitoring	Sensors
Safety Management	2018	Martínez-Aires et al. [128]	Safety management	Safety Science
Safety Management	2018	Guo et al. [67]	Safety management	Automation in Construction

Safety, University of Kansas, USA [142,143].

In the prevention through design category, construction safety practices can be improved through two areas, including planning/design for safety and safety risk management. The goal of the safety improvement areas is to proactively address safety concerns by integrating safety principles into the design and planning processes rather than relying solely on protective measures after construction has begun. By planning and designing for safety, project participants, including architects, engineers, construction managers, and safety professionals, can collaborate and ensure that safety considerations are integrated into the design process from the beginning. Implementing prevention through design can also incorporate necessary design safety features into the project, such as safe access and egress points, proper lighting, ergonomic workspaces, and clear signage. The safety risk management area aims to identify potential hazards associated with the construction project, such as fall hazards, electrical hazards, and hazardous materials, to conduct further assessment of the safety risks for mitigation. The safety risk assessment outcomes can also provide feedback to selecting design alternatives that minimize or eliminate hazards. In the safety management category, construction safety practices can be improved through three areas, including hazard identification, safety equipment, and healthy workplace. Hazard identification is a critical process in safety management that involves identifying and recognizing potential hazards or risks in the construction workplace to reduce the risk of accidents, injuries, and fatalities. In safety management protocols, safety equipment is essential to protect workers from various hazards and risks in the workplace or during specific construction activities. Various types of safety equipment, such as hard hats, safety glasses, face shields, earplugs, respirators, slip-resistant shoes, and safety harnesses, are used in managing and monitoring construction safety practices. In the safety culture and awareness category, construction safety practices can be improved through two areas, including safety education and training and mental health of workers. Safety education and training play a crucial role in fostering a strong safety culture and raising awareness of safety practices. By implementing a well-rounded safety education and training program that addresses the specific needs of your organization, you can build a safety-conscious workforce, promote a strong safety culture, and reduce the risk of accidents and injuries. Safety awareness and education should be ongoing processes that evolve with changing conditions and industry standards. In the computing in construction safety category, construction safety practices can be improved through two areas, including information technology and big data analytics. Information technology and big data analytics play a crucial role in enhancing computing in construction safety by providing tools and solutions that enable better risk management, communication, and decision-making. By integrating information technology solutions into construction safety practices, organizations can enhance safety awareness, reduce risks, improve incident response times, and ultimately create safer working environments for construction workers.

The results of this study provide a checklist of frequently used technologies for specific construction safety improvement areas, as shown in Table 9. The advanced technologies are recommended based on the frequency of their implementation in specific construction safety improvement areas. For example, technologies that were indicated in ten or more papers across the nine safety improvement areas were rated *High*. Technologies that were indicated in five to ten papers across the nine safety improvement areas were rated *Medium*. Technologies that were indicated in less than five papers across the nine safety improvement areas were rated *Low*. Technologies that were not indicated in any of the nine safety improvement areas were rated *None*.

Table 9 shows that Artificial Intelligence applications are frequently used in the safety improvement areas of safety management, including hazard identification and safety equipment. Applications of Artificial Intelligence in construction safety are used to complement existing safety management with human oversight and interventions. For instance, construction site safety requires a collaborative environment where supervisors, safety personnel, and workers actively engage with the support from Artificial Intelligence applications, such as computer visions, to promote and maintain a safe workplace [31]. Nonetheless, Artificial Intelligence applications were not found to be used in improving workers' mental health. Construction means and robotics are frequently used in the safety equipment and risk management areas and rarely used in multiple safety improvement areas, including designing for safety, safety training, and improving workers' mental health. The designs of construction robotics incorporate various safety features, such as harnesses and tethering systems, that can detect workers' loss of balance and respond by stabilizing the worker to prevent falls from heights and serious injuries [83]. Applications of construction robotics, such as exoskeletons, can also help reduce fatigue and increase endurance for construction workers by minimizing the physical demands of repetitive and prolonged tasks and providing support to muscles and joints, allowing them to perform tasks for longer periods without experiencing excessive strain [42]. Another application of construction robotics, UAVs and drones were commonly used in multiple safety areas, including safety planning, construction site safety compliance, accidents' prevention, safety inspection, and construction equipment safety monitoring. UAVs and drones are used on site to enhance construction operations and maintain safety with their emergency response capabilities and real-time monitoring [51]. UAVs equipped with high-resolution cameras and sensors can provide a comprehensive overview of the entire construction site to support site inspections and monitoring [125]. No implementation of UAVs and drones was found in the safety areas of workplace hazard recognition and risk management, safety training and education, workers' safety behaviors, manual material handling, and communications between workers. However, no application of construction robotics was found in the computing in construction safety areas, including information technology and big data analytics.

Sensing technologies are frequently used to improve safety management on construction job sites and promote a healthy workplace. Implementing sensing technologies, such as wearable sensors, can help construction companies facilitate workers' safety culture and awareness and improve their safety measurements [101]. Furthermore, wearable sensor data also assist safety personnel in post-incident analysis to understand the causes of accidents and develop appropriate preventions [11]. IoT sensors are commonly used in the safety areas of workplace hazard recognition and risk management, construction site safety compliance, accidents' prevention, and safety inspection. The use of IoT also enables the integration of multiple wearable devices, such as smart helmets, vests, and gloves in monitoring workers' vital signs, body temperature, and fatigue levels for specific construction activities [122]. However, sensing technologies were not found in designing for safety and computing in construction safety. It is noticed that sensing signal data can complement the use of big data analytics to accommodate construction safety issues. Digital technologies, including A.R., V.R., and BIM, are frequently used across designing for safety and hazard identification. A.R. and V.R. technologies were recommended in the areas of safety planning, safety training and education, construction site safety compliance, workers' safety behaviors, accidents' preventions, and safety inspection. The use of A.R. and V.R. technologies is recommended

Table 9
Recommendations of advanced technologies for construction safety improvement areas ($n = 129$).

Construction Safety Category	Safety Improvement Areas	Advanced Technologies			
		Artificial Intelligence	Construction Means and Robotics	Sensing Technologies	Digital Technologies
Prevention through Design	Designing for safety	Low*	Low	None	Medium
	Risk management	None	Medium	Low	Low
Safety Management	Hazard identification	High	High	Medium	Medium
	Safety equipment	High	High	High	Low
	Healthy workplace	Medium	Low	Medium	None
Safety Culture and Awareness	Safety education and training	Low	Low	Low	Low
	Mental health	None	None	Low	None
Computing in Construction Safety	Information technology	Low	None	None	None
	Big data analytics	Low	None	None	None

* High: applied by more than ten studies; Medium: applied by five to ten studies; Low: applied by one to 4 studies; None: Not applied.

to provide interactive virtual safety training environments and experiences for construction workers through simulated work scenarios [126]. However, for workplace hazard recognition and risk management, construction equipment safety monitoring, manual material handling, and communications between workers, there was no application of AR or VR BIM is recommended in various safety areas, including safety planning, workplace hazard recognition and risk management, construction site safety compliance, workers' safety behaviors, accidents' preventions, safety inspection, and construction equipment safety monitoring. The use of BIM allows for the integration of safety-related data, such as fire escape routes, emergency exits, and hazardous material locations, into the virtual model to help the project team identify potential safety risks early in the design phase [128]. On the other hand, BIM applications were not found in safety training and education, manual material handling, and communications between workers. Practitioners in the construction safety domain can utilize this checklist of frequently used technologies in various construction safety improvement areas to select appropriate technologies for their projects to create safer working environments.

In summary, the results of this study complement the current construction safety literature by providing a systematic review and itemized categorization of major existing and emerging technologies in the field of construction safety. Specifically, the findings of this study expand the existing investigations of advanced technologies to improve construction safety performance and outcomes, including (a) digital technologies from Dobrucali et al. [3] and Hou et al. [13], (b) Artificial Intelligence applications from Akinosho et al. [9], Guo et al. [28], and Zhang et al. [32], and (c) wearable sensing technologies from Ahn et al. [8], Hallowell et al. [144], and Hallowell at el. [145]. In addition, this study is in line with Okpala et al. [146] and provides further insights into emerging technologies, including construction robotics and automation, additive manufacturing, modular/prefabrication construction methods, and IoT devices, to identify further opportunities to optimize the construction safety planning and management in order to enhance construction safety performance. The results of this study also provide the itemized categorization of four major safety technology groups to enlarge the findings of the previous literature review studies that mostly concentrated on a single group of safety technologies, such as Information Technology [147,148], virtual design and construction [67,149], immersive technologies [138,150], sensing technologies [151,152], digital technologies [1,153], and extended reality [154]. The itemized categorization of the advanced technologies helps identify specific application areas for the implementations of Artificial Intelligence, construction means and robotics, sensing technologies, and digital technologies throughout the four primary construction safety categories: prevention through design, safety management, safety culture and awareness, and computing in construction safety. Additionally, this study provides detailed descriptions of the advanced technologies and discussions of advantages, disadvantages, and existing issues in their current implementations in construction safety. Accordingly, the findings of this study support the safety decision-making process throughout the project development when practitioners wish to apply particular technologies for their construction safety management. For instance, appropriate advanced technologies can be selected by the owner in the pre-construction phase and by the contractor in the construction phase to manage construction safety performance [155]. The results of this study also include recommendations of frequently used advanced technologies to address construction safety problems in specific safety improvement areas, including designing for safety, risk management, hazard identification, safety equipment, healthy workplace, safety education and training, mental health, information technology, and big data analytics. By deepening the understanding of the existing and emerging technologies used for construction safety, the findings of this study are expected to assist practitioners in the construction industry in selecting appropriate technologies based on their safety goals and purposes.

6. Conclusions and future research

This paper presents a state-of-the-art review of applications of existing and emerging advanced technologies in construction safety research. Many technologies, such as Artificial Intelligence, construction means and robotics, sensing technologies, and digital technologies, have been widely used to enhance construction safety. There are possible integrations of these technologies that can dramatically improve their capability in identifying and mitigating safety risks and hazards on the construction sites. A research gap exists regarding a comprehensive investigation of how to categorize the existing and emerging technologies for construction safety management. The objective of this paper was to identify and categorize the current advanced technologies used in the construction safety domain. A systematic literature review methodology was performed to collect and analyze 129 journal articles focusing on state-of-the-art applications of construction safety technologies. The results of this study include a categorization of the technologies of Artificial Intelligence, construction means and robotics, sensing technologies, and digital technologies, based on specific application areas, including prevention through design, safety management, safety culture and awareness, and computing in construction safety. In addition, a checklist of frequently used technologies for specific safety improvement areas was developed.

This study makes several contributions to the body of knowledge by providing a systematic review of existing and emerging technologies in the construction safety domain. First, the results of this study provide detailed and integrated categorization of advanced technologies across different construction safety application areas that match with specific safety phases, including prevention through design, safety management, safety culture and awareness, and computing in construction safety. The categorization also helps illustrate the capabilities of the technologies in providing a lasting solution for specific construction safety problems. Second, this study identifies and develops a list of recommended technologies for specific construction safety improvement areas, including planning/designing for safety, risk management, hazard identification, safety equipment, healthy workplace, safety education and training, mental health, information technology, and big data analytics. The developed checklist in this study can support industry practitioners in selecting an appropriate technology as well as an integration between multiple technologies for improving safety in their construction projects.

This study has several limitations. First, this study only reviewed recent journal articles published in the past five years (2018 to 2023). Future research can expand the time span to a decade to increase the coverage of safety technology-related studies in construction. Second, the number of papers obtained from journals for each safety technology category was uneven because of different usages and the commonness of the advanced technologies in the construction safety domain.

Future research directions of construction safety technologies can be made based on potential integrations between multiple safety technology categories and their applicability to the construction site. For example, some sensing technologies are designed for use in open sites, while others are better suited for indoor use. Some technologies require an initial setup and minimal calibration thereafter, while others must be continuously relocated and recalibrated as the construction project progresses. Also, some technologies require the pre-installation or availability of other infrastructure, such as mobile internet or Wi-Fi, while some work sites restrict the user of application-specific devices such as smartphones, cameras, and the Global Positioning System (GPS). Other technologies installed in machinery or tools that can have a positive impact on the health and safety of workers, such as collision avoidance systems, vibration reduction technology, and safety sensors, should also be considered in future studies. Future research can also focus on examining the impact of social (e.g., privacy, security, and legal) issues related to the use of wearable systems. For instance, wearable devices are vulnerable to security breaches and require strong security measures to protect data processing and transmission. Another research direction can refer to investigating the long-term use of sensing and automated alert systems to increase workers' safety behaviors in recognizing unsafe activities or conditions. Future research can focus on investigating new emerging technologies for construction work-zone safety to reduce accidents, injuries, and fatalities on the construction job sites.

CRediT authorship contribution statement

Omar Maali: Conceptualization, Investigation, Visualization. **Chien-Ho Ko:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Phuong H.D. Nguyen:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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