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Review

Review of Emerging Technologies for Reducing Ergonomic Hazards in Construction Workplaces

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Abstract: In the era of Industry 4.0, marked by the integration of digitization, automation, and data synthesis, emerging technologies play a vital role in mitigating ergonomic hazards within construction work environments. This study investigates the research trends encompassing the adoption of three categories of emerging technologies—(1) wearable sensors; (2) extended reality, which combines virtual reality (VR), augmented reality (AR), and mixed reality (MR); and (3) exoskeletons and robotics—as the means to mitigate the risk of occupational nonfatal injuries in the construction industry. Employing bibliometric and scientometric analyses, a quantitative examination of the relationship in the literature is performed. From the Scopus database, 347 papers were selected from a pool of 1603 publications from 2018 to 2022. The conducted scientometric analyses encompass annual publication trends, keyword co-occurrence analysis, journal-source analysis, author analysis, and country analysis using VOSviewer (version 1.6.19) and bibliometrix software (version 4.1.3). The findings highlight the crucial role of advanced technologies in enhancing safety and health management in the construction industry. Wearable sensors, for example, offer promising capabilities for real-time monitoring, potentially reducing the risk of onsite injuries by alerting workers to hazards. Extended reality, especially VR, can enhance the effectiveness of safety-training education by simulating realistic scenarios while minimizing exposures to hazardous conditions that workers may face onsite challenges. Furthermore, the integration of exoskeletons and robotics has the potential to reduce physical strain and injury risks among workers, particularly in physically demanding tasks. The review paper identifies current research trends in applying emerging technologies to occupational safety and health within the construction industry, while also suggesting future research directions in this dynamic field.

Keywords: scientometric analysis; construction; hazard; safety and health; emerging technology; human–machine interaction; industry 4.0

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1. Introduction

The construction industry is considered labor intensive, where the workers often perform physically demanding tasks, including heavy manual lifting and repetitive activities, that can lead to work-related musculoskeletal disorders (WMSDs) and reduced productivity [1,2]. Previous research has demonstrated that WMSDs account for 27.5% of nonfatal injuries in U.S. construction workplaces [2], and 59% of recognized occupational diseases are associated with WMSDs [3]. Prolonged exposure to the risks of WMSDs is also linked to increased worker absenteeism, decreased productivity, and escalated healthcare expenditure and compensation claims [4]. Compounding these challenges are issues such as suboptimal worksite design, deficient tooling, improper equipment utilization, inadequate training, and a paucity of effective interventions, all of which exacerbate the risks of WMSDs in construction workplaces.

Amidst these complexities, the Occupational Safety and Health Administration (OSHA) remains committed to prioritizing worker safety and the cultivation of an ergonomic-friendly work environment [5,6]. OSHA emphasizes the assessment and mitigation of WMSDs and ergonomic hazards to create a safe work environment, which not only reduces mental stress, musculoskeletal pain, and absenteeism but also increases confidence and job satisfaction [5,7,8]. Therefore, identifying and mitigating ergonomic hazards is vital for the safety and wellbeing of workers and, in turn, for overall productivity, efficiency, and revenue within the construction industry.

In recent years, driven by the convergence of Industry 4.0 and Industry 5.0, there has been growing attention to emerging technologies to enhance safety within construction workplaces. These technologies include wearable sensors, virtual reality (VR), augmented reality (AR) and mixed reality (MR) (collectively called extended reality or XR), exoskeletons, and robotics [9–16]. Wearable motion-capture systems, equipped with multiple inertial measurement units (IMUs), are instrumental in tracking and analyzing workers' postures and movements [9,17]. These systems have been used to identify unsafe work postures and motions by capturing data on joint angles, range of motion, and body positioning, thereby facilitating ergonomic risk assessments [18–20]. Furthermore, physiological wearable sensors, such as heart-rate monitors, electrodermal activity sensors, skin-temperature sensors, eye trackers, and brainwave monitors, continuously monitor workers' activities and provide real-time feedback, effectively identifying high-risk activities and reducing occupational injuries [11]. Research efforts have been also focused on the development of safer personal protective equipment (PPE), clothing, and sustainable industrial solutions as key strategies for ensuring health, safety, and sustainability in various industrial environments [21,22]. While wearable sensors offer significant advantages in monitoring workers' safety and health, they also present challenges. These include discomfort due to the need for firm attachment to the body, potential interference with ongoing tasks, and concerns regarding data privacy and security [23].

XR technologies, through immersive training and assessment, empower workers to pretrain, assess, and rectify their hazardous tasks in an immersive environment, thereby proactively mitigating the risks of occupational injuries [14,24,25]. Furthermore, exoskeletons and robotics emerge as innovative solutions to alleviate muscular and joint strain and enhance workers' capabilities in physically demanding tasks [15,16,26,27]. Specifically, exoskeletons are wearable devices that provide physical support, reducing loads, strain, and force on muscles and joints, and augment workers' capacity in demanding activities such as heavy lifting and repetitive motions [16,26]. Robotics, on the other hand, comprise autonomous and remotely operated machines and assist in strenuous tasks, thereby reducing the reliance on manual material handling.

In the existing body of literature, numerous studies have explored the application of wearable sensors, XR, exoskeletons, and robotics to enhance safety within the construction industry. In a recent study conducted by Awolusi et al. [28], the potential of wearable technology for personalized construction safety monitoring and trend analysis was comprehensively explored. The study unveiled the transformative capabilities of wearable technologies, which have already found widespread use in other industries to enhance safety and productivity. They highlighted that the sensors and systems employed in existing wearable technologies from other sectors can be adapted for measuring and monitoring a wide range of safety performance metrics in construction. Ahn et al. [11] provided a comprehensive review of this category, highlighting the five key applications of these sensors, which include the prevention of WMSDs, fall prevention, workload and fatigue assessment, hazard recognition, and mental status monitoring. They identified challenges, such as signal artifacts, variable safety standards, technology adoption resistance, and uncertainty, surrounding return on investment.

Within the realm of XR, one notable study was conducted by Okpala et al. [29], which investigated the applications of emerging technologies, including building information modeling (BIM), unmanned aerial vehicles (UAVs), internet of things (IoT), exoskeletons, robotics, artificial intelligence (AI), VR, and AR in mitigating construction-safety risk [30–32]. They highlighted the potential of these technologies across different levels of the hierarchy of controls and throughout the project life cycle. However, the limitations of XR technologies include physical constraints on users, challenges in achieving accurate simulations, the need for substantial training and familiarization, significant costs, and limitations in real-time interaction and user immersion [33].

As for a review of exoskeletons and robotics, Zhu et al. [16] conducted an extensive review of the utilization of exoskeleton technologies in the construction industry. They thoroughly examined the advantages of exoskeletons, including fatigue reduction and muscle-strain alleviation, while also acknowledging potential issues such as load redistribution. By categorizing construction trades based on injury risks, they offered tailored recommendations for the adoption of exoskeletons, providing nuanced insights into the benefits and challenges. Wang et al. [34] explored exoskeleton technology in construction, assessing its potential to reduce physical strain and injuries. They also noted significant challenges, such as the need for more evidence to support widespread adoption, safety concerns, high costs, regulatory barriers, and technical limitations, including limited versatility, mobility, and battery life, as well as issues with user perception and acceptance. They emphasized the need to address these hurdles for successful integration, benefiting worker wellbeing and industry productivity. Moreover, a comprehensive exploration of advancements in the field of robotics in construction was presented by Xiao et al. [35]. Their methodology involved a mixed-method approach that combined bibliometric analysis with qualitative discussion. One of the significant contributions of this research lies in its quantitative presentation of the current publication landscape within robotics in construction on a macrolevel. However, there are limitations in using robotics for industrial safety, such as complex programming requirements, high costs, limited adaptability and flexibility, ongoing maintenance requirements, and concerns over potential job displacement [36]. To overcome the limitations, integrating digital fabrication (Dfab) and additive manufacturing technologies in construction has gained significant attention recently. These cutting-edge technologies have the potential to revolutionize traditional construction methods by increasing efficiency, reducing costs, and improving safety in construction workplaces. To achieve these goals, many research studies have explored implementing design for manufacture and assembly (DfMA) principles in Dfab and additive manufacturing processes [37–39].

Despite the extensive research conducted on the utilization of wearables, XR, exoskeletons, and robotics to advance the body of knowledge in the construction industry, it remains imperative to undertake a comprehensive examination of the research in these emerging technologies, with a specific focus on mitigating the risks of WMSDs and ergonomic hazards, as well as the bibliometric relationship of the literature and the impact of research themes in the field. Therefore, this study aims to analyze the publications, keywords, and citations' relationships with the three broad categories of emerging technologies: wearable sensors [40–43], XR [24,25,44], exoskeletons, and robotics technologies [15,16,27,45,46], in the field of occupational safety and health using scientometric analysis [47]. This study identifies the trends and key research themes and subsequently provides recommendations for future research directions.

2. Materials and Methods

This study employed bibliometric and scientometric analyses to review articles pertaining to three categories of emerging technologies: wearable sensors, XR, exoskeletons, and robotics. These analyses were conducted using VOSviewer software (version 1.6.19) [48] and biblioshiny (the shiny app for bibliometrix) software in the R programming language within R-studio [49]. The overall research procedure is illustrated in Figure 1. In the first stage, we conducted a bibliometric analysis, which involved the selection of an appropriate database, keyword search, and screening of papers based on titles and abstracts. For this review paper, articles were retrieved from the Scopus database, renowned as one of the largest repositories of peer-reviewed literature [50]. The second stage encompassed an exploration of annual publication trends and scientometric analyses of the selected documents, conducted using VOSviewer and biblioshiny software. The final stage involved presenting and discussing the findings derived from the bibliometric and scientometric analyses, as well as outlining potential avenues for future research.

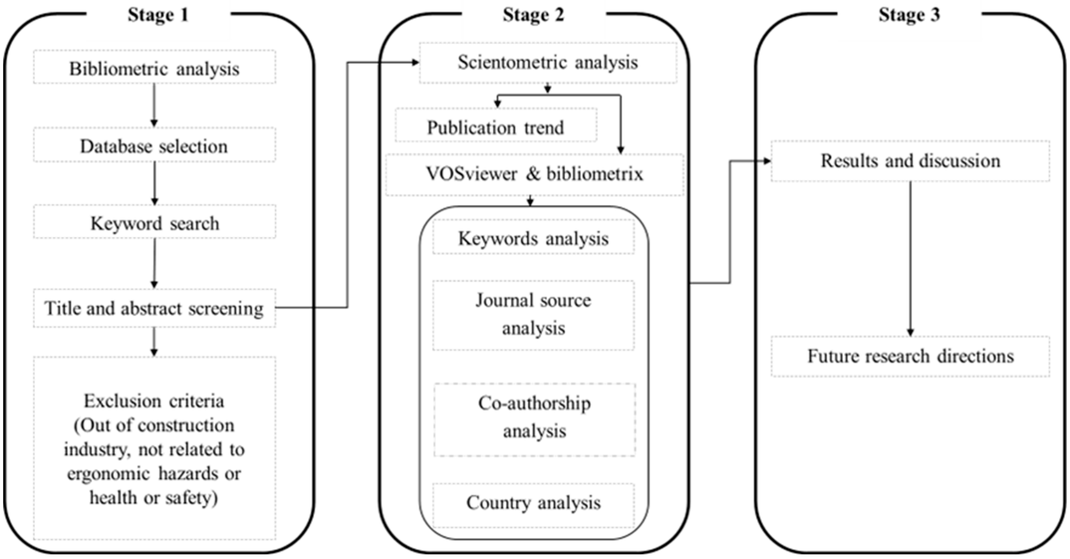

Figure 1. Overall research procedure with three stages.

2.1. Bibliometric Analysis

Bibliometric analysis was employed to identify the database, conduct keyword searches, and screen titles and abstracts within the field of study. This allowed for the identification of potential articles, journals, and authors, thereby providing a broader context for the research being conducted. Bibliometric analysis is a quantitative method applied to scientific literature that utilizes bibliographic data to identify trends, patterns, and relationships among different publications [51,52]. The statistical and mathematical approach enables researchers to gain insights into the intellectual structure and impact of research in a specific field. It also facilitates the evaluation of research productivity at both the individual and institutional levels. Additionally, bibliometric analysis is instrumental in identifying research gaps, emerging trends, and potential future research directions, thereby assisting in the formation of research questions and hypotheses [51,53,54].

Search Terminology and Data Processing

The initial stage of this paper entailed a literature search in the Scopus database accessed through the West Virginia University (WVU) library database system in March 2023. The search was conducted to retrieve publications related to emerging technologies in the reduction of ergonomic hazards in construction workplaces. Specific search terminologies were employed for each category, namely (1) wearable sensors: (wearable*) and ((ergonomic*) or (hazard*) or (safety*) or (health*)) and (construction*), (2) VR/AR/MR: ((“virtual reality*”) or (“augmented reality*”) or (“mixed reality*”)) and ((ergonomic*) or (hazard*) or (safety*) or (health*)) and (construction*), and (3) exoskeletons and robotics: ((exoskeletons*) or (robotic*)) and ((ergonomic*) or (hazard*) or (safety*) or (health*)) and (construction*).

In this study, we initially analyzed a comprehensive dataset of 2866 papers spanning the past two decades. This extensive pool allowed us to capture broad trends and developments in emerging technologies. To focus on the most recent and significant advancements, particularly in the era of Industry 4.0, we limited our analysis to 1603 publications from the period from 2018 to 2022. Specifically, these papers were selected based on specific criteria. The language of the document language was restricted to English; English language and the document types included journal papers, conference papers, review papers, and book chapters. Further refinement involved a detailed review of titles and abstracts from this subset, focusing on their relevance to ergonomic hazards, health, and safety in construction workplaces. This process led to the selection of 347 papers for indepth scientometric analysis. Finally, this screening process selected 347 papers for the scientometric analysis in the second stage, comprising 58 on wearable sensors, 152 on VR/AR/MR (collectively represented as XR subsequently), and 137 on exoskeletons and robotics.

2.2. Scientometric Analysis

The scientometric analysis aims to map and visualize the knowledge base within a specific field. This process involves the examination of publication trends, citation patterns, coauthorship networks, and collaborative efforts within the selected domain [47]. Throughout the process, it becomes feasible to identify key contributions, compare institutional research productivity, assess research articles, and determine the countries making substantial contributions. Furthermore, scientometric analysis provides insights into the evolution and impact of scientific research within the studied field. Notably, it offers advantages over manual analysis by providing a systematic and indepth exploration of the field through text mining and citation analysis, which can be challenging to achieve manually [55].

In this study, the scientometric analysis was conducted using VOSviewer, selected for its robust capacity to handle a substantial dataset and generate high-quality visual representations [55]. The specific analyses performed with VOSviewer encompassed keyword co-occurrence analysis, journal-source analysis, author analysis, and country coauthorship analysis. Additionally, this study employed bibliometrix analysis, a well-regarded tool for assessing and analyzing patterns, relationships, and trends within a specific body of literature. This analysis allowed for the computation of key metrics, such as the annual growth rate (%), international coauthorship (%), average citations per document, and coauthorship per document [47].

3. Results

3.1. Annual Publication Trends

The annual publication trends within three categories—wearable sensors, XR, and exoskeletons and robotics—are shown in Figure 2, spanning the years from 2000 to 2022. During this period, a total of 636 publications were dedicated to wearable sensors, 916 publications focused on XR, and 1314 publications centered on exoskeletons and robotics. Between 2000 and 2010, a gradual and intermittent growth pattern prevailed, characterized by a nominal volume of publications. Throughout this time frame, the number of publications within the domain of exoskeletons and robotics consistently exceeded that of the other two categories. An additional examination was conducted into the details of the technologies, including the range of sensors and devices utilized in each of the three categories. Wearable sensors include mainly IMUs for kinematics [40,56], photoplethysmography (PPG) or electrocardiography (ECG) sensors for cardiac activity [57,58], and electromyography (EMG) for muscle activity [59,60]. For XR, commonly used head-mounted displays include HoloLens, HTC Vive Pro2, Oculus Quest 2, and Google Glass Enterprise Edition 2 [61]. For exoskeletons and robotics, applications in industrial and research settings involve devices such as EksoVest [62], Levitate Airframe [63], Shimizu Manufacturing System by Advanced Robotics Technology (SMART) system [64], self-leveling automation [65], and 3D printing [66].

Starting from 2011 through 2017, a discernible upward trend in publications emerged across all three categories. Subsequently, spanning from 2018 to 2022, the annual publication growth rates were observed to be 68.18% for wearable sensors, 73.21% for XR, and 13.92% for exoskeletons and robotics. Notably, the publication counts for XR experienced significant growth, surging from 29 in 2016 to a peak of 157 in 2022, marking the highest number of publications for this category. Exoskeletons and robotics consistently maintained a higher publication volume than other categories, with a peak in 2021, recording the highest number of publications at 163. However, this trend shifted in 2022 when wearables sensors and XR attracted increasing research interest. This notable increase in publications during 2022 can be attributed to advancements in sensing technologies, which have enabled the capture of diverse types of data, thereby expanding research opportunities [27,61]. Furthermore, the global pandemic has accelerated the demand for XR applications across various disciplines, ranging from remote work and education to virtual healthcare and immersive training simulations in various industries [67–70].

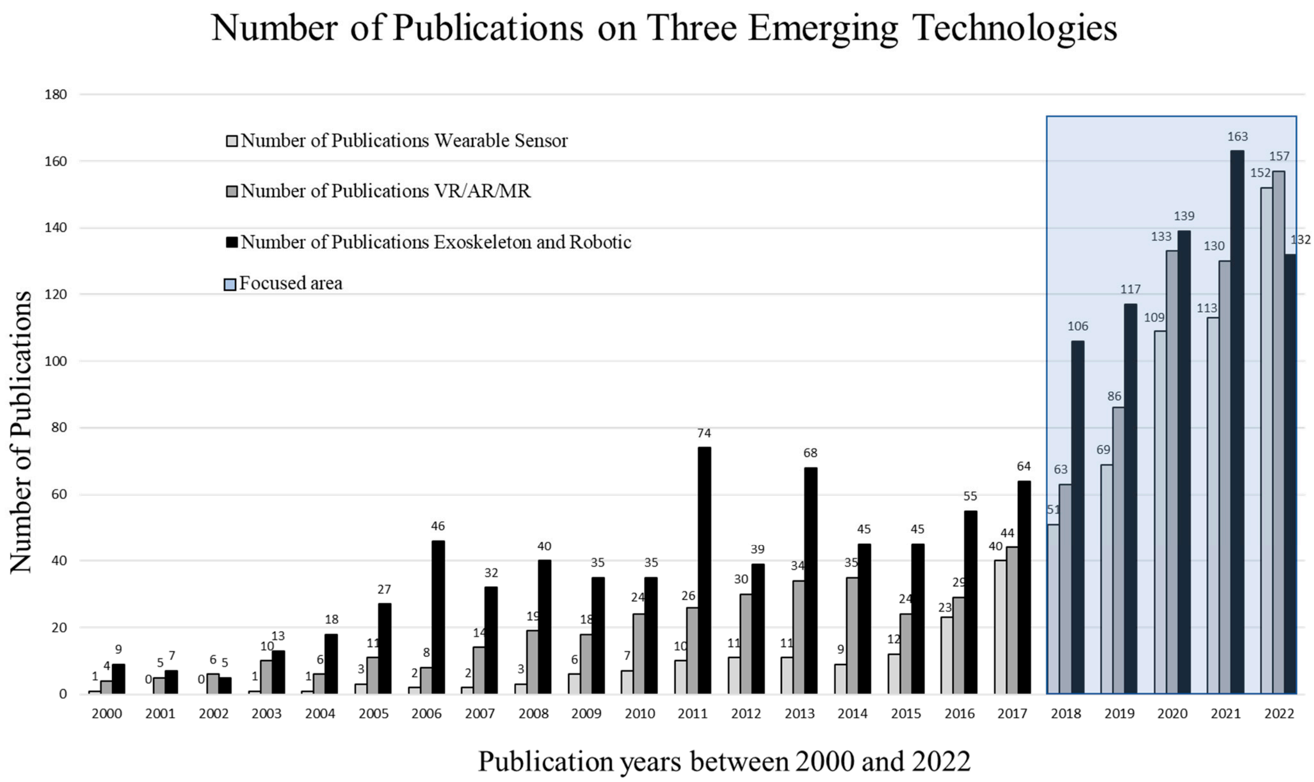

Figure 2. Annual publication trends of wearable sensors (light grey), XR (dark grey), and exoskeleton and robotics (block).

While the average annual publication numbers were around 64 between 2000 and 2017, this figure surged to 344 from 2018 to 2022, encompassing all three categories. This remarkable increase, amounting to a growth rate of 437.5% between 2018 and 2022, indicates the escalating research interest in the reduction of ergonomic hazards, signifying the increasing significance accorded to this field of inquiry by researchers. Consequently, these five years, spanning from 2018 to 2022, were selected for further analysis using VOSviewer and biblioshiny software.

3.2. Keyword Analysis

The keyword co-occurrence analysis was conducted to identify the primary research areas and significant keywords within each technology category. Co-occurrence refers to the frequency with which keywords appear together in a single document [71]. To enhance the precision of the analysis, synonymous terms were consolidated. For example, "construction environment" and "construction industry" were merged into "construction industry", while "health risks" and "health and safety" were combined into "health and safety". Subsequently, to refine the analysis, a minimum threshold of five occurrences was established.

Within the wearable-sensors category, an initial set of 589 keywords was selected. After refinement, 11 co-occurring keywords were identified and represented as nodes in the network map (Figure 3). The size of each circle corresponds to the frequency of the keyword's occurrence in the literature, with larger circles indicating more frequent usage and a greater number of associated documents [72]. The three most-prevalent keywords were "wearable technology", "ergonomic hazard", and "health and safety", highlighting the popularity and significance of "wearable technology" in mitigating ergonomic hazards and promoting health and safety in construction workplaces.

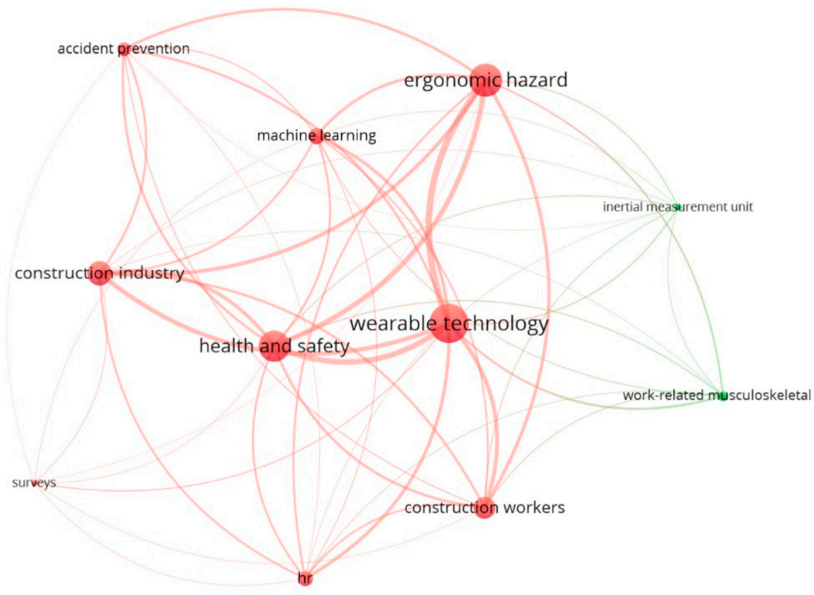

Figure 3. Keywords co-occurrence network map (wearable sensors).

The color of each circle indicates the degree of similarity among elements in the database. The width of the links connecting two circles within the network reflects the strength of the relationship or co-occurrence between these keywords. Wider links indicate stronger associations or co-occurrences. The presence of wide links between "wearable technology", "ergonomic hazard", and "health and safety" indicated the considerable emphasis placed by researchers on using wearable technology to identify and reduce ergonomic hazards, prioritizing health and safety considerations within construction workplaces.

The co-occurrence analysis of keywords in the XR category initially encompassed 1214, which were refined to a total of 36 keywords (Figure 4). The keywords "VR" and "construction workplaces" occupied the largest circle nodes within the network. Additionally, keywords such as "safety training", "health and safety", "education", "occupational risk", "BIM", and "AR" displayed larger circle nodes, signifying their close association with the XR domain to other keywords. An examination of link strength revealed a robust connection between "VR" and the keywords "safety training", "accident prevention", and "education", indicating a strong association with VR technology. Furthermore, the links extending from "construction industries" to "safety training", "VR", "AR", and "BIM" exhibited greater width, highlighting substantial connections between these keywords. These findings collectively indicate that XR technology has gained significant attention from researchers for applications in safety training, accident prevention, the reduction of ergonomic hazards, and educational purposes in construction workplaces. Yellow, blue, green and red colors refer to the four different clusters based on co-citations and co-authorship network (Figures 4 and 5).

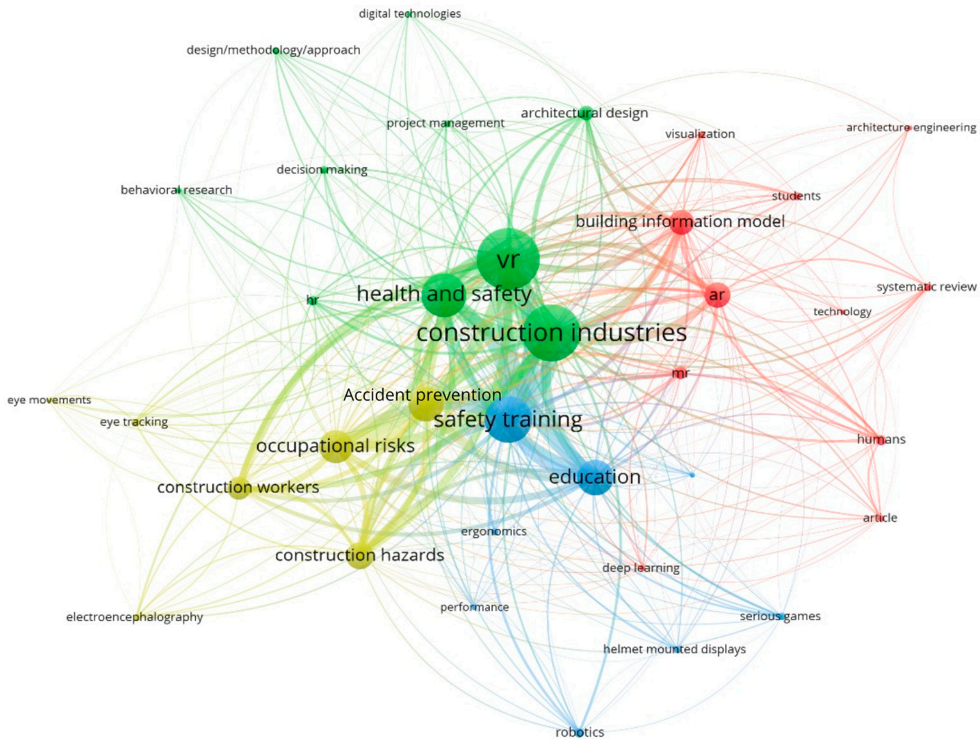

Figure 4. Keywords co-occurrence network map (XR).

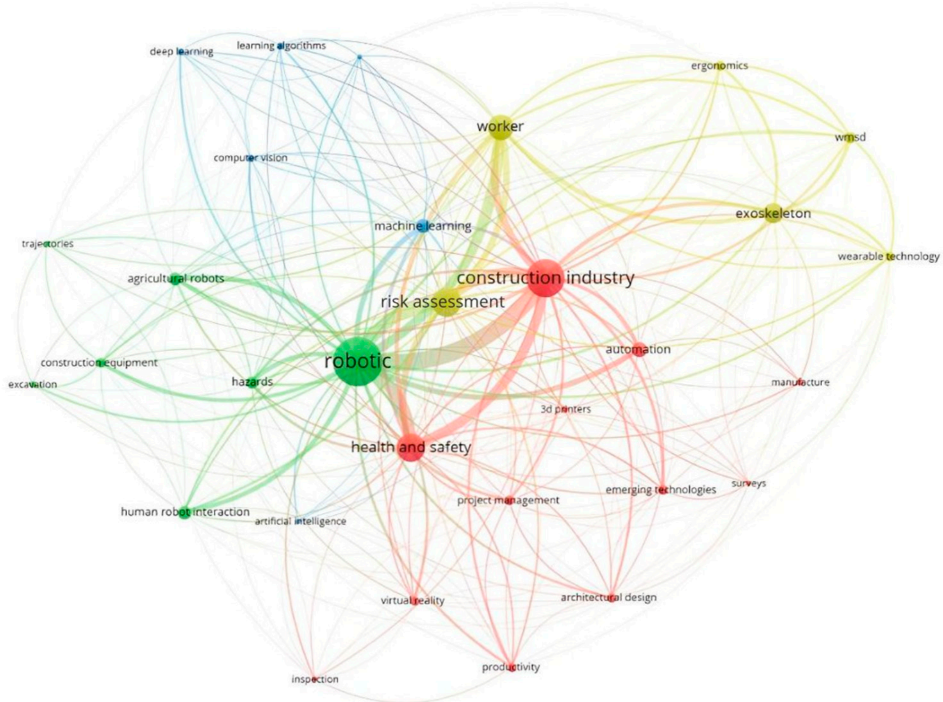

Figure 5. Keywords co-occurrence network map (exoskeletons and robotics).

Similarly, the keyword co-occurrence analysis within the exoskeletons and robotics category is presented in Figure 5. Out of 1299 keywords, 31 met the established threshold requirements. The circle nodes representing "robotic", "construction industry", "health and safety", and "risk assessment" were larger than other nodes, indicating their higher frequency of occurrences in the selected publications. Furthermore, the wider link strength between "robotic" and "construction industry" and "health and safety" underscored the substantial application of robotic technology within construction workplaces, specifically in addressing health and safety concerns and introducing exoskeletons and robotics to conventional worksites. These findings collectively indicate that, over the past five years, researchers have increasingly recognized the significance of risk assessment to ensure the health and safety of construction workers for the adoption of robotic technology.

3.3. Journal-Source Analysis

During the journal-source analysis, we selected "citations" as the type of analysis and "source" as the unit of analysis. Table 1 shows the summary of the selected publications with at least one citation, encompassing 14 different publication sources in the dataset. Within the wearable-sensors category, the results showed that "Automation in Construction" had the highest number of publications (N = 9) and total citations (C = 244). The "Journal of Construction Engineering and Management" followed as the second most influential journal (N = 7 and C = 233). Moreover, the bibliometrix analysis revealed that the average citations per document amounted to approximately 15.18, surpassing the other two categories. Similarly, it demonstrates that the "Automation in Construction" journal stands out with the highest number of publications (N = 12) and citations (C = 790) within the XR category. The "International Journal of Environmental Research and Public Health" had the second most citations (C = 426) with only four publications, signifying its influential research within this category. On the other hand, within the exoskeletons and robotics category, the conference proceedings of "The International Symposium on Automation and Robotics in Construction" featured the highest number of documents (N = 35), indicating it as a prominent platform for researchers to disseminate their work and findings. While "Automation in Construction" ranked second in terms of the number of publications (N = 5), it had the highest citation counts (C = 202). The bibliometrix analysis revealed an average of 9.61 citations per document, which is lower than the other two categories of emerging technologies. Collectively, the journal-source analysis collectively suggests that research published in "Automation in Construction" has garnered more attention and recognition within the scholarly community, with articles from this journal being frequently cited and referenced in other publications.

Table 1. Sources of publication and their citation numbers.

Category	Source	Numbers (N)	Citations (C)
Wearable sensors	Automation in Construction	9	244
	Journal of Construction Engineering and Management	7	233
	Construction Research Congress	5	13
	Advanced Engineering Informatics	4	73
	Engineering, Construction and Architectural Management	4	11
	Sensors	3	79
	Journal of Building Engineering	2	29
	Safety Science	2	79
XR	Automation in Construction	12	790
	Construction Research Congress	9	29
	Advanced Engineering Informatics	7	114
	Construction Innovation	7	62
	Engineering, Construction and Architectural Management	6	103
	Journal of Construction Engineering and Management	5	39
	Proceedings of the International Symposium on Automation and Robotics in Construction	5	7
	ASEE Annual Conference and Exposition, Conference Proceedings	4	1
	International Journal of Environmental Research and Public Health	4	426
	Safety Science	4	67
	Smart and Sustainable Built Environment	4	25

Table 1. *Cont.*

Category	Source	Numbers (N)	Citations (C)
Exoskeletons and robotics	Proceedings of the International Symposium on Automation and Robotics in Construction	35	106
	Automation in Construction	5	202
	Computing in Civil Engineering	4	5
	Construction Research Congress	3	5

3.4. Coauthorship Analysis

The coauthorship network analysis serves as a valuable tool to investigate author–publication relationships and research collaboration efforts among researchers [73,74]. Figure 6 shows the coauthorship network map within the domain of wearable sensors for occupational safety and health, generated using VOSviewer Coauthorship analysis. This network includes authors with a minimum of two joint publications, and the different cluster colors of the clusters represent distinct groups of authors based on their collaborative publications. The intensity of the connection between two authors is proportional to their number of coauthored publications, influencing their placement within the same cluster. The largest coauthorship cluster is comprised of a group of researchers from The Hong Kong Polytechnic University [75,76]. The second noteworthy group, exhibiting a substantial total link strength, originates from the University of Michigan [11]. The bibliometrix analysis further revealed an international coauthorship rate of 29.51%, with an average of 3.74 authors collaborating on each publication.

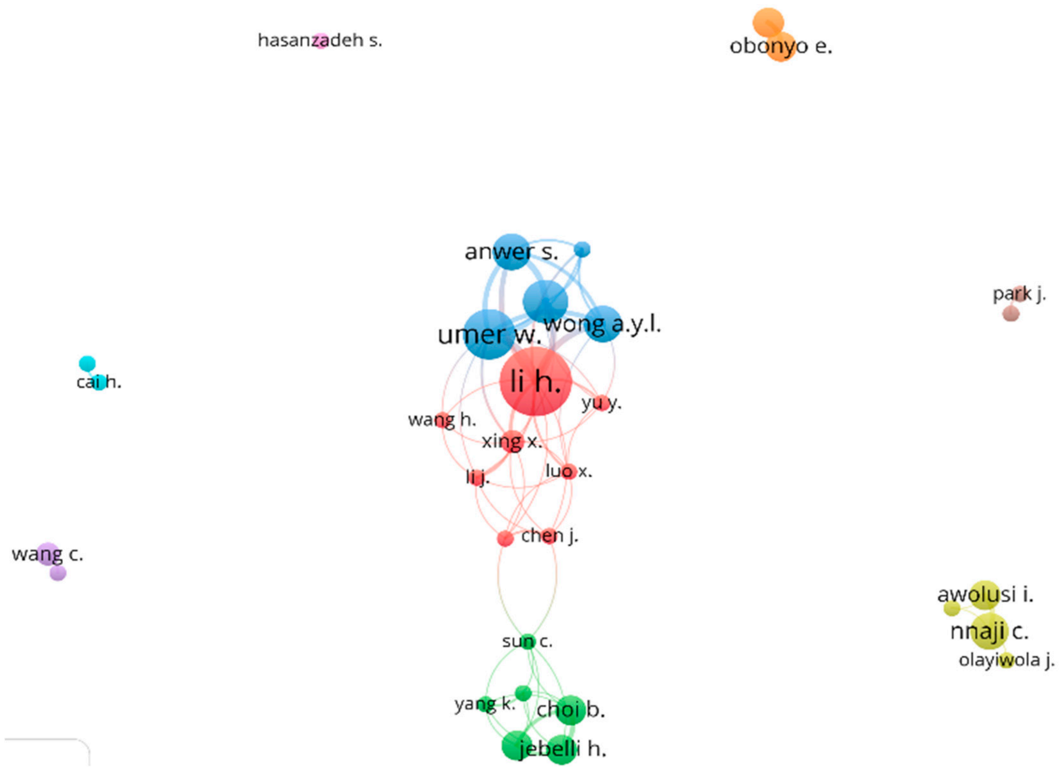

Figure 6. Coauthorship network map (wearable sensors).

The coauthorship network maps for the XR and exoskeletons and robotics categories are presented in Figures 7 and 8, respectively. Unlike the network map of wearable sensors, these two categories' coauthorship network maps show sparse clusters. The largest coauthorship cluster in XR consists of a group of researchers from Aarhus University, Denmark [77,78]. However, the coauthorship network map for exoskeletons and robotics shows similar cluster sizes, with researchers from the Georgia Institute of Technology [15,79] contributing the highest number of publications (N = 4). The bibliometrix analysis for the XR category resulted in an international coauthorship rate of 23.68% and an average of 3.83 coauthors per document, while the exoskeletons and robotics category revealed an international coauthorship rate of 20.44% and an average of 3.9 coauthors per document. The presence of sparse clusters in the XR and exoskeletons and robotics maps suggest that research efforts in these technologies within the field of occupational safety and health in construction are limited, as only a few coauthors have published at least two articles. Additionally, the international coauthorship rate of less than 25% indicates that research in this field should be expanded to include more regions and researchers.

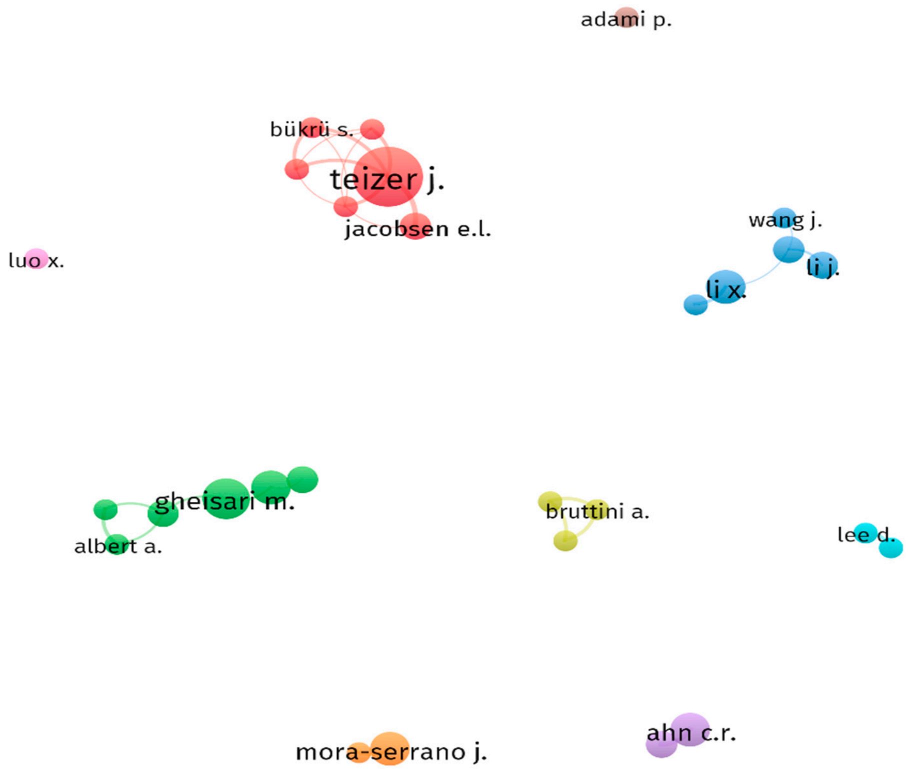

Figure 7. Coauthorship network map (XR).

The presence of sparse clusters in the XR and exoskeletons and robotics maps suggest that research efforts in these technologies within the field of occupational safety and health in construction are limited, as only a few coauthors have published at least two articles. Additionally, the international coauthorship rate of less than 25% indicates that research in this field should be expanded to include more regions and researchers. Table 2 presents a comprehensive breakdown of each author's contributions in terms of the number of publications, citations, and total link strength in each category.

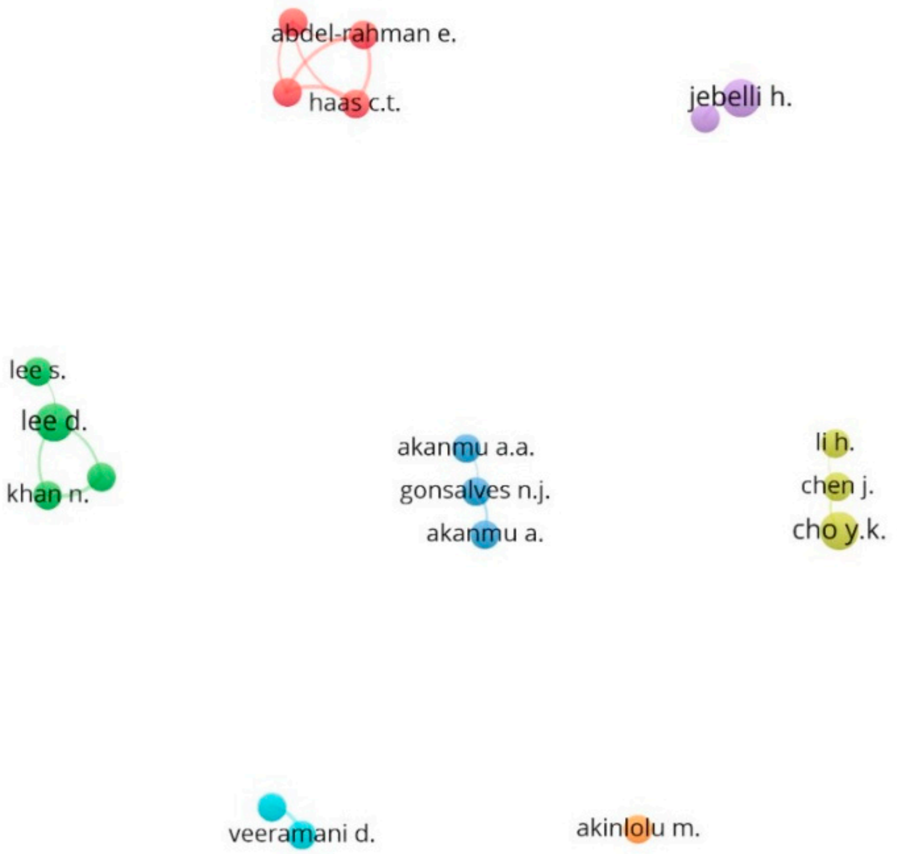

Figure 8. Coauthorship network map (exoskeletons and robotics).

Table 2. Comprehensive breakdown of publications, citations, and link strength for authors in each category.

Category	Author	Documents (N)	Citations (C)	Total Link Strength (T)
Wearable sensors	Li, H.	10	276	34
	Umer W.	7	154	26
	Antwi-Afari M.F.	6	76	22
	Anwer S.	5	49	18
	Nnaji C.	5	53	6
	Wong A.Y.L.	5	137	19
	Awolusi I.	4	50	5
	Choi B.	4	230	10
	Jebelli H.	4	230	10
	Lee S.	4	174	9
	Obonyo E.	4	49	4
	Zhao J.	4	49	4
XR	Teizer J.	9	62	16
	Gheisari M.	6	170	4
	Ahn C.R.	5	136	4
	Esmaeili B.	5	105	3
	Li X.	5	516	4
	Mora-Serrano J.	5	22	3
	Hasanzadeh S.	4	8	1
	Jacobsen E.L.	4	15	5
	Jeelani I.	4	50	6
	Kim N.	4	33	4
	Li J.	4	16	2
	Wang X.	4	846	4

Table 2. *Cont.*

Category	Author	Documents (N)	Citations (C)	Total Link Strength (T)
Exoskeletons and robotics	Cho Y.K.	4	78	2
	Jebelli H.	4	7	3
	Lee D.	4	20	5
	Abdel-Rahman E.	3	35	8
	Akanmu A.	3	3	2
	Akanmu A.A.	3	42	1
	Akinlolu M.	3	44	0
	Chen J.	3	46	3
	Gonsalves N.J.	3	12	3
	Haas C.T.	3	35	8
	Khan N.	3	4	5
	Lee S.	3	141	1

3.5. Country Analysis

The coauthorship by country analysis effectively assesses and visually represents collaboration patterns between or among countries [80]. In this analysis, a minimum threshold of two documents from a country was set, resulting in 8 countries meeting the requirements for wearable sensors, 14 countries for XR, and 14 countries for exoskeletons and robotics. Table 3 lists a summary of the number of publications per country, total citations, and total link strength in the context of coauthorship across all categories. Across all three categories, the United States emerges as the most prolific contributor, with 29 documents in wearable sensors, 46 documents in XR, and 47 documents in exoskeletons and robotics. These findings indicate the influential and widely cited research conducted in the United States. Hong Kong stands out for its robust coauthorship relationships with other countries, such as China, the United Kingdom, and Canada, indicating a strong international coauthorship network.

Table 3. Coauthorship by countries for wearable sensors, XR, and exoskeletons and robotics.

Category	Country	Numbers (N)	Citations (C)	Total Link Strength (T)
Wearable sensors	United States	29	444	6
	Hong Kong	11	294	14
	China	10	167	6
	South Korea	6	216	7
	United Kingdom	5	68	9
	Saudi Arabia	4	54	8
	Canada	3	20	3
	Australia	2	10	1
XR	United States	46	571	4
	China	17	487	15
	Australia	15	926	13
	United Kingdom	13	106	11
	Hong Kong	9	901	14
	South Korea	9	880	7
	Denmark	8	56	5
	Chile	7	30	7
	Germany	7	51	4
	Spain	6	34	6
	Canada	5	42	0
	Italy	5	122	0
	New Zealand	5	576	7
	South Africa	5	48	3

Table 3. *Cont.*

Category	Country	Numbers (N)	Citations (C)	Total Link Strength (T)
Exoskeletons and robotics	United States	47	601	6
	China	15	160	9
	Hong Kong	10	119	8
	Italy	8	69	1
	South Korea	8	27	2
	Canada	7	41	0
	India	7	36	1
	United Kingdom	7	243	8
	Germany	6	48	0
	South Africa	6	94	1
	Japan	5	8	0
	Australia	4	22	2
	Switzerland	4	89	4
	United Arab Emirates	4	60	4

In the XR category, the United States leads with the highest number of publications (N = 46), although it has relatively lower total citations (C = 571) and total link strength (T = 4) compared to other counties, such as Hong Kong, South Korea, and Australia. Notably, Australia, despite having one-third the number of published documents compared to the United States (N = 15), records the highest number of total citations (C = 926). Additionally, China exhibits the highest total link strength (T = 15), closely followed by Hong Kong (T = 14), suggesting that publications from these countries are frequently cocited with papers from other countries. Conversely, Canada and Italy show no connections in terms of research collaboration with other countries.

Similar patterns are observed in the exoskeletons and robotics category. The United States takes the lead with the highest number of publications (N = 47) and citations (C = 601), highlighting its significant research contributions in this category. China demonstrates strong total link strength (T = 9), indicating a high level of international collaboration, coauthorship, and significant connections and interactions among international researchers. Collectively, the United States leads in all categories within occupational health and safety in the construction domain in terms of the number of publications and citations, while China and Hong Kong exhibit robust international coauthorship networks.

4. Discussion

This section presents a detailed analysis of significant findings and emerging trends, providing insights into the evolving landscape of emerging technologies aimed at reducing ergonomic hazards within construction work environments. First, regarding the annual publication trends, it was observed that over two decades, spanning from 2000 to 2022, there was a notable increase in publications across all three categories, particularly in the most recent five-year period from 2018 to 2022, which exhibited a remarkable growth rate of 437.5%. This highlights the increasing recognition of the importance of this research domain among scholars and industry professionals. Furthermore, these results indicate a clear and sustained trend of rising research interest in the selected three categories of emerging technologies for mitigating ergonomic hazards in construction workplaces.

The keyword analysis revealed distinct research trends within each category. In the wearable-sensors category, the research emphasis has primarily been on leveraging wearable technologies to identify and mitigate ergonomic hazards, thereby prioritizing health and safety within construction workplaces. This research direction aligns with advancements in sensing technologies that enable the collection and analysis of various work-related datasets without interfering with workers' ongoing tasks. On the other hand, XR technology has gained significant attention for its applications in safety training and education. These immersive technologies create virtual training scenarios, enabling workers to acquire essential safety knowledge and techniques before applying them in real worksites, thus minimizing exposure to hazardous work scenarios. In contrast, research within exoskeletons and robotics technologies has centered on risk assessment to ensure the safety and health of workers before the adoption of these technologies, which are intended to enhance physical capabilities or facilitate human–robot collaborative work.

The analysis of journal sources found distinct patterns of citations and publications among the three technology categories. Notably, "Automation in Construction" emerged as a prominent source with the maximum number of citations and publications in the wearable-sensors and XR categories, signifying its potential impact in these areas. On the other hand, the "International Symposium on Automation and Robotics in Construction" stood out as the primary platform for research articles within the category of exoskeletons and robotics. These findings highlight the importance of leveraging these journal sources to facilitate effective communication and knowledge sharing within the selected field.

Through coauthorship analysis, two primary research clusters were identified in the category of wearable sensors. The first cluster is associated with the Hong Kong Polytechnic University, while the second is linked to the University of Michigan. Conversely, the coauthorship analysis within the categories of XR and exoskeletons and robotics revealed sparse clusters, suggesting limited research collaboration in these fields. These findings showed the need for broader geographical and interdisciplinary cooperation to advance research in occupational health and safety in construction industries.

The coauthorship by country analysis showed varying collaboration patterns between countries. While Hong Kong and China exhibit strong collaboration networks with the United Kingdom and Canada, the United States, despite having the highest number of publications across all three categories, showed a lower total link strength. These findings suggest that there is ample room for the United States to explore opportunities for international collaboration in the realm of construction workplace-safety technologies and make meaningful strides forward in this important field.

Future Research Directions

Based on the research trends in occupational safety and health in construction over the past five years, several emerging research directions are recommended. First, as indicated by the scientometric analysis results, most research in the three categories has centered on risk assessments and injury prevention. While many applications in the construction industry—particularly those utilizing wearable sensors and machine-learning algorithms such as support vector machine (SVM), *k*-nearest neighbors (KNN), artificial neural network (ANN), recurrent neural network (RNN), and long short-term memory (LSTM)—have extensively focused on recognizing or predicting predefined activities [40,81–85], it is essential to address the unstructured and dynamic nature of work environments in construction. Workers often perform a wide range of different risky tasks that are difficult to predefine. Therefore, future research should prioritize robust onsite and real-time recognition of unsafe activities to prevent injuries. Furthermore, the continuous collection of activity-related data in such technologies may raise privacy concerns among workers. Future research should, therefore, also focus on developing secure and encrypted data-process methods to safeguard workers' privacy.

The emergence of Industry 4.0 has marked a new phase of construction, characterized by the integration of digital technologies and cyber–physical systems, often referred to as smart construction. This transformation relies on disruptive technologies, such as AI, IoT, and big data, to make construction increasingly autonomous, dynamic, and demand driven [86]. However, this shift requires a highly skilled and trained workforce capable of operating and maintaining the advanced machinery and systems associated with these technologies [87,88]. Attracting such a skilled workforce has become a challenge in both major developed economies experiencing an aging and shrinking working-age population and in emerging economies grappling with rising labor costs. Addressing the growing challenge of attracting such a skilled workforce has become a challenge, especially in both major developed economies experiencing an aging and shrinking working-age population and in emerging economies grappling with rising labor costs. Future research should focus on requalifying and upskilling the existing workforce, identifying technical and nontechnical skills relevant to digital transformation and deriving requirements for training programs using XR. In addition, future study could focus on gathering qualitative data from construction workers through interviews and surveys to understand their perceptions of wearable sensors, XR, exoskeletons, and robotics technologies, and explore how these technologies affect their comfort, ability to work, work performance, and overall job satisfaction [89].

Exoskeletons offer substantial support for tasks involving heavy lifting or repetitive motions, thereby reducing physical strain and the risk of musculoskeletal injuries. However, their use can also impact mobility and may require adjustments in how certain tasks are executed. For example, while an exoskeleton can significantly reduce the effort required to lift heavy objects, it may also limit the range of motion, necessitating changes in work practices or the work environment. These tradeoffs are important to consider when integrating such technologies into construction work, ensuring adjustments in work practices or environments to accommodate these technologies.

While the adoption of full automation in construction has experienced a surge in research interest with the potential to enhance worker health and productivity by taking over physically demanding and repetitive tasks, full automation faces various practical challenges. These challenges include the intrinsic dynamic changes in worksites, the need for continued worker interventions, and regulatory considerations [65]. To overcome these hurdles, human–robot collaboration is essential; however, safety concerns in this context take precedence. Therefore, future research should systematically investigate the impact of safety and health for human–robot collaboration in the construction context. Consideration should also be given to developing safety standards specific to construction robots, addressing cost and technical barriers to industry adoption, and improving worker acceptance and receptivity to construction robots.

Lastly, considering the coauthorship analysis, future research should prioritize identifying the factors that significantly contribute to successful collaborations, such as institutional partnerships, funding initiatives, and knowledge-sharing platforms. Furthermore, examining the similarities and differences in technologies, strategies, policies, regulations, cultural contexts, and work environments among countries can provide valuable insights. Notably, previous research has highlighted that Japan and the United Kingdom have the second- and fourth-largest construction workplaces worldwide based on market size [90]. The results indicate the existence of significant partnership opportunities between researchers, universities, and industry stakeholders in those countries.

5. Conclusions

This study investigates the scientometric relationships within the field of occupational safety and health in the construction industry, with a specific focus on three emerging technology categories: wearable sensors, XR, and exoskeletons and robotics. Utilizing bibliometric and scientometric analyses, we examined 1603 articles for annual publication trends and performed keyword co-occurrence, journal-source, author, and coauthorship by country analyses on a selected subset of 347 articles. Notably, from 2018 to 2022, the annual growth rates were 68.18% for wearable sensors, 73.21% for XR, and 13.92% for exoskeletons and robotics. This analysis highlights significant trends in knowledge dissemination, collaboration patterns, and the impactful role of these technologies in enhancing construction health and safety.

The findings of this study highlight the significant role of advanced technologies in improving safety and health management within the construction industry. Wearable sensors show promise for real-time monitoring, potentially reducing onsite injury risks by alerting workers to hazards. Extended reality, particularly VR, significantly enhances safety training by simulating realistic scenarios while minimizing exposures to hazardous conditions that workers may face during onsite challenges. Furthermore, the integration of exoskeletons and robotics is increasingly recognized for its potential to reduce physical strain and injury risks in physically demanding tasks. These developments represent a crucial shift in the application of emerging technology for construction safety.

The conclusions provided in this study should be considered in the context of the limitations. The exclusive use of the Scopus database for data collection may have influenced the findings, suggesting that future research could benefit from a multidata base approach. Moreover, while this study relied primarily on publication analysis, the use of publication counts alone as an impact metric may be subject to ongoing debate. Future studies should consider incorporating additional indicators to offer a more nuanced understanding of the research landscape. Lastly, our study focused on quantitative analysis; a qualitative review in future research would provide a deeper insight into each paper, addressing another limitation of our current approach.

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