A science mapping-based review of work-related musculoskeletal disorders among construction workers

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Highlights

- A science mapping-based review on WMSDs among construction workers was conducted.
- Key collaboration networks in WMSDs among construction workers are visualized.
- Mainstream research topics within the studied research domain are discussed.
- Research gaps and directions for future studies are proposed.

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Abstract

Work-related musculoskeletal disorders (WMSDs) are recognized as a leading cause of non-fatal injuries in construction, but no review of existing studies has systematically analyzed and visualized the trends of WMSDs among construction workers. The current science mapping-based review summarized research published between 2000 and 2021 related to WMSDs among construction workers through co-word, co-author, and citation analysis. A total of 63 bibliographic records retrieved from the Scopus database were analyzed. The results identified influential authors with high impacts in this research domain. Moreover, the results indicated that musculoskeletal disorders, ergonomics, and construction not only had the highest occurrence of been studied but also the highest impact in terms of total link strength. In addition, the most significant contributions to research relating to WMSDs among construction workers have originated primarily from the United States, Hong Kong, and Canada. Furthermore, a follow-up in-depth qualitative discussion was conducted to focus on summarizing mainstream research topics, identifying existing research gaps, and proposing directions for future studies. This review provides an in-depth understanding of related research on WMSDs among construction workers and proposes the emerging trends in this research field.

Keywords: Construction workers, Literature review, Science mapping, Scientometric analysis, Work-related musculoskeletal disorders.

1. Introduction

The construction industry is one of the most important economic sectors across the globe due to its socio-economic influence (e.g., employment) and contribution to the gross domestic product (GDP) (Bogue, 2018). In the United States, the construction industry employs 11 million workers (Center for Construction Research and Training, 2018). In most countries worldwide, the construction industry contributes about 9% to 15% of GDP (Oesterreich and Teuteberg, 2016). Despite its huge economic importance, the construction industry is still globally regarded as one of the most hazardous and unsafe industries (Kong et al., 2018; Anwer et al., 2021a; Anwer et al., 2021b; Yu et al., 2021). According to the Bureau of Labor Statistics (BLS) in the United States, there were 5,333 fatal occupational injuries in 2019, representing a 2% increase from 5,250 in 2018 (BLS, 2020). Apart from these fatalities and nonfatal injuries, the annual cost of these construction injuries exceeds $48 billion—adversely impacting project success, profit margins, and the financial stability of construction practitioners (Zou and Sunindijo, 2015). Among the diverse sources of construction injuries, construction workers are at a high risk of developing work-related musculoskeletal disorders (WMSDs) (Wang et al., 2015a; Antwi-Afari et al., 2021).

WMSDs refer to injuries or disorders that affect the muscles, joints, nerves, tendons, cartilage, and spinal discs that occur due to work-related activities such as working in sustained positions and awkward postures, overexertion in carrying and lifting heavy loads, repetitive tasks, and whole-body vibrations (Wang et al., 2015a; Valero et al., 2016). As stated by the Health and Safety Executive (HSE) in the UK, WMSDs accounted for 57% of 81,000 work-related ill health cases (HSE, 2020). Examples of WMSDs include low back pain, shoulder pain, tendonitis, and carpal tunnel syndrome (Umer et al., 2017a; Antwi-Afari et al., 2018a; Anwer et al., 2021a). According to the Center for Construction Research and Training (CPWR), roofers and painters are on their knees, crouching or stooping more than 60% of the time, and brickmasons spend 93% of their time bending and twisting the body or doing repetitive motions (CPWR, 2018). The high prevalence rate of WMSDs among construction workers not only causes work absenteeism, schedule delays, and increased medical expenses, but also leads to loss of income and productivity, and early retirement (Umer et al., 2017a; Yu et al., 2021). Given the above, the prevention of WMSDs not only improves the health and safety of workers but also reduces the direct costs of WMSDs.

Numerous reviews have reported various aspects of WMSDs among construction workers. Sobeih et al. (2006) appraised the epidemiological literature linking psychosocial work factors to musculoskeletal disorders (MSDs) among construction workers. These authors used qualitative analyses such as a quality scoring checklist to assess and identify relevant articles. A state-of-the-art review has focused on risk factors of WMSDs in the construction industry and an overview of existing assessment methods regarding their advantages, limitations, applicability, efficiency, cost, and labor requirement (Wang et al., 2015a). Similarly, Valero et al. (2016) reviewed existing risk assessment frameworks of WMSDs among construction workers and presented a novel wearable wireless system based on wearable inertial measurement units (WIMUs) for tracking body postures and motions. Recently, Anwer et al. (2021a) conducted a systematic review to summarize the prevalent rates of WMSDs and quantified the associations between physical or psychosocial risk factors and WMSDs among construction workers. While other systematic reviews focused on synthesizing the global prevalence of MSDs in different construction trades, genders, and age groups (Choi et al., 2016; Umer et al., 2017a), very few traditional literature reviews had also focused on WMSDs among construction workers from secondary data in specific countries like India (Jaiswal and Veerkumar, 2016) and the United States (Schneider, 2001). Collectively, the traditional literature review studies that were based on manual analyses had provided relevant findings on the prevalent rates or associated risks for developing WMSDs among construction workers. Despite the numerous traditional review studies, research still lacks the exact dimensions of knowledge discovered, potential interventions, and emerging research areas. It is, therefore, crucial to conduct a review study that seeks to provide pathways for future research and a point of reference for practitioners, policy makers, and other researchers.

Given above, several areas of construction-related research fields such as building information modeling research (Zhao, 2017; Akram et al., 2019), construction safety research (Jin et al., 2019), sensor-based safety management (Asadzadeh et al., 2020), digital twin applications (Opoku et al., 2021), and off-site construction research (Hosseini et al., 2018) have utilized a science mapping approach. Science mapping— “a generic process of domain analysis and visualization” (Chen, 2017)—aims at the spatial representation of how disciplines, fields, and authors are related to one another within a body of literature (Small, 1999). The science mapping approach enables the measurement of research impact, the analyses of institutions and peer-reviewed journals, and provide a deeper understanding of scientific knowledge and citations (Leydesdorff et al., 2015).

Consequently, previous traditional review studies in the domain of WMSDs could be enhanced. However, no reviews have used the science mapping approach to analyze the existing global body of knowledge on WMSDs among construction. Therefore, this study aimed to conduct a science mapping-based review of the scientific literature relating to WMSDs among construction workers and to gain a deeper understanding of this research field over the past two decades (2000 to 2021). The specific research objectives of this review study included: (1) applying a science mapping approach to analyze the keywords, authors, countries/regions, journals citation, and documents analysis related to WMSDs among construction workers; (2) analyzing the existing key research topics in WMSDs among construction workers; and (3) highlighting the limitations or gaps for future research studies in WMSDs among construction workers. The findings of this review can provide researchers and construction practitioners with a better understanding of the holistic body of knowledge of WMSDs among construction workers and identify key research topics and preventive measures to mitigate the risk of developing WMSDs.

2. Methods

To achieve the overarching goal, this review study adopted a four-step comprehensive literature review approach. Figure 1 depicts the outline of the research methods. The four main steps involved: (1) literature search; (2) literature selection; (3) science mapping analysis; and (4) qualitative discussion. A detailed discussion of four main steps is presented in the following sections.

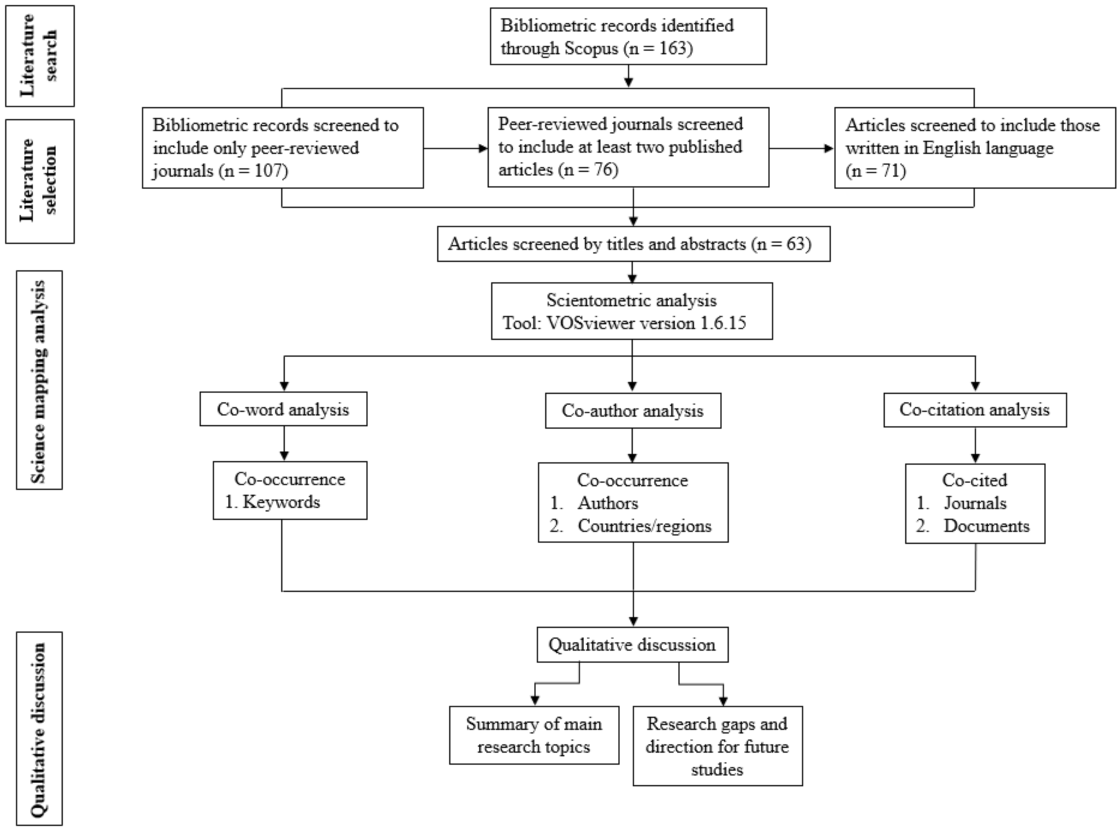

Fig. 1. Outline of research methods

2.1. Literature search

The first step of this research was to conduct a systematic literature search in the Scopus database. In this review, two main keywords, namely: “work-related musculoskeletal disorders” and “construction workers” were used as search terms in Scopus to retrieve the bibliographic records associated with published articles in the domain of WMSDs among construction workers. A systematic literature search was conducted under the “article title/abstract/keywords” field in Scopus to identify bibliographic records. The Scopus database was selected because it performs better in terms of its accuracy, faster indexing process, relatively wide range of coverage, and the availability of more recent publications compared with other databases such as PubMed, Web of Science, Google Scholar, and among others (Falagas et al., 2008; Mongeon and Paul-Hus, 2016). The search period was set to include bibliographic records from the last 21 years, 2000 to 2021 (as of the end of 31st May 2021). As such, the full search string for Scopus was: (TITLE-ABS-KEY (work-related AND musculoskeletal AND disorders) AND TITLE-ABS-KEY (construction AND workers) AND DOCTYPE (all) AND ACCTYPE (all) AND PUBYEAR > 1999). A total of 163 bibliographic records including articles, book chapters, reviews, and conference papers were identified in the first step through Scopus.

2.2. Literature selection

The second step of this review study involved the selection of relevant articles. The following criteria were used in this research. First, bibliographic records related to book chapters, reviews, and conference papers were excluded. As such, a total of 56 bibliometric records were excluded. Second, the selection criterion of peer-reviewed journal articles was to include only journals that have at least published 2 peer-reviewed articles during the studied period. Accordingly, a total of 31 articles were excluded. The third criterion was to include articles that are written in English. Five articles written in other languages were identified and excluded. After removing the ineligible peer-reviewed articles, all potential articles were exported into EndNote X9 (Thompson Reuters, New York, USA). The authors then conducted a comprehensive review by screening the titles and abstracts of 71 articles to identify the relevant articles related to the main theme of this study—"WMSDs among construction workers". During this screening process, articles were removed when the contents did not specifically involve WMSDs among construction workers. For instance, articles (see e.g., Stocks et al., 2010; Van der Molen et al., 2012;

Marcum and Adams, 2017) that reported the annual incidence rate of occupational diseases (e.g., hearing loss, contact dermatitis, pneumoconiosis) among major occupations and economic sectors were excluded. As a result, 8 articles were excluded and a total of 63 articles were used for further analysis as of 31st May 2021.

2.3. Science mapping analysis

In the third step, a science mapping approach was adopted to analyze the included articles on WMSDs among construction workers. A science mapping analysis can be applied to a bibliometric or scientometric analysis techniques (Hosseini et al., 2018). While bibliometric analysis focuses on the literature, a scientometric analysis measures research impact and maps the current scientific knowledge and its evolution in a specific domain based on a body of literature (Zhao, 2017; Martinez et al., 2019; Wu et al., 2020). Therefore, the current study adopted a scientometric analysis technique to provide a scientific domain and visualization of research on WMSDs among construction workers. Numerous science mapping tools such as BibExcel, CiteSpace, CoPalRed, Gephi, IN-SPIRE, Science of Science tool, VOSviewer, and among others are available for analyzing and visualizing the bibliometric network of scientific research (Cobo et al., 2011; Kumar et al., 2015). Among them, VOSviewer version 1.6.15 was selected because it is a freely available visualization and user-friendly tool for network mapping analyses (Van Eck and Waltman, 2010). By adopting VOSviewer as a science mapping tool, five types of scientometric analyses and visualizations were conducted in this research. They were: (1) co-occurrence of keywords; (2) co-occurrence of authors; (3) co-occurrence of countries/regions; (4) journal citation network; and (5) document citation analysis.

2.4. Qualitative discussion

Following the science mapping analyses, the final step was a qualitative discussion that aims to provide an in-depth evaluation underlying the scientific contribution to the key research areas in WMSDs among construction workers, research gaps in the current study, and directions of future studies in the domain of WMSDs among construction workers.

3. Results

3.1. Selection of relevant peer-reviewed journals

The literature selection strategies as discussed in Section 2.2 were used to identify relevant articles published in peer-reviewed journals. Table 1 illustrates the selection of relevant peer-reviewed journals with related articles on WMSDs among construction workers during the studied period. As shown in Table 1, a total of 13 peer-reviewed journals were identified from search strategies. Among the top 5 peer-reviewed journals were *American Journal of Industrial Medicine, Work, Automation in Construction, Journal of Construction Engineering and Management, and Applied Ergonomics,* representing 68.25% of the total published articles on WMSDs among construction workers. The highest number of relevant articles was published in *American Journal of Industrial Medicine* (Table 1).

Table 1. Selection of relevant peer-reviewed journals with related articles on WMSDs among construction workers from 2000 to 2021 (31^{st} May 2021)

Journal name	Number of relevant articles	% Total publications
American Journal of Industrial Medicine	11	17.46
Work	10	15.87
Automation in Construction	9	14.29
Journal of Construction Engineering and Management	7	11.11
Applied Ergonomics	6	9.52
Ergonomics	4	6.35
Journal of Safety Research	3	4.76
Occupational and Environmental Medicine	3	4.76
Advanced Engineering Informatics	2	3.17
Applied Occupational and Environmental Hygiene	2	3.17
International Journal of Occupational Safety and Ergonomics	2	3.17
Journal of Computing in Civil Engineering	2	3.17
Journal of Occupational and Environmental Hygiene	2	3.17
Total	**63**	

3.2. Keywords co-occurrence analysis

Keywords mostly represent the core content of published articles, and they describe specific areas of research topics conducted within any given domain (Van Eck and Waltman, 2010). In this review, keywords co-occurrence analysis was conducted to construct and map the knowledge domain of WMSDs among construction workers. By using “author keywords” as the unit of analysis and “full counting” as the counting method in VOSviewer and by setting the minimum number of occurrences of a keyword to 2, only 28 out of the total 191 keywords met the threshold. It is noteworthy that the threshold selection was based on multiple trials with other parameters to generate the optimal clusters. Further investigation was performed on some keywords with similar contextual meanings such as: (1) “work-related musculoskeletal disorders” and “work-related musculoskeletal disorder” and (2) “musculoskeletal disorders” and “musculoskeletal disorder”. This investigation of keywords analysis was conducted to either remove general keywords or combine keywords with similar meanings. Ultimately, the network of keywords co-occurrence analysis showed 26 items, 5 clusters, 66 links, and 99 link strengths, as depicted in Fig. 2.

As shown in Fig. 2, author keywords such as “work-related musculoskeletal disorders”, “musculoskeletal disorders”, “construction”, “construction workers”, and “ergonomics” have larger font size, indicating the frequency of how these keywords have been used in previous studies in the studied research domain. The distances and connection lines in Fig. 2 show the inter-relatedness between a pair of keywords. For example, the keyword “ergonomics” was closely related to biomechanical analysis, construction worker safety, prevention through design, residential construction, and risk assessment. From the different colors as illustrated in Fig. 2, the authors' keywords can be categorized into 5 main clusters of keywords that represent the mainstream knowledge domains of research related to WMSDs among construction workers:

1. Ergonomic risk assessment methods have been widely studied to identify potential risk factors associated with WMSDs among construction workers (Choi, 2010; Antwi-Afari et al., 2017b; Wang et al., 2017; Nath et al., 2018; Antwi-Afari et al.,

2020a; Yang et al., 2020; Seo and Lee, 2021; Antwi-Afari et al., 2022). Several practical ergonomic recommendations such as prevention through design, which allow for proactive control of WMSD risks have been conducted to have substantial benefit among residential construction workers (Albers et al., 2005; Nussbaum et al., 2009; Kim et al., 2011). With the recent ergonomic risk assessment methods (e.g., vision-based and wearable sensors), human motion data are used to improve construction workers' safety through biomechanical analysis (Golabchi et al., 2015; Seo et al., 2015; Antwi-Afari et al., 2017b; Valero et al., 2017; Lee et al., 2020).

2. Understanding the perception and knowledge of workers and safety managers in the construction industry has shown a critical role to prevent musculoskeletal injuries and implement participatory ergonomics interventions such as ergonomic training programs, education, and policies (Goldsheyder et al., 2004; Albers et al., 2005; Dale et al., 2016; Sneller et al., 2018; Akanmu et al., 2020; Gholami et al., 2020; Kincl et al., 2020; Anumba et al., 2021).

3. There is a high prevalence rate of WMSDs among construction workers such as rebar workers and masons. Effective ergonomics interventions have been demonstrated to reduce masons' exposure to WMSDs risks (Anton et al., 2005; Entzel et al., 2007; Hess et al., 2010; Anton et al., 2020). Similar studies have been conducted during manual rebar tying and bricklaying (Choi, 2010; Umer et al., 2017c; Ryu et al., 2021).

4. Numerous health and economic issues of construction workers have been associated with WMSDs risks. By using administrative data, previous studies have examined the association between workers' compensation and musculoskeletal injuries among a cohort of union carpenters over a period of time (Lipscomb et al., 2009; Lipscomb et al., 2015). The prevalence of work-related disability associated with MSDs symptoms among construction workers has been well-studied (Merlino et al., 2003; West et al., 2016; Yang et al., 2021).

5. With the advancement of wearable sensing techniques (e.g., wearable measurement inertial units, wearable insole pressure system) combined with data mining techniques such as supervised machine learning classifiers and deep learning networks, researchers have demonstrated the feasibility of collecting human motion and gait patterns for recognizing work-related risk factors and workplace activities that may lead to WMSDs (Antwi-Afari et al., 2018f; Nath et al., 2018; Antwi-Afari et al., 2020a; Anwer et al., 2020; Lee et al., 2020; Yang et al., 2020; Antwi-Afari et al., 2022).

Table 2 shows the keyword occurrences and each node strength. As shown in Table 2, "musculoskeletal disorders", "ergonomics", and "construction" were the most frequently used keywords among all the list of keywords, indicating that they have been widely researched in the domain of WMSDs among construction workers. While the links are the number of linkages between a given node and other nodes, the total link strength shows the total strength linked to a specific item (Van Eck and Waltman, 2010). Notably, the authors' keywords listed in Table 2 follow the ranking of the total link strength. For instance, the total link strength of "ergonomics" is 20, which shows a strong inter-relatedness between "musculoskeletal disorders" and "ergonomics".

To present an overview of the keyword co-occurrence network over changes in time, the current study used the overlay visualization function in VOSviewer. Fig. 3 depicts the timeline of keyword co-occurrence network related to WMSDs among construction workers. At the beginning of the studied period, from 2000 to 2005 (years inclusive), previous studies focused on symptoms of MSDs among construction workers (i.e., mason tenders, floor layers, ironworkers, and concrete workers) (Goldsheyder et al., 2002; Jensen et al., 2002; Goldsheyder et al., 2004; Hess et al., 2004; Forde et al., 2005). Ergonomic training was the main participatory ergonomic intervention used to mitigate the potential risk factors for developing symptoms of WMSDs. Between 2006 and 2010 (years inclusive), extant literature focused on adopting ergonomic risk assessment tools such as the BodyMap instrument to evaluate the risk of WMSDs in highway construction and residential construction workers (Choi, 2010). Overall, the findings indicated that ergonomic assessment tools could assist in the early identification of work-related risk factors and could be used as effective interventions to mitigate such risks. Unsurprisingly, more generalized keywords such as "construction workers", "prevention through design", "risk factors", "biomechanical analysis", "rebar tying" are shown in several years from 2011 to 2015. This result could be due to the application of biomechanical models to assess work-related risk factors (e.g., awkward postures, forceful exertions) for the development of WMSDs based on motion data collected from construction workers during occupational tasks. In the recent 6 years (i.e., 2016 to 2021), keywords such as "supervised machine learning classifiers", "wearable insole pressure system", and "construction worker safety" were frequently used by researchers within the studied domain. It indicated that wearable sensing technologies and more advanced computational analyses (e.g., machine learning classifiers, deep learning networks) have been gaining wider applications in WMSDs among construction workers in recent years. The latest published articles on automated recognition of work-related risk factors and workers' activities that could lead to WMSDs show a potential shift in the focus of research in this studied domain (Antwi-Afari et al., 2018f; Nath et al., 2018; Antwi-Afari et al., 2020a; Lee et al., 2020; Yang et al., 2020; Seo and Lee, 2021; Antwi-Afari et al., 2022). While earlier research contributions considered recommending ergonomics interventions to mitigate the risk of developing WMSDs among construction workers, recent publications are more specific on the advancement of using wearable sensing technologies combined with either machine learning classifiers or deep learning networks for automated identification and classification of work-related risk factors and workers' activities that may lead to the development of WMSDs.

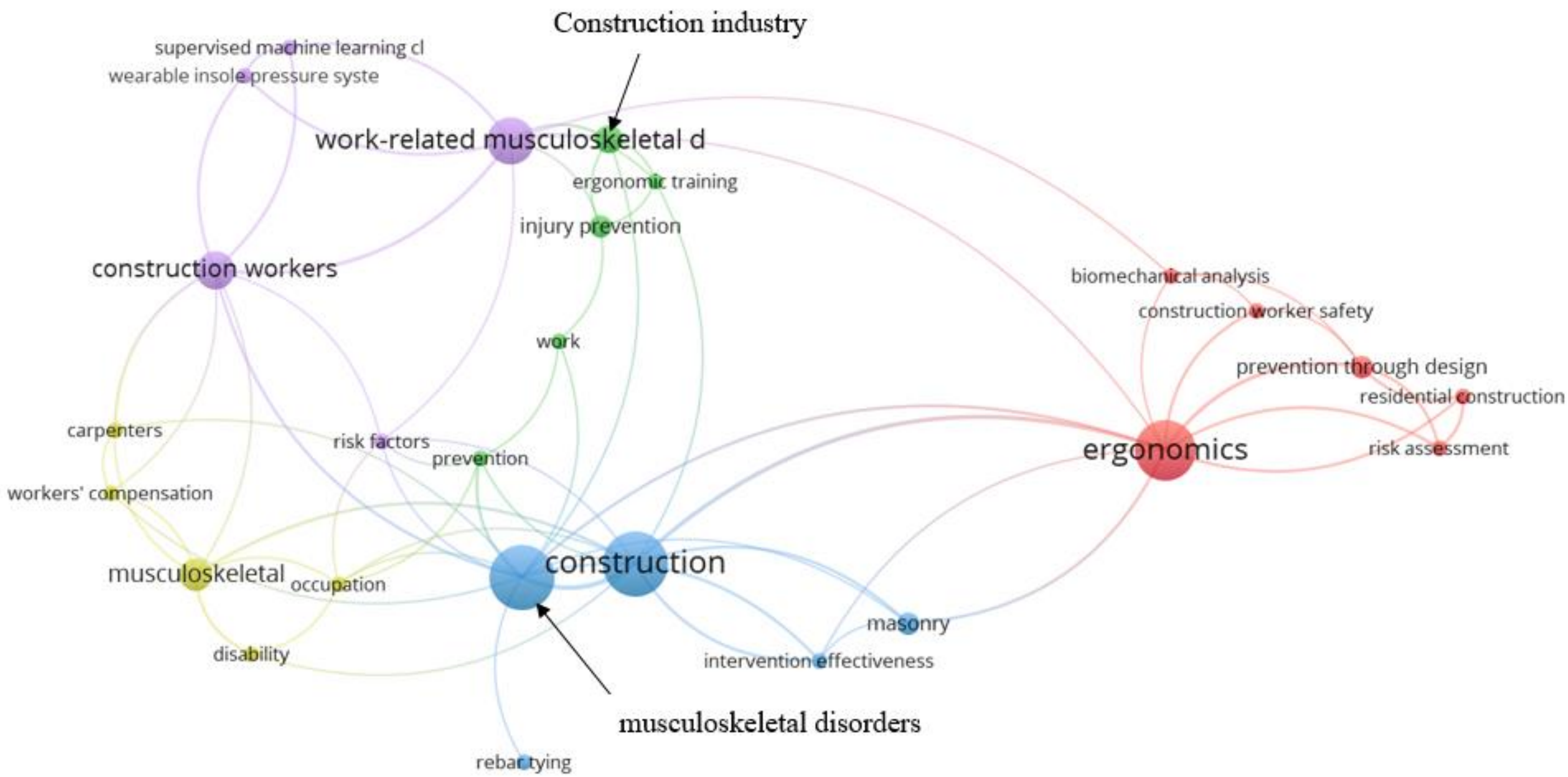

Fig. 2. A network of co-occurring keywords related to WMSDs among construction workers (2000 to 2020)

Table 2. List of selected keywords and relevant network data

Keywords	Occurrences	Avg. pub. year[a]	Links	Avg. citations[b]	Avg. norm. citations[c]	Total link strength
Musculoskeletal disorders	12	2009	13	19.42	0.67	21
Ergonomics	11	2012	10	21.45	1.10	20
Construction	12	2010	10	25	0.89	20
Work-related musculoskeletal disorders	8	2015	9	17	1.17	14
Construction workers	6	2013	8	13.67	0.90	14
Prevention through design	3	2011	5	23	1.26	9
Musculoskeletal	5	2011	6	25.60	0.77	8
Construction industry	4	2007	4	25.25	0.90	5
Masonry	3	2007	4	31.33	1.30	6
Intervention effectiveness	2	2006	4	16	0.45	6
Occupation	2	2007	6	50.50	0.85	6
Prevention	2	2007	5	20	0.69	6
Residential construction	2	2010	3	19	1.10	6
Risk assessment	2	2010	3	19	1.10	6
Risk factors	2	2013	6	14.50	1.10	6
Supervised machine learning classifiers	2	2019	3	3.50	0.94	6
Wearable insole pressure system	2	2019	3	3.50	0.94	6
Injury prevention	3	2011	4	16	0.81	4
Biomechanical analysis	2	2015	4	34.5	1.76	4
Carpenters	2	2012	4	7.50	0.53	5
Construction worker safety	2	2016	3	17.50	0.89	4
Disability	2	2009	3	49.50	0.88	4
Ergonomic training	2	2003	4	42	0.93	4
Work	2	2009	3	21.50	0.96	3
Workers' compensation	2	2014	4	8	0.56	4
Rebar tying	2	2013	1	9	0.44	1

[a] Avg. pub. year represents the average publication year of articles

[b] Avg. citations represent the average citations

[c] Avg. norm. citations represent the average normalized citations

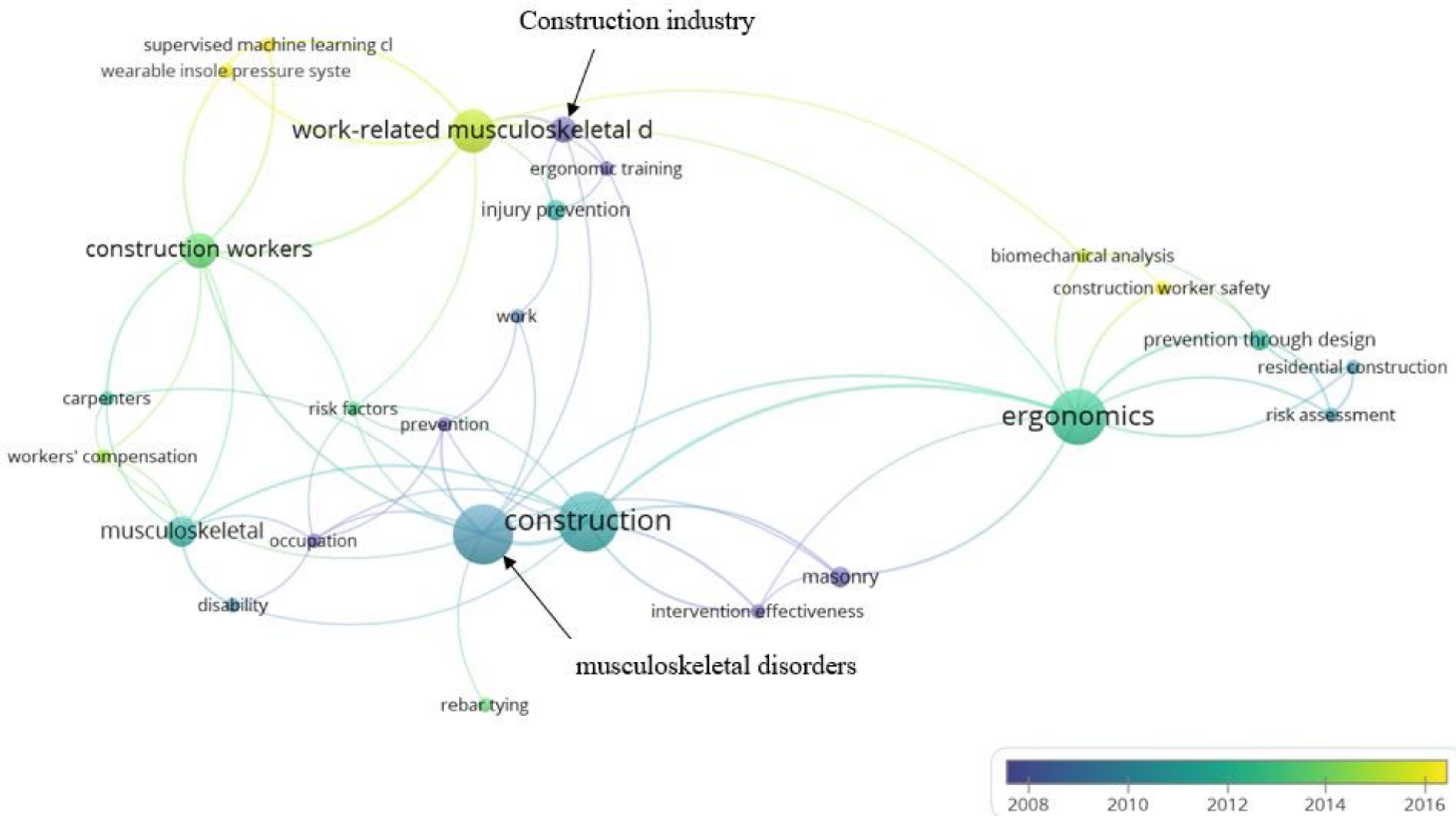

Fig. 3. A network of co-occurring keywords timeline related to WMSDs among construction workers

3.3. Co-author co-occurrence analysis

Since bibliographic records include information regarding the names of authors, it is plausible to present the leading researchers in the studied domain by using VOSviewer. In this study, the minimum number of documents of an author and the minimum number of citations of an author were set at 2 and 25, respectively. Consequently, out of 198 authors, a total of 24 authors met the thresholds.

Table 3 summarizes the quantitative analysis of co-occurrence of authors in the studied domain. The authors are listed based on their total link strength. As depicted in Table 3, Cameron, W., Lipscomb, H. J., and Schoenfisch, A. I. occupied the top three influential authors measured by their total link strength in the studied research domain. The average publication year represents the recentness of publications of authors. As seen in Table 3, Antwi-Afari, M. F., Yu, Y., and Li, H. are the most active researchers in the research domain of WMSDs among construction workers. It was found over the past decade (i.e., 2010 to 2019) that about 20 authors have been the most active researchers (Table 3). Lastly, as shown in Table 3, Cameron, W., Lipscomb, H. J., Anton, D., and Li, H. are the most productive authors with the highest number of articles related to WMSDs among constructions during the studied period.

Table 3. Quantitative summary of impacts of authors in the research domain related to WMSDs among construction workers

Author name	Number of articles	Total citations	[a]Norm. citation	[b]Avg. pub. year	[c]Avg. citations	[d]Avg. norm. citations	Total link strength
Cameron, W.	4	35	2.08	2013	8.75	0.52	10
Lipscomb, H. J.	4	35	2.08	2013	8.75	0.52	10
Schoenfisch, A. I.	3	27	1.46	2015	9.00	0.49	8
Han, S.	3	95	4.41	2016	31.67	1.47	7
Lee, S.	3	83	10.07	2017	27.67	3.36	7
Seo, J.	3	83	10.07	2017	27.67	3.36	7
Adams, D.	3	39	1.37	2016	13.00	0.46	6
Anton, D.	4	82	2.03	2013	20.50	0.51	6
Golabchi, A.	2	58	2.57	2016	29.00	1.29	5
Welch, L.	3	65	3.93	2013	21.67	1.31	5
Al-Hussein, M.	2	67	3.70	2014	33.50	1.85	4
Antwi-Afari, M. F.	2	26	3.25	2019	13.00	1.63	4
Buchholz, B.	2	36	2.22	2016	18.00	1.11	4
Cook, T. M	2	80	1.29	2005	40.00	0.65	4
Dale, A. M.	3	36	2.22	2017	12.00	0.74	4
Li, H.	4	145	6.36	2018	36.25	1.59	4
Rosecrance, J. C.	2	80	1.29	2005	40.00	0.65	4
Yu, Y.	2	26	3.25	2019	13.00	1.63	4
Hess, J. A.	3	29	2.39	2017	9.67	0.80	3
Kim, S.	2	44	2.38	2010	22.00	1.19	2
Nussbaum, M. A.	2	44	2.38	2010	22.00	1.19	2
Silverstein, B.	2	148	2.61	2006	74.00	1.30	2
Albers, J.	2	60	2.52	2006	30.00	1.26	1
Kincl, L.	2	27	1.65	2016	13.50	0.83	1

[a]Norm. citation = Normalized citation; [b]Avg. pub. year = Average publication year; [c]Avg. citations = Average citations; [d] Avg. norm. citations = Average normalized citations.

3.4. Countries/regions co-occurrence analysis

This section discusses the contributions of countries/regions in the research domain of WMSDs among construction workers. By using VOSviewer as a science mapping tool, the minimum number of documents of a country/region and the minimum number of citations of a country/region were set at 2 and 25, respectively. Out of 20 countries, a total of 5 countries/regions met the threshold.

Table 4 illustrates the quantitative analysis of active countries/regions in the research of the studied domain. The countries/regions listed in Table 4 are based on the normalized citations during the studied period. In terms of the number of published articles and total link strength, the most productive country/region is the United States, followed by Hong Kong, Canada, China, and the United Kingdom (Table 4). As depicted in Table 4, the United States is the most influential country/region based on normalized citations in the studied research domain. While the average publication year of Canada, China, and the United Kingdom was 2017, that of the United States and Hong Kong were 2013 and 2018, respectively. These findings indicate the researchers in Hong Kong were involved in active research in WMSDs among construction workers in recent years. Although China had only two publications, the average citations and the average normalized citations showed that China had the highest contribution to the domain of WMSDs among construction workers.

Table 4. Quantitative summary of active countries/regions in research related to WMSDs among construction workers

Country/ Region name	Number of articles	Total citations	[a]Norm. citation	[b]Avg. pub. year	[c]Avg. citations	[d]Avg. norm. citations	Total link strength
United States	45	1184	43.02	2013	26.31	0.96	4
Hong Kong	7	292	11.15	2018	41.71	1.59	4
Canada	7	139	8.92	2017	19.86	1.27	2
China	2	193	4.67	2017	96.50	2.34	2
United Kingdom	2	100	2.42	2017	50.00	1.21	1

[a]Norm. citation = Normalized citation; [b]Avg. pub. year = Average publication year; [c]Avg. citations = Average citations; [d] Avg. norm. citations = Average normalized citations

3.5. Journal citation network

Based on the bibliographic records from the Scopus database and the literature selection strategies (see Section 2.2), Table 1 presents the selection of relevant peer-reviewed journals with related articles on WMSDs among construction workers during the studied period. Besides, a journal citation network was generated by using VOSviewer from the references cited in these published articles in the domain of WMSDs among construction workers. By using "citation" as the type of analysis, "sources" as the unit of analysis and "full counting" as counting method in VOSviewer, and by setting the minimum number of citations of a source to five, 48 out of the total 790 sources met the threshold. Fig. 4 depicts the network of journal citations related to WMSDs among construction workers. The presented network in Fig. 4 consists of a total of 48 nodes, 436 links, and 10,088 total link strengths. As indicated in Fig. 4, the node size reflects the number of citations of a cited journal, whilst the links between journals show the number of citation links of a given journal with other journals. In terms of the total citations, the top 5 most influential journals were *American Journal of Industrial Medicine* (citations = 87), *Applied Ergonomics* (citations = 82), *Ergonomics* (citations = 77), *Automation in Construction* (citations = 66), and *Spine* (citations = 42). Apart from *Spine*, the top 5 most influential journal citations (Fig. 4) were also among the selected peer-reviewed journals with related articles on WMSDs among construction workers during the studied period (see Table 1). Given the above, it is plausible to mention that the journals with more contributions to this studied research domain also received more citations. However, it is worth mentioning that the top-cited journals as shown in Fig. 4 mostly focus on research articles relating to occupational safety and health, occupational health psychology, and environmental medicine other than aspects relating to construction and engineering informatics.

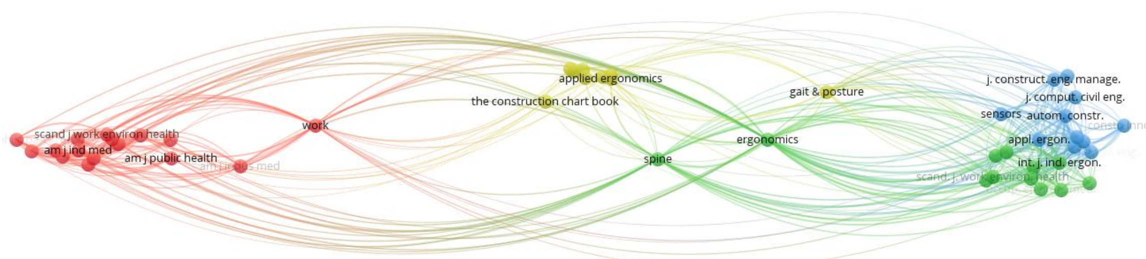

Fig. 4. A network of journal citations related to WMSDs among construction workers

3.6. Document analysis

Document analysis reveals the most outstanding research themes conducted in a research field as well as enables the scientific knowledge of the quantity and quality of references cited by other articles. This section focuses on using VOSviewer as a science mapping tool to generate a network of document analysis of published articles related to WMSDs among construction workers. By setting the minimum citation of a document to 25, a total of 19 out of 63 documents met the threshold.

Table 5 presents a summary of highly cited articles related to the studied research domain. It is worth noting that the 19 articles are listed in Table 5 in order of their total citations during the studied period. As shown in Table 5, the top three most cited articles related to WMSDs among construction workers during the studied period are Silverstein et al. (2002) (140 citations), Yan et al. (2017) (102 citations), and Merlino et al. (2003) (75 citations). Yan et al. (2017) focused on developing a real-time motion warning personal protective equipment (PPE) that enabled workers' self-awareness and self-management of ergonomically hazardous operational patterns for the prevention of WMSDs based on WIMUs received highest normalized citations than all other articles. Most of the highly cited articles listed in Table 5 generally used survey questionnaires to determine the magnitude and musculoskeletal injury characteristics among construction workers, and to identify work-related activities perceived to contribute to specific disorders (Silverstein et al., 2002; Merlino et al., 2003; Forde et al., 2005). Findings from these studies have suggested that preventive strategies are needed in the earlier stages of an apprentice training program to reduce the potential risk factors associated with MSDs symptoms.

Table 5. Summary of highly cited published article related to WMSDs among construction workers

Article	Title	Total citation	Normalized citation
Silverstein et al. (2002)	Use of a prevention index to identify industries at high risk for work-related musculoskeletal disorders of the neck, back, and upper extremity in Washington State, 1990-1998	140	1.99
Yan et al. (2017)	Wearable IMU-based real-time motion warning system for construction workers' musculoskeletal disorders prevention	102	2.66
Merlino et al. (2003)	Symptoms of musculoskeletal disorders among apprentice construction workers	75	1.00
Chen et al. (2017)	Construction worker's awkward posture recognition through supervised motion tensor decomposition	74	1.93
Forde et al. (2005)	Prevalence of musculoskeletal disorders in union ironworkers	58	1.53
Hess et al. (2004)	A participatory ergonomics intervention to reduce risk factors for low-back disorders in concrete laborers	54	1.00
Antwi-Afari et al. (2017b)	Biomechanical analysis of risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers	48	1.25
Goldsheyder et al. (2002)	Musculoskeletal symptom survey among mason tenders	47	0.67
Golabchi et al. (2015)	An Automated Biomechanical Simulation Approach to Ergonomic Job Analysis for Workplace Design	45	2.23
Valero et al. (2017)	Analysis of construction trade worker body motions using a wearable and wireless motion sensor network	41	1.07
Seo et al. (2015)	Motion data-driven biomechanical analysis during construction tasks on sites	37	1.83
Albers et al. (2005)	Identification of ergonomics interventions used to reduce musculoskeletal loading for building installation tasks	31	0.82
Ekpenyong and Inyang (2014)	Associations between worker characteristics, workplace factors, and work-related musculoskeletal disorders: A cross-sectional study of male construction workers in Nigeria	31	1.86
Entzel et al. (2007)	Best practices for preventing musculoskeletal disorders in masonry: Stakeholder perspectives	29	1.71
Hess et al. (2010)	Ergonomic evaluation of masons laying concrete masonry units and autoclaved aerated concrete	27	1.65
Kim et al. (2011)	Low back injury risks during construction with prefabricated (panelised) walls: Effects of task and design factors	26	1.00
Nath et al. (2018)	Automated ergonomic risk monitoring using body-mounted sensors and machine learning	26	1.73
Lee et al. (2017)	An evaluation of wearable sensors and their placements for analyzing construction worker's trunk posture in laboratory conditions	26	0.68
Anton et al. (2005)	Effect of concrete block weight and wall height on electromyographic activity and heart rate of masons	25	0.66

4. Qualitative discussions

Following the science mapping of the selected bibliographic records within the studied period, an in-depth qualitative discussion was conducted to summarize the mainstream research topics within related research domains of WMSDs among construction workers, which helped to identify the current research gaps and future research directions.

4.1. Summary of main research topics related to WMSDs among construction workers

4.1.1. Ergonomic risk assessment methods

From the selected bibliographic data, there are four main ergonomic risk assessment methods for identifying potential risk factors for developing WMSDs. They include: (1) self-reported methods; (2) observational-based methods; (3) vision-based methods; and (4) direct measurement methods.

In the self-reported methods, both physical (e.g., awkward working posture, overexertion) and psychosocial (e.g., mental workload, social support, and job insecurity) risk factors are collected from construction personnel on construction sites through interviews and/or questionnaires such as Nordic Musculoskeletal Questionnaire (Kuorinka et al., 1987), and Borg Scale (Borg, 1998). The Nordic musculoskeletal questionnaire is the most widely used self-reported risk assessment tool. Jensen et al. (2002) used questionnaires and interviews—as methods of data collection—to describe the possibilities of preventing WMSDs among floor layers. Similarly, Merlino et al. (2003) studied the prevalence of musculoskeletal symptoms among young construction workers. Musculoskeletal symptoms and job factor surveys were self-administered to 996 construction apprentices by using a modified Standardized Nordic Questionnaire. Self-reported methods have the advantages of being straightforward to use, applicable to a wide range of working situations on real-world construction sites, and require low initial cost (David, 2005). However, despite the direct and initially inexpensive application on real-world construction environment, it relies on the worker's perception, which is usually imprecise, unreliable, and biased.

Observational-based methods evaluate the workplace risk exposure by manual observation during construction tasks in a workplace setting or real-time assessment of recorded videos. As such, there are two main types of observational-based methods, namely, simpler and advanced methods. The simpler types of observational-based methods require ergonomist experts to calculate overall scores that indicate the level of risk associated with a given task through manual observation. They include guidelines that typically require ergonomist experts to input the angles between body joints, which are the main inputs for the evaluation. Examples include but not limited to *Ovako Working Analysis System (OWAS)* (Kivi and Mattila, 1991), *Posture, Activity, Tools, and Handling (PATH)* (Buchholz et al., 1996), *Rapid Upper Limb Assessment (RULA)* (McAtamney and Corlett, 1993; McGorry and Lin, 2007), *Rapid Entire Body Assessment (REBA)* (Hignett and McAtameny, 2000). These methods have the advantages of being inexpensive and practical for use in a wide range of real-world construction tasks where it is difficult to use other methods to observe workers (David, 2005). Despite being affordable and noninvasive, these observational-based methods highly rely on ergonomist expertise when evaluating parameters such as the worker's joint angle, which diminishes the objectiveness, precision, and repeatability of the methods. On the other hand, the advanced observational-based methods involve real-time assessment of recorded video using computerized software. They provide postural, static, and dynamic biomechanical load analyses in two-dimensional or three-dimensional models. In other industries such as automobile and manufacturing, several computerized software programs have been developed to evaluate the performance of workers in these industries. Examples are SAMMIE (Porter et al., 1995), APOLIN (Grobelny et al., 1992), ErgoSHAPE (Launis and Lehtela, 1992), RAMSIS (Seidl 1997), and ANYBODY (Porter et al. 1995). In the realm of construction, researchers have utilized the 3D Static Strength Prediction Program (3DSSPP) (The Center for Ergonomics at the University of Michigan, 2016) to evaluate risk factors that can produce excessive physical loads on the human body through a biomechanical analysis (Golabchi et al., 2015). They also include models that use specialized ergonomic analysis models (e.g., fuzzy-based systems) based on expert knowledge and experience for evaluating work-related risks (Umer et al., 2018). Although they provide more precise results, the costs are substantially higher, time-consuming, and require highly specialized trained staff to analyze simulated workplace activities (David, 2005).

Vision-based methods are mostly used to track human motion data with or without markers being attached to workers' body parts. As such, there are two main tracking systems of vision-based methods, namely: (1) marker-based; and (2) markerless optical motion tracking systems. Marker-based optical motion tracking systems (e.g., VICON, Qualysis, Optotrak) consist of a camera, passive (e.g., retroreflective), or active (e.g., light-emitting diode) markers and a personal computer. The collected whole human motion data in a simulated laboratory setting are usually used to carry out kinematic movement for biomechanical analyses. Previous biomechanical studies have demonstrated the use of marker-based optical motion tracking systems by simulating several construction tasks in a laboratory setting (Jia et al., 2011; Kim et al., 2011). Despite their precision in data collection, they are limited to light sensitivity and restrict the detectable range of motion due to marker placement and size. In contrast, markerless optical motion tracking systems (e.g., Microsoft Kinect, depth cameras, RGB-D) do not require markers to be attached to the human body during data collection. In the construction realm, Han et al. (2013b) applied a Microsoft Kinect sensor to detect unsafe actions during construction tasks. Ray and Teizer (2012) also suggested the automatic ergonomic monitoring system to identify nonergonomic postures using RGB-D sensors. Markerless optical motion tracking systems have great potentials as a vision-based assessment method for identifying workers' risk of developing WMSDs and classifying different movements on construction sites. However, a major practical limitation of these vision-based systems is that a direct line of sight is required to register the movements (Valero et al., 2017).

Direct measurement methods include all measurement techniques that capture workers' risk exposure and workplace activities by attaching different types of sensors directly on the worker's body (Awolusi et al., 2018; Antwi-Afari et al., 2019a). They include but are not limited to surface electromyography (sEMG) (Antwi-Afari et al., 2017b; Umer et al., 2017b; Wang et al., 2017; Antwi-Afari et al., 2018a), electroencephalography (EEG) (Jebelli et al., 2018; Xing et al., 2019), heart rate (HR) monitors (Gatti et al., 2014; Anwer et al., 2020), Lumbar motion monitor (LMM) (Marras et al., 1993), inertial measurement units (IMUs) (Chen et al., 2017; Umer et al., 2017b; Valero et al., 2017; Yan et al., 2017;

Nath et al., 2018; Lee et al., 2020; Yang et al., 2020), and wearable insole pressure system (Antwi-Afari et al., 2018e; Antwi-Afari and Li, 2018g; Antwi-Afari et al., 2020b; Antwi-Afari et al., 2020c). Antwi-Afari et al. (2017b) evaluated the effects of lifting weights and postures on spinal biomechanics (i.e., muscle activity and muscle fatigue) during a simulated repetitive lifting task in a laboratory experimental environment by using sEMG. Xing et al. (2019) proposed a multicomponent (with two intervention sessions) and neurophysiological intervention conducted during working intervals in a lounge environment by using EEG sensor. Valero et al. (2017) presented a novel system and data processing framework to deliver intuitive and understandable motion-related information about workers by using WIMUs. Their results suggested its applicability in real-world construction environments. Nath et al. (2018) designed a novel methodology where an unobtrusive and automated data processing framework is used to calculate ergonomic risks associated with occupational tasks (i.e., overexertion) by using body-mounted IMU system embedded in smartphones. Yan et al. (2017) developed a warning system for construction workers to prevent WMSDs. They attach two wireless IMU sensors to the worker's head and lower back to infer the angles described by the head, neck, and trunk. Antwi-Afari et al. (2020a) examined the feasibility of using acceleration and foot plantar pressure distribution data captured by a wearable insole pressure system for automated recognition of overexertion-related construction workers' activities and for assessing ergonomic risk levels. The advantages of direct measurement methods include (1) continuous assessment of workers' body motion in both laboratory and real-world construction working environments; (2) provision of large quantities of highly accurate and objective data on a range of exposure variables. However, these methods require sensors to be attached to the workers' skin, which makes them feel uncomfortable and inconvenient while performing a given task.

4.1.2. Prevalence of musculoskeletal symptoms among construction workers

The construction industry is one of the most hazardous occupations and labor-intensive industries (Wang et al., 2015a). Due to the nature of the construction industry, construction workers are often exposed to several work-related risk factors associated with workplace activities. Consequently, construction workers may develop musculoskeletal symptoms such as low back pain, neck/shoulder pain, tendonitis, and carpal tunnel syndrome. The prevalence rate of musculoskeletal symptoms among construction workers not only causes work absenteeism, schedule delays, and increased the cost of insurance premium but also leads to loss of productivity and early retirement (Umer et al., 2017a; Anwer et al., 2021a; Yu et al., 2020). Accordingly, previous studies related to the prevalence of musculoskeletal symptoms are discussed to identify work-related activities and risk factors contributing to these symptoms. The findings from previous studies not only help other researchers to address similar MSDs among specific workers but also assist construction managers to provide effective ergonomic interventions to mitigate these symptoms.

Jensen et al. (2002) conducted a study to describe possibilities of preventing work-related MSDs among floor layers and to analyze the factors that promote or constrain innovation in prevention. The findings indicated that the primary prevention of work-related knee disorders and accompanying stress requires reduced work tasks performed in kneeling positions. Moreover, it revealed that tools that could be used in a standing position for floor laying work tasks were considered useful for preventing MSDs. Goldsheyder et al. (2004) reported that low back pain (66%) was the most frequently experienced musculoskeletal symptom among cement and concrete workers. Similarly, Goldsheyder et al. (2002) found low back pain (65%) as the most prevalent musculoskeletal symptom among mason tenders. They also showed that bending or twisting the back, working in a sustained position, and heavy lifting were perceived as the most problematic work-related activities. Moriguchi et al. (2013) explored the exposure of postures of the upper arms, head, and neck during work and breaks among Brazilian and Norwegian electricians in the construction industry. They found that electricians' postural exposure was a risk factor for MSDs requiring ergonomic improvements in work conditions to prevent MSDs among these workers. Another study by Forde et al. (2005) highlighted that the prevalence of self-reported MSD symptoms among construction ironworkers was high for the lower back (56%), wrists/hands/fingers (40%), knees (39%), and shoulders (36%). Their findings suggest that some musculoskeletal morbidity in construction ironworkers may be work-related and thus preventable. According to Merlino et al. (2003), low back pain was the most commonly reported musculoskeletal symptom among apprentice construction workers. In addition, working in the same position for long periods was the job factor identified as most problematic, with 49.7 percent of all construction apprentices rating it as a major problem contributing to musculoskeletal symptoms.

In summary, most of the existing studies found low back pain as the most prevalent self-reported MSD symptom among construction workers, suggesting the need for adopting effective ergonomic interventions on construction sites to mitigate such disorders. On the other hand, they suggested that the prevention of MSD symptoms among construction workers must be related to each specific work-related activity frequently performed by workers on site.

4.1.3. Ergonomic interventions for preventing WMSDs risk factors

Researchers have evaluated several ergonomic interventions to mitigate the exposure of risk factors for developing WMSDs. To explore the use of best practices for preventing WMSDs in the masonry industry, Entzel et al. (2007) provided a list of equipment, tools, materials, engineering controls, administrative controls, and work practices. These authors also identified various barriers to intervention implementation, including business considerations, quality concerns, design issues, supply problems, jobsite conditions, and management practices that can slow or limit intervention diffusion. Moreover, the findings suggested future courses of action to improve the acceptability and implementation of ergonomics interventions in the masonry trades: refinements of existing interventions; solutions in short supply; interventions for future development; areas for future research and analysis; dissemination of best practice information; training; safety in design; and regulation, public policy, and regulatory enforcement. Similarly, Albers et al. (2005) identified the implementation of engineering interventions (e.g., tools, equipment, and engineered building materials) and administrative controls (e.g., training, educational programs, and modifications of work and management practice) to reduce musculoskeletal loadings for building installation tasks. Antwi-Afari et al. (2017b) highlighted six key ergonomics interventions to reduce the risk of developing WMSDs during repetitive lifting tasks. They include: (1) reducing the weight of load being lifted and avoiding lifting below their knee height; (2) estimated the normative duration of repetitive lifting at different lifting weights prior to the worker experiencing subjective fatigue; (3) team lifting (i.e., two or more rebar workers); (4) adopting proper ergonomic interventions such as adjustable lift tables; (5) planning the work schedule of workers based on an individual's physical capability; and (6) the use of assistive devices (e.g., cranes, exoskeletons, forklift, back belts, or hoists). Anton et al. (2007) studied the effect of aviation snip design and work height on muscle activity, wrist posture, and user satisfaction among sheet metal workers, finding that work height has a greater effect on muscle activity and wrist posture than snip design. Umer et al. (2017c) developed a low-cost and wearable domestic stool to reduce the physical discomfort of Asian workers during manual rebar tying. The findings revealed that the ergonomic intervention has beneficial effects on both physical and subjective outcomes and has great potential in reducing WMSDs among Asian rebar workers. Yan et al. (2017) developed a WIMU-based real-time motion warning system that improves construction workers' self-awareness and self-management of risk factors for developing WMSDs around lower back and neck without disturbing their operations. These authors proposed that the developed warning system has practical values and economic benefits due to its small size, cost-effectiveness, and suitability for construction tasks. Despite significant efforts by researchers and practitioners to develop task-specific ergonomic interventions for the construction industry, more construction ergonomics studies are warranted to help construction and safety managers design effective mitigation strategies to reduce risk factors for developing WMSDs among construction workers.

4.2. Research gaps and directions for future studies

Research on WMSDs among construction workers has made significant contributions to the construction industry, especially in the health and safety of construction workers. Due to enormous progress achieved on ergonomic risk assessment methods and proactive effective intervention, workers' quality of life has been enhanced and their construction performance has been improved. Nonetheless, several limitations in experimental protocol and ergonomic risk assessment methods, including accuracy, robustness, user compliance, intrusiveness, and among others, impose challenges to the research on WMSDs among construction workers.

4.2.1. Application-oriented data acquisition and analyses

Given the diverse approaches to ergonomic risk assessment methods, construction managers should particularly be aware of the limitations regarding data acquisition and analyses for mitigating exposure to WMSDs' risk factors. For example, self-reported methods are mostly subjective and have low inter-rater reliability; thereby might lead to biased results. Direct measurement methods like WIMUs and sEMG can provide more accurate and objective results but require sensors to be attached to the human skin, which may cause discomfort and affect workers' productivity on sites. Although wearable sensors have become popular in construction safety research, the usability and comfort of these sensors' securing means (e.g., belt, strap, and wristband) should be investigated. These will allow practitioners to embrace wearable sensor applications and use the new wearable technologies for mitigating WMSDs' risk factors and allow researchers to apply them to their construction safety research. Marker-based optical motion tracking systems such as

VICON are sensitive to illumination and occlusion and therefore, may not be practically useful on construction sites. To address the limitations in data acquisition, one may explore the benefits of combing two or more methods so that the strengths of different methods may overcome their limitations. For example, wearable sensors can be integrated with vision-based techniques in future studies to gain an in-depth understanding of workers' physical conditions, thus more convenient and less obtrusive for WMSDs risk assessment. Integrating two or more sensor modalities improve data accuracy, but more practical and effective integration between wearable sensors and vision-based techniques still need to be investigated.

4.2.2. Construction workers and real-world experimental settings

So far, most of the existing studies on the identification of risk factors for developing WMSDs are conducted using novice participants and in controlled laboratory settings. These studies usually involved healthy participants, which affect the generalizability of the results to the construction industry or related research fields. Therefore, future research is warranted to compare the findings of previous studies with a large sample of experienced construction workers from different construction trades. Moreover, future research should evaluate the reliability and validity of the proposed approaches and experimental protocols in real-world settings. This could further be used to refine/develop a real-time WMSDs risk monitoring tool. Moreover, the data collected by any reliable ergonomic risk assessment method would help identify workers at risk of developing WMSDs and enable construction managers to take proactive measures to prevent musculoskeletal injuries.

4.2.3. Assessing work-related risk factors by using biomechanical analysis

Numerous previous studies have demonstrated how physical (biomechanical) risk factors in the workplace could lead to WMSDs (Seo et al., 2015; Antwi-Afari et al., 2017b; Chen et al., 2017; Antwi-Afari et al., 2018f; Yang et al., 2020). Compared to other types of risk factors, few studies have been conducted to demonstrate the causal relationship between either psychosocial (e.g., family problems, time pressure) or individual (e.g., gender, age) risk factors and WMSDs (Ekpenyong and Inyang, 2014). Future studies should focus on the effects of psychosocial and individual risk factors that contribute to the development of WMSDs among workers. Previous studies on assessing work-related physical risk factors using biomechanical analysis were limited to specific construction workers such as rebar workers (Choi, 2010; Antwi-Afari et al., 2017b; Umer et al., 2017c), roofing workers (Wang et al., 2017), and masons (Hess et al., 2010). In addition, existing biomechanical studies were mostly conducted during manual material handling activities such as lifting, holding, carrying tasks (Seo et al., 2015; Antwi-Afari et al., 2018a; Antwi-Afari et al., 2020a; Umer et al., 2020). Moreover, the most studied musculoskeletal symptom was low back disorder (Wang et al., 2017; Antwi-Afari et al., 2018a). Future studies could apply biomechanical analysis to assess the effects of work-related physical risk factors on (1) different construction workers (e.g., drywallers), (2) several workplace activities (e.g., sawing, hammering), and (2) diverse musculoskeletal symptoms (e.g., shoulder pain, knee pain).

4.2.4. Integrating different ergonomic risk methods and adopting advanced information technologies to enhance the identification of WMSDs' risk factors

Previous studies have demonstrated the possibility of automated ergonomic risk monitoring and construction workplace physical activity measurement by using wearable sensing technologies (Chen et al., 2017; Antwi-Afari et al., 2018f; Nath et al., 2018; Antwi-Afari et al., 2020a). However, the adopted methods in these studies were limited to the application of machine learning classifiers. For example, Nath et al. (2018) designed a novel methodology to calculate ergonomic risks associated with occupational tasks (i.e., overexertion) by using body-mounted IMU systems embedded in smartphones and a machine learning classifier. Similarly, Antwi-Afari et al. (2018f) developed a novel and non-invasive method to automatically detect and classify awkward working postures by using a wearable insole pressure system and four supervised machine learning classifiers. Although previous studies achieved high performance, future research directions are warranted to develop non-invasive methods by using other wearable sensing techniques such as temperature sensors, humidity sensors, light sensors, and smart clothes. These wearable sensing techniques have been applied across other occupational industries such as clinical, manufacturing, mining, security, and sports science for remote patient monitoring and balance assessments, physical activity monitoring, proximity warning systems, remote communication services, and athletes' performance, respectively (Ruff and Holden, 2003; Queen et al., 2007; Gietzelt et al., 2009; Lo et al., 2022). With these other wearable sensing techniques, more sensors could be embedded for data processing while delivering contextual information between the body parts and the sensors during conducting a workplace activity. Besides, machine learning classifiers require the extraction of quantitative and informative features that are used as input variables. Most of these feature extraction techniques are performed manually and thereby may lead to reliability and bias issues. Future studies should focus on the application of deep learning techniques (e.g., convolutional neural network, recurrent neural network) to automatically extract features from raw sensor data without the requirements of pre-processing and manual labeling of features.

4.2.5. Developing ergonomic intervention based on construction automation and robotics

There are significant research studies that focused on the application of ergonomic interventions to mitigate the risk of developing WMSDs among construction workers (Albers et al., 2005; Anton et al., 2007; Entzel et al., 2007; Umer et al., 2017c; Yan et al., 2017). It was found that ergonomic interventions should meet the needs of construction workers through engineering controls (e.g., redesign of tools, equipment), administrative controls (e.g., safety training), and work practices (e.g., improved working environment) (Albers et al., 2005; Anton et al., 2007). Since ergonomic risk factors and hazards vary from trade to trade, future ergonomic intervention studies must be developed for a specific construction trade. Although previous studies have achieved useful findings, workers are still exposed to several physically demanding activities which exposed them to risk factors for developing WMSDs. With the recent advancement of construction automation and robotics (Pan et al., 2018; Cai et al., 2019; Antwi-Afari et al., 2021), future studies should investigate the benefits and challenges of adopting wearable exoskeletons for mitigating the exposure of WMSDs' risk factors and injuries in construction workers. In addition, it remains unclear whether the users' acceptance and privacy issues influence the application of exoskeletons in research related to WMSDs among construction workers. Furthermore, the impacts of using exoskeletons on workers' productivity and project performance are warranted.

5. Conclusions

This study adopted a science mapping-based method to review research related to WMSDs among construction workers published from 2000 to 2021, through co-word, co-author, and citation analysis. To do this, a four-step holistic review approach consisting of literature search, literature selection, science mapping analysis, and an in-depth qualitative discussion was used to review related research in the domain of WMSDs among construction workers. Out of 13 peer-reviewed journals that were identified from search strategies within the studied period, *American Journal of Industrial Medicine, Work, Automation in Construction, Journal of Construction Engineering and Management,* and *Applied Ergonomics* were the top five journals with the highest number of relevant articles, representing 68.25% of the total published articles on WMSDs among construction workers. With regards to the co-occurrence of keywords analysis, "musculoskeletal disorders", "ergonomics", "construction", "work-related musculoskeletal disorders", and "construction workers" had the highest frequencies, indicating that they have been widely researched in the domain of WMSDs among construction workers. Regarding the distribution of journal articles related to WMSDs among construction workers, most of them originated from the United States, Hong Kong, and Canada. Moreover, Silverstein et al. (2002), Yan et al. (2017), and Merlino et al. (2003) received the most document citations.

The in-depth qualitative discussion mainly focused on three key research areas, namely; (1) ergonomic risk assessment methods; (2) prevalence of musculoskeletal symptoms among construction workers; and (3) ergonomic interventions for preventing WMSDs risk factors. Lastly, the current review proposed five research gaps and directions for future studies that could benefit both researchers and industry practitioners in mitigating WMSDs risk factors in construction. They include: (1) application-oriented data acquisition and analyses; (2) construction workers and real-world experimental settings; (3) assessing work-related risk factors by using biomechanical analysis; (4) integrating different ergonomic risk methods and adopting advanced information technologies to enhance the identification of WMSDs' risk factors; and (5) developing ergonomic intervention based on construction automation and robotics.

6. Limitations of this study and potential future directions

As with other reviews related to WMSDs among construction workers, the current study had limitations. First, the number of relevant included articles was limited to only peer-reviewed journal articles, and the designed search strategy was limited to the selected literature found in Scopus. Second, the selection criterion of peer-reviewed journal articles was limited to journals that had published at least 2 peer-reviewed articles during the studied period. Third, only English journal articles were included. Future studies are warranted to extend the inclusion criteria by considering other publication outlets (e.g., conference articles, books) with articles published in other languages and other types of databases such as PubMed, Web of Science, Google Scholar, and among others. Despite the given limitations, the significance of this study would be realized by researchers and practitioners in the construction industry and beyond.

Acknowledgements

The authors acknowledged the following three funding grants: 1. General Research Fund (GRF) Grant (BRE/PolyU 152047/19E) entitled "In Search of a Suitable Tool for Proactive Physical Fatigue Assessment: An Invasive to Non-invasive Approach"; 2. General Research Fund (GRF) Grant (BRE/PolyU 15210720) entitled "The development and validation of a non-invasive tool to monitor mental and physical stress in construction workers"; and 3. Aston Research and Knowledge Exchange Pump Priming Fund 2021/22 entitled "Digital Twin-Enabled Wearable Sensing Technologies for Improved Workers' Activity Recognition and Work-Related Risk Assessment".

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