Towards Safer Human-Robot Collaboration in Construction: A Scoping Review of Ergonomic Factors and MSD Risks

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Abstract -

Human-Robot Collaboration (HRC) is increasingly explored in construction. However, the health and safety implications of HRC remain only partly understood, particularly ergonomic risks leading to musculoskeletal disorders (MSDs) of construction workers in HRC. This review synthesized existing research on health and safety in construction HRC and examined ergonomic risks leading to MSDs. This research reviewed 68 relevant studies, identified and synthesized ergonomic risk factors into four domains: physical, cognitive, task-based, and organizational/ environmental ergonomics. Within these domains, the analysis focused specifically on ergonomic risk factors associated with MSD risk, highlighting how HRC reduce, redistribute, or introduce new ergonomic risk exposures contributing to the occurrence of MSDs. Significance of this research lies in highlighting the changing landscape of ergonomic risks in construction HRC and the need to systematically examine the long-term ergonomic implications of HRC on the health and safety of construction workers.

Keywords -

Human-Robot Collaboration; Construction Robotics; Health; Safety; Ergonomics; Musculoskeletal Disorders

1 Introduction

Construction is a physically demanding industry. It has many hazardous manual tasks such as heavy lifting, repetitive motion, and prolonged awkward position. Construction workers undertaking these tasks are susceptible to prolonged exposure to ergonomic risks lead to musculoskeletal disorders (MSDs). According to Safe Work Australia, MSDs are the second most prevalent type of serious injury claims in the Australian construction industry in 2023/2024 [1]. To protect health and safety of construction workers, there has been increasing research interest in Human-Robot Collaboration (HRC). For example, HRC has been adopted in bricklaying tasks which robot is tasked with lifting bricks to reduce the ergonomic risk of repeated bending posture of workers. Workers can concentrate on precise positing of the bricks to ensure workmanship and improve productivity. While HRC has promising benefits in mitigating some of the ergonomic risks exposed to construction workers, HRC may also lead to new or unknown ergonomic risks due to changed work processes and work environment. It is expected that HRC will change the landscape of ergonomic risks in the construction industry. Despite this, there is limited research on the ergonomic implications of HRC for construction workers.

Ergonomic risk factors in construction can be categorized into biomechanical factors, environmental factors, psychosocial factors, individual factors, work design and task factors [2]. In the context of HRC, existing research has predominantly focused on physical ergonomics, particularly the reduction of manual handling and forceful exertion through robotic assistance [3]. A smaller body of work has acknowledged cognitive ergonomics [5, 15, 18]. However, these ergonomic dimensions are often addressed in isolation and are primarily framed within safety or performance considerations rather than systematically examined in relation to the risk of MSDs. To address this gap, this research aims to systematically examine the ergonomic risk factors associated with MSDs in construction HRC. Accordingly, this study addresses the following research question: What ergonomic risk factors associated with MSDs emerge in construction HRC, and how can they inform safer system design and task allocation? This research will contribute to better understanding of ergonomic risks in construction HRC.

2 Method

2.1 Data Collection

This scoping review followed the PRISMA-ScR guidelines [4]. The review focused on peer-reviewed studies examining health, safety, and human-related aspects of human–robot collaboration (HRC) in construction. Eligible sources included journal articles, conference papers, and book chapters published in English. To capture a broad range of evidence, quantitative, qualitative, and mixed-method studies were included.

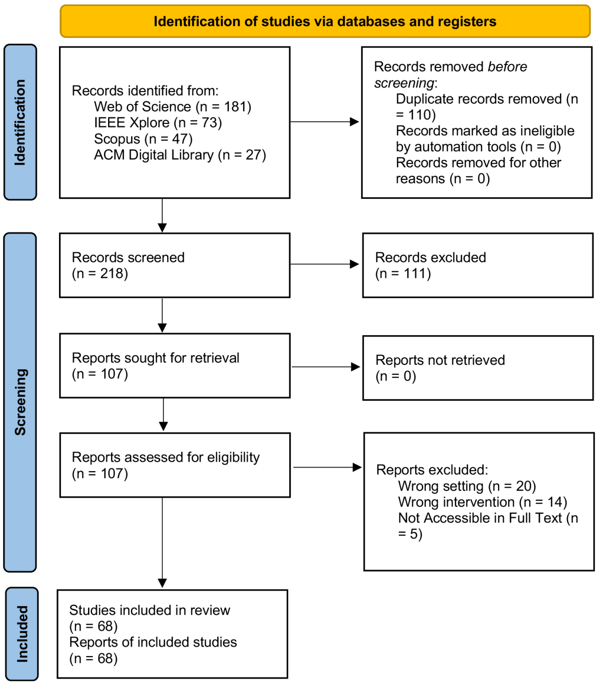

Figure 1. PRISMA Flow Chart

To ensure comprehensive coverage and address limitations in keyword indexing, two complementary search strategies were employed. Strategy 1 combined ("human-robot collaboration" OR "human-robot interaction" OR cobot) AND construction AND (safety OR "health risk" OR hazard OR accident OR injury). Strategy 2 combined ("human-robot collaboration" OR "human-robot interaction" OR "human–robot teaming") AND "construction industry" AND (safety OR health OR hazard OR accident OR injury). These strategies were applied across four databases: Scopus, Web of Science, IEEE Xplore, and the ACM Digital Library. After removing duplicates, 219 studies were retained for title and abstract screening.

Although ergonomics was not included as a primary search keyword, it is inherently embedded within occupational health and safety and closely linked to MSD risk in construction. Therefore, ergonomics was treated as an integral component of safety. Studies were included if they reported health- or safety-related outcomes associated with factors relevant to ergonomic risk (e.g., physical workload, awkward postures, manual handling, task and workspace design, cognitive workload, and human–robot interaction demands) [5].

Titles and abstracts were screened to assess relevance to construction HRC and to exclude studies that did not address human-related safety considerations. Studies were included if they: (1) focused on HRC in construction, (2) addressed health or safety aspects, (3) were peer-reviewed publications, and (4) were written in English. Studies were excluded if they were not related to construction, did not involve human–robot interaction, were non-peer-reviewed or incomplete, duplicated, or lacked accessible full text.

Following title and abstract screening, 107 studies were retained for full-text review. At this stage, studies were excluded if they did not involve HRC in construction, focused solely on automation without human interaction, or lacked relevance to health, safety, or ergonomic considerations. Studies on drones, teleoperation systems, or purely technical approaches without human evaluation were also excluded. After full-text screening, 68 studies met the inclusion criteria and were included in the final synthesis (Figure 1).

2.2 Data Synthesis and Analysis

A descriptive and thematic synthesis approach was adopted to analyse the included studies. Extracted data were first summarised using descriptive statistics to capture construction contexts, task types, and research methods.

Subsequently, ergonomic factors were identified through both explicit reporting and implicit evidence inferred from task descriptions, safety analyses, and accident causation. These factors were systematically coded and categorised using a structured framework comprising four domains: physical, cognitive, task-based, and organisational/environmental ergonomics.

To examine health implications, identified ergonomic factors were further mapped to established MSD risk pathways, including posture, force, repetition, static work, and fatigue. This mapping enabled an assessment of how HRC may reduce, redistribute, or introduce ergonomic risks that could contribute to MSD development under prolonged exposure.

The classification of ergonomic factors was informed by established ergonomics frameworks [6, 5], which distinguish between physical, cognitive, and organizational dimensions of work systems. In this study, factors were categorised based on their primary pathway of influence on human exposure and MSD risk. Physical ergonomics includes factors that directly affect biomechanical loading and physiological responses (e.g., posture, force, vibration, and noise), while cognitive ergonomics relates to mental processes influencing human performance. Task-based and organisational/environmental ergonomics capture work design, procedures, and contextual conditions shaping ergonomic exposure.

Although some factors may span multiple domains, each factor was assigned to the category representing its dominant ergonomic effect to ensure analytical clarity and consistency.

3 Results

To provide a comprehensive synthesis of ergonomic risks leading to potential development of MSDs in construction HRC, ergonomic risks were identified from both explicit and implicit sources. Explicit evidence referred to studies that directly assessed ergonomic or MSD-related outcomes, while implicit evidence was inferred from task characteristics, safety rationales, interaction descriptions, or accident causation analyses. Based on this evidence, ergonomics-related factors relevant to the potential development of MSDs were categorized into four domains: physical ergonomics, cognitive ergonomics, task-based ergonomics, and organisational/ environmental ergonomics (Figure 2).

3.1 Physical Ergonomics and MSD risk

A total of ten types of physical ergonomic factors were identified from most of the included studies (n = 67). These factors were discussed in relation to task demands, workspace constraints, and changes in manual workload resulting from robot assistance. While many studies framed HRC to reduce physically demanding work, direct measurement of physical ergonomic exposure was rare. Instead, MSD risks were predominantly addressed implicitly through task descriptions, safety rationales, or accident causation analyses rather than through formal ergonomic assessment. Force/ exertion, awkward posture, repetition, fatigue, static posture and vibration were directly influencing the potential development of MSDs. However, these MSD-related risk factors were seldom evaluated explicitly, limiting understanding of how physical ergonomic exposure is reduced, redistributed, or newly introduced through construction HRC (Figure 2).

Human-robot proximity/ collision was the most frequently mentioned physical ergonomic factors in the included studies, indicating that unique physical ergonomic factor that did not exist in traditional construction would emerge in HRC. Force/ exertion was the second most frequently mentioned physical ergonomic factor. While force/ exertion was a common ergonomic factor in construction, it appeared to be different in the context of HRC. Construction workers need to use new level of force/ exertion to effectively collaborate with robots. The same ergonomic factors can exit in both traditional construction and HRC but they would look diffident in different context. It is worth noting that manual material handling was the second least mentioned physical ergonomic factors, indicating that such risk may have been substantially reduced in HRC.

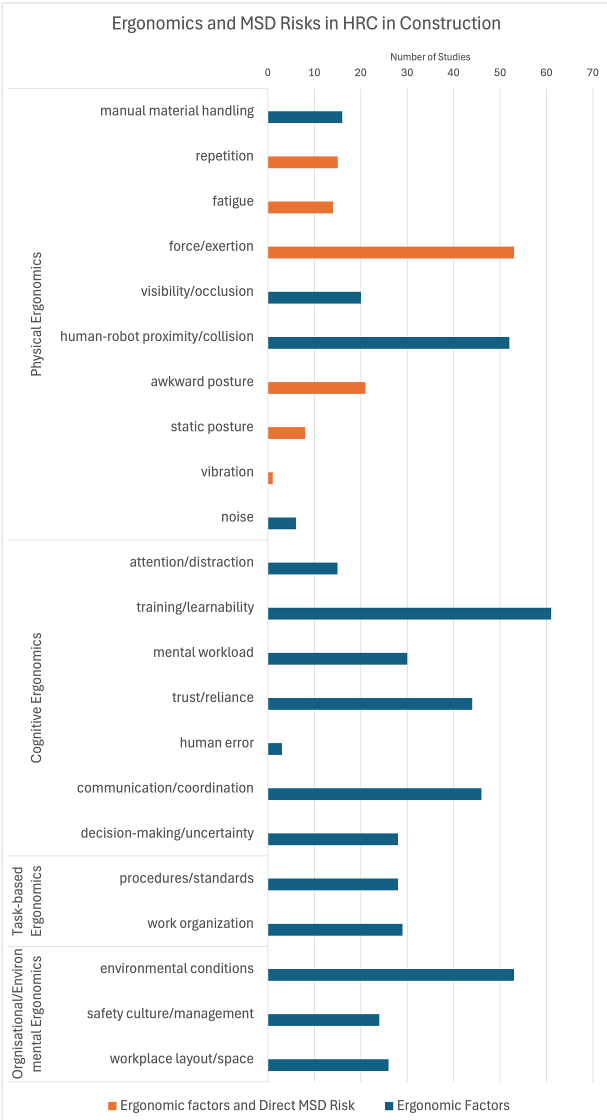

Figure 2. Ergonomics and MSD Risk of HRC in Construction

3.2 Cognitive Ergonomics and MSD Risk

Seven types of cognitive ergonomic factors were identified from the 68 included studies. Notably, their existence was often embedded within safety or interaction-focused discussions rather than evaluated as standalone outcomes. Cognitive ergonomics therefore emerged as an indirect yet largely under-evaluated pathway through which HRC may influence MSD risk in construction.

Training/ learnability, communication/ coordination, and trust/ reliance were the top three mostly mentioned cognitive ergonomic factors identified across the studies. The importance of these factors may have been intensified or they may mean differently to construction workers in HRC. Although they are rarely linked explicitly to MSD outcomes, these factors can shape physical behavior by influencing posture, muscle tension, movement variability, and task pacing. As a result, changing cognitive demands may indirectly contribute to cumulative MSD risk, particularly in collaborative scenarios requiring sustained monitoring, rapid judgment, or close coordination with robotic systems (Figure 2).

3.3 Task-based Ergonomics and MSD risk

Two types of task-based ergonomic factors, namely work organization, and procedures/ standards respectively, were identified in N=41 of the included studies. Similar to cognitive ergonomics, task-based ergonomics, encompassing work procedures, operational standards, and work organization, were primarily discussed as indirect influences on MSD risk in construction HRC. These factors were most often embedded within safety management or productivity considerations rather than examined as distinct ergonomic outcomes.

Several studies emphasized task sequencing, role allocation between humans and robots, and the use of standard operating procedures as central to enabling safe collaboration (Figure 2). However, the ergonomic implications of these task design decisions were rarely assessed explicitly. Task organization and procedural design can shape work pacing, repetition, opportunities for recovery, and postural variability, thereby influencing cumulative MSD risk over time. Despite their potential impact on musculoskeletal health, task-based ergonomic factors were seldom evaluated systematically, highlighting a gap in current HRC research.

3.4 Organisation/Environmental Ergonomics and MSD risk

Three types of organizational/ environmental ergonomic factors were identified in most of the included studies (n = 65). These factors, encompassing workspace layout and spatial constraints, safety culture and management practices, and broader environmental conditions, were predominantly discussed as contextual influences on safe HRC rather than as direct contributors to the potential development of MSDs.

Several studies highlighted the role of workspace layout, available space, and site configuration in shaping HRC and task execution. Environmental conditions, such as constrained or dynamic construction environments, were frequently noted as challenges for safe HRC . In addition, organizational aspects, including safety culture, supervision, and management practices, were recognized as important for risk mitigation (Figure 2). However, the ergonomic implications of these organizational and environmental factors, particularly their influence on posture, movement flexibility, and cumulative physical exposure, were rarely assessed explicitly. As a result, the importance of organizational/environmental ergonomics on MSD risk was under-examined in construction HRC research.

4 Discussion

The findings of this review indicate that while HRC in construction is frequently promoted as a strategy to reduce physical strain and improve health and safety of construction workers [7, 8, 9], its overall implications on ergonomic risks leading to MSDs are complex. For example, new ergonomic risks will arise in HRC. Even the same type of ergonomic risks may have different meaning in HRC. Some prevalent ergonomic risks in traditional construction may become less important in HRC. They require further research. In general, the landscape of ergonomic risk factors would be changed in HRC. It is likely that ergonomic risks are redistributed across physical, cognitive, task-based, and organizational/ environmental dimensions.

These ergonomic risk shifts were rarely evaluated systematically, with most studies addressing MSD risk implicitly through task descriptions or safety rationales rather than through direct ergonomic assessment [10, 11]. This may indicate that current HRC research in construction prioritizes immediate operational safety over longer-term musculoskeletal health of construction workers, highlighting a critical gap between safety-oriented system design and sustainable work outcomes in construction.

Many studies reported reductions in traditional physical risk factors such as heavy lifting or forceful exertion through robotic assistance[12, 13]. However, these benefits were often accompanied by increased exposure to other ergonomic risks, including static or constrained postures during robot monitoring, sustained attention demands, close-proximity interaction, and reduced movement variability. Cognitive ergonomics, although rarely linked directly to MSD outcomes, play an important indirect role by shaping physical behavior, posture, and work pacing [14, 15, 16]. As a result, MSD risk in HRC scenarios emerges as a cumulative and system-level issue rather than a task-specific one.

The findings also reveal that task-based, organizational/ environmental ergonomics remain under-examined in construction HRC research. Work procedures, task sequencing, role allocation, and standard operating practices were frequently discussed as enablers of safe collaboration, yet their ergonomic consequences were seldom assessed explicitly [17, 18, 19]. Similarly, organizational/ environmental factors, such as workspace layout, spatial constraints, site dynamics, and safety culture, were treated primarily as contextual conditions rather than determinants of ergonomic risk exposure [20, 21]. This narrow perspective limits understanding of how HRC systems operate in on-site construction environments, where variability and constraint are inherent.

5 Conclusion

This study makes both theoretical and practical contributions to safer human–robot collaboration (HRC) in construction. Theoretically, it advances existing research by conceptualizing ergonomic risks as a multi-dimensional system spanning physical, cognitive, task-based, and organizational/environmental domains, and by linking these domains to MSD risk pathways. This extends prior work that has largely focused on physical ergonomics in isolation.

Practically, the findings provide insights for the design and implementation of safer HRC systems. The review highlights that while robotic assistance may reduce certain physical demands, it can also introduce or redistribute ergonomic risks across other domains. These insights can inform task allocation, workspace design, and human–robot interaction strategies to mitigate long-term MSD risks and support safer and more sustainable construction practices.

This scoping review examined health and safety evidence for HRC in construction, with a particular focus on ergonomics and MSD risk. The findings indicate that ergonomic considerations are pervasive across construction HRC research; however, they are predominantly addressed implicitly and rarely evaluated using explicit ergonomic or MSD assessment methods. Physical, cognitive, task-based, and organizational/ environmental ergonomic risks will jointly contribute to the potential development of MSDs, yet these domains are seldom considered together within existing safety-oriented studies.

Rather than eliminating ergonomic risk, robotic assistance may reduce exposure to some harmful ergonomic risks such as forceful manual handling and repetitive tasks. However, new ergonomic demands are likely to emerge through static postures, sustained monitoring, close-proximity interaction, and organizational/ environmental constraints. These shifts highlight the importance of viewing MSD risk in HRC as a system-level, rather than a task-specific outcome.

Overall, this review reveals a gap between the safety motivations driving HRC adoption and the limited evaluation of long-term musculoskeletal health outcomes. To support safer and more sustainable deployment of HRC in construction, future research should integrate ergonomic assessment across physical, cognitive, and organisational/ environmental domains, and explicitly consider MSD risk alongside traditional safety metrics. Such an approach is essential to ensure that HRC not only improves productivity and short-term safety, but also contributes to long-term health of construction workers.

Acknowledgment

The authors acknowledge support from the Australian Cobotics Centre (Grant IC200100001), the QUT Construction and Architectural Robotics Lab (CARL) and the QUT Centre for Robotics (QCR).

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