Human–Robot Collaboration in Architecture, Engineering and Construction: A Thematic Review

Taylor M. Foster

Ira A. Fulton School of Engineering, Arizona State University

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Dr. Qiaoning Carol Zhang

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Introduction

The Problem

Worker-safety risks in collaborative workspaces are the most critical barrier to the widespread adoption of robotics across architecture, engineering, and construction (AEC). Construction tasks routinely expose crews to struck-by, caught-between, musculoskeletal, and fatigue-related hazards; adding mobile, force-capable robots can exacerbate those risks when lines of sight are poor, tasks are highly variable, or responsibilities are ill-defined (Burden et al., 2022; Sun et al., 2023). Empirical studies consistently show that excessive mental workload and poorly designed interfaces erode situational awareness, elevate error rates, and diminish trust in robotic teammates (Liang et al., 2021; Nassar et al., 2024). Unless human factors principles are embedded from the outset, collaborative robots intended to reduce injuries may instead introduce novel physical, cognitive, and psychosocial dangers, slowing or even reversing technology adoption.

Background

Psychological theory and human systems engineering (HSE) offer actionable lenses for understanding these hazards. Dual-process frameworks (Litvinova, Mikalef, & Luo, 2024) explain how workers toggle between rapid, intuitive judgments (System 1) and slower, analytical reasoning (System 2) when monitoring unpredictable robot motions; excessive switching taxes working memory and heightens slip-lapse errors. Distributed-cognition models of human-autonomy teams (Myers et al., 2024) show that shared mental models and transparent intent communication are prerequisites for calibrated trust and effective delegation. Ergonomics reviews in construction robotics (Onososen & Musonda, 2022) document how sub-optimal task allocation and unclear haptic or visual feedback channels amplify physical strain and mental fatigue, while interface studies (Brosque et al., 2020) illustrate the benefits of multimodal cues for maintaining awareness under

confined or noisy site conditions. Therefore, from an HSE perspective, safe and productive HRC is a socio-technical problem requiring insights from cognitive psychology, safety science, and robotics.

Overview of the Present Review

The current narrative literature review integrates 22 peer-reviewed sources spanning construction engineering, human factors, safety science, and computer science to clarify how human-robot collaboration can be made safe, effective, and acceptable in AEC contexts. Organized thematically, the review (1) examines physical and cognitive safety risks inherent to mixed human-robot teams, (2) analyzes the trust dynamics that govern collaboration quality, (3) summarizes methods for measuring and mitigating cognitive workload, (4) evaluates the role of immersive and augmented reality environments for training and system design, and (5) explores organizational and cultural factors influencing technology adoption.

Methods

This narrative literature review synthesizes current research on human–robot collaboration (HRC) within the construction industry, focusing on the interconnected themes of worker safety, cognitive load, and trust. The selection of peer-reviewed articles included in this review was guided by a focused search strategy aimed at identifying key contributions to these specific areas. Initial searches were conducted across major academic databases, including Google Scholar, Science Direct, and the ASCE Library, using a combination of keywords such as “human–robot collaboration,” “HRC for construction,” “construction robot teams,” “robotics and building science,” “physical Human Robot Interaction,” and related terms. After duplicate removal and abstract screening, 22 papers met all criteria and were subjected to full-text review and thematic coding.

A systematic search strategy was used to locate and synthesize scholarship on human–robot collaboration (HRC) in construction. Four inclusion filters guided selection:

1. **Domain relevance.** Sources had to examine HRC in the architecture, engineering, and construction (AEC) sector or in comparable high-risk settings whose findings were explicitly generalized to construction practice. Studies centered on manufacturing, agriculture, or service robotics were excluded unless they offered direct, construction-specific implications.
2. **Topical focus.** Eligible papers reported empirical data or substantive theoretical analyses on at least one core human-factor dimension (worker safety, trust calibration, cognitive workload, or ergonomic intervention). Papers describing fully autonomous systems with no human involvement or purely mechanical/software design briefs lacking significant human-interaction discussion were omitted.
3. **Peer Review.** Only peer-reviewed journal articles and archived conference proceedings were included. Editorials, opinion pieces, and non-archival workshop abstracts were excluded to maintain methodological quality.
4. **Recency.** To capture state-of-the-art developments, the search window was limited to publications from 2018 through 2024, a period that corresponds with the surge of mobile and collaborative robots on construction sites.

The synthesis of the selected literature followed a thematic organization strategy. This approach involved a close reading of each article to identify, analyze, and interpret recurring concepts and significant themes aligned with the review's focus.

Findings

Table 1

Thematic coding of reviewed literature across five key human–robot collaboration themes in construction

Citation	Safety Risks and Situational Awareness	Trust and Worker Perception	Cognitive Workload and Ergonomics	Immersive and Augmented Training Environments	Organizational and Adoption Perspectives
Begerowski et al. (2023)	✓	✓			✓
Burden et al. (2022)	✓				✓
Chauhan et al. (2024)	✓	✓	✓	✓	
Lin et al. (2024)	✓				
Schöberl et al. (2023)	✓				
Shayesteh et al. (2023)	✓	✓	✓	✓	
Sun et al. (2023)	✓		✓	✓	
Villani et al. (2018)	✓		✓	✓	✓
You et al. (2018)	✓	✓	✓	✓	
Zhang et al. (2023)	✓	✓	✓		✓
Kim et al. (2022)		✓			✓

Citation	Safety Risks and Situational Awareness	Trust and Worker Perception	Cognitive Workload and Ergonomics	Immersive and Augmented Training Environments	Organizational and Adoption Perspectives
Obi-Rapu & Simmons (2024)		✓			✓
Chen J. et al. (2023)			✓	✓	
Nassar et al. (2024)			✓		
Onososen & Musonda (2022a)			✓		
Parascho (2023)					✓
Brosque et al. (2020)					✓
Shayesteh & Jebelli (2022)		✓			
Chen et al. (2022)			✓		
Liang et al. (2021)	✓				
Onososen & Musonda (2022b)		✓			✓
Bademosi & Issa (2021)		✓			✓

Safety Risks and Situational Awareness

Safety remains the foremost concern in the integration of robotics into construction sites, where dynamic, unstructured environments amplify the risks of close-proximity human–robot collaboration

(HRC). Unlike controlled industrial settings, construction workspaces present fluctuating hazards that challenge traditional safety mechanisms.

Research has identified physical risks such as robot collisions, falling components, and unpredictable movements due to terrain variability. These risks are being addressed through motion planning strategies, environment-aware system design, and adherence to safety standards adapted from industrial robotics (Zhang et al., 2023; Lin et al., 2024). Lin et al., for instance, propose coupled risk assessment methods that account for both environmental conditions and human behavioral factors contributing to unsafe interactions.

Beyond the physical, cognitive risks emerge when robots introduce new attentional demands that distract workers from their primary tasks. Attentional costs, as identified by Sun et al. (2023), include visual and auditory distractions that increase mental workload and reduce hazard detection performance. Shayesteh et al. (2023) respond to this challenge by proposing immersive virtual environment (IVE)–based training platforms to evaluate cognitive load and optimize HRC training. These simulations replicate realistic site scenarios in controlled settings, enabling researchers to test interventions without exposing workers to physical danger.

Psychological risks, including anxiety, perceived surveillance, and emotional fatigue, are also prominent in HRC contexts. The presence of robots can alter workers' comfort levels and trust, factors critical to safe interaction. You et al. (2018) found that separating workspaces between humans and robots improves perceived safety and team identification. Similarly, Chauhan et al. (2024) employed immersive VR to analyze how robot workspace characteristics, interaction levels, and proximity influence trust through a combination of subjective surveys and psychophysiological measures. Their findings suggest that well-designed interaction zones and robot approach behaviors significantly improve trust and reduce discomfort. Studies like those by Schöberl et al. (2023) and Villani et al. (2018) further argue that system-level design, including interaction frameworks and collaboration definitions,

must be tailored to the complexity of construction sites to avoid misaligned expectations and unsafe coordination.

Taken together, these studies point to an emerging consensus: improving safety in HRC requires not only robust physical safeguards but also psychologically attuned system design, workload-aware training strategies, and trust-building mechanisms.

Trust and Worker Perception

A growing body of research demonstrates that trust in robots is shaped by the physical environment, robot behavior, communication efficacy, and social and professional context, with environmental configuration playing a significant role in trust calibration. Chauhan et al. (2024), using an immersive virtual construction environment, found that open workspaces positively influenced human trust in robots, whereas more confined or cluttered environments introduced discomfort. This supports findings by You et al. (2018), who showed that separation between human and robot work areas improves perceived safety, which in turn enhances trust and future willingness to collaborate. System behavior also matters since Chauhan et al. further revealed that robot proximity, interaction level, speed, and approach angle all contribute to trust dynamics, with proximity generally correlating positively with perceived trust, especially in low-risk scenarios.

In addition to spatial and behavioral factors, the quality of communication pathways between human and robot is pivotal. Shayesteh et al. (2023) emphasized that insufficient feedback or interaction clarity can undermine worker trust in collaborative systems, even when physical safety measures are in place. As trust depends on both transparency and predictability, systems that fail to communicate intentions clearly may be perceived as unsafe or untrustworthy.

Perceptions of trust also vary based on workers' roles, trade backgrounds, and expectations of robotic capabilities. Kim et al. (2022) found that workers in different trades expressed varying preferences for robot attributes depending on task complexity and perceived risk. However, the study

also revealed that many workers' expectations of robot capabilities were misaligned with current technological limitations, which could result in both underuse and misplaced reliance. Organizational dynamics further influence trust. Obi-Rapu and Simmons (2024) provided qualitative insights into how robots impact workers' professional values, such as a sense of belonging, job security, and communication in the workplace. These psychosocial dimensions often underlie trust even more than technical performance. Finally, Zhang et al. (2023) highlighted that trust in robotic teammates is often contingent on well-managed safety risks and clearly defined human roles within HRC teams.

Collectively, these studies show that trust is not a fixed or isolated attribute, but a multifaceted construct shaped by environmental, operational, psychological, and organizational factors. A failure to attend to any of these elements can compromise collaboration, while trust that is well calibrated can facilitate smoother task coordination, improved safety, and more widespread adoption of robotics in construction.

Cognitive Workload and Ergonomics

Several studies identify mental overload as a primary concern in HRC environments. Sun et al. (2023) highlight attentional costs (visual, cognitive, and auditory distractions) as significant contributors to safety incidents, particularly when robotic presence disrupts a worker's focus on primary tasks. Similarly, Zhang et al. (2023) frame safety risks in on-site HRC as an emergent theme, noting that both physical ergonomics (e.g., awkward posture, musculoskeletal strain) and cognitive stress (e.g., uncertainty, task switching) contribute to hazardous work conditions. These findings underscore the necessity of accounting for both psychological and physical strain in system design.

To address these issues, researchers have turned to immersive simulation and physiological sensing technologies to study and manage cognitive workload. Shayesteh et al. (2023) developed a virtual avatar-based training platform that employs EEG, EDA, and PPG sensors to monitor workers' mental workload during simulated HRC tasks. This setup provides a risk-free environment to evaluate

how cognitive demands affect learning curves and safety performance. Nassar et al. (2024) complement this by quantitatively exploring how different levels of collaboration (such as monitoring versus co-working) affect perceived cognitive load on jobsites. While tasks in their study were not reported as highly demanding, the variability in responses across interaction levels emphasizes the importance of aligning collaboration intensity with mental bandwidth.

Augmented reality (AR) offers another promising strategy for reducing ergonomic and cognitive strain. Chen J. et al. (2023) demonstrated that AR-enabled interfaces in construction waste sorting tasks helped workers maintain spatial awareness, reduced exposure to hazardous environments, and potentially minimized overload by delivering information visually rather than through verbal or written instruction. Villani et al. (2018) further advocate for interfaces that support intuitive interaction and minimize cognitive friction, arguing that “mental safety”, including stress and anxiety from robot proximity, deserves equal consideration alongside physical safety. Overall, the integration of immersive technologies, real-time feedback mechanisms, and adaptive collaboration protocols holds significant potential to improve both productivity and safety in construction.

Immersive and Augmented Training Environments

Immersive and augmented reality technologies are increasingly being explored as valuable tools for training construction workers in human–robot collaboration (HRC) and for evaluating critical factors like trust and safety. Virtual reality (VR) environments offer safe and cost-effective platforms to simulate realistic HRC scenarios, allowing workers to gain hands-on experience without exposure to actual jobsite hazards. You et al. (2018) demonstrated that immersive virtual environments (IVEs) can enhance workers' perceived safety by allowing them to experience different workspace configurations, such as spatial separation from robotic systems. This improved sense of safety was also associated with increased trust and willingness to collaborate. Expanding on this, Shayesteh et al. (2023) introduced a virtual avatar-based training system that enables more accurate assessments of training effectiveness

and helps identify moments of cognitive overload that could compromise performance and safety. Chauhan et al. (2024) further explored the relationship between robot design factors and human trust using a fully immersive virtual construction site. By analyzing physiological responses alongside subjective trust measures, their study revealed that variables such as proximity, speed, interaction level, and workspace layout significantly influence trust formation. In parallel, augmented reality (AR) is being employed to assist workers during live collaborative tasks. AR systems can provide real-time guidance, visual overlays, and intuitive interaction pathways that reduce cognitive load and improve ergonomics. Chen J. et al. (2023) demonstrated this through an AR-enabled collaborative waste-sorting system, where visual instructions enhanced both worker performance and safety. Villani et al. (2018) support this direction by advocating for the use of AR and VR as more intuitive modalities for robot interaction, especially in environments with limited prior exposure to robotics. Together, these immersive and augmented technologies offer promising avenues for both practical training and foundational research. They support the development of standardized, scalable, and user-centered training protocols while also serving as platforms for evaluating critical human–robot factors under controlled conditions. As the construction industry increasingly adopts robotics, the integration of VR and AR will be vital in equipping workers with the skills, confidence, and situational awareness necessary for effective and safe collaboration.

Organizational and Adoption Perspectives

The successful integration of human–robot collaboration (HRC) in the construction industry hinges not only on technological advancements but also on organizational readiness, stakeholder alignment, and long-term workforce engagement. These factors go beyond functional capabilities and extend into cultural, institutional, and perceptual domains that ultimately shape adoption outcomes. A growing body of research has begun to address these multidimensional barriers, emphasizing that the

deployment of collaborative robots must be situated within the broader ecosystem of construction practice.

Worker perception is a central determinant of adoption viability. Kim et al. (2022) found that perceived task complexity and safety risks strongly influence how workers assess the usefulness and desirability of robotic systems. However, the study also revealed a mismatch between actual robotic capabilities and user expectations, which may lead to distrust, rejection, or underutilization. Begerowski et al. (2023) argue that the literature too often marginalizes the lived experiences of workers, thereby neglecting an essential dimension of system integration: the subjective, context-bound knowledge of the human collaborators themselves.

The introduction of robotics can also disrupt professional identity and team dynamics. Obi-Rapu and Simmons (2024) found that while some workers associate robotic tools with enhanced career development, others report concerns about reduced social interaction, declining communication quality, and a loss of workplace belonging. These psychosocial impacts, though less quantifiable than efficiency metrics, are pivotal in shaping resistance or acceptance among the workforce. This underscores the need to consider human values and interpersonal dynamics as part of the design and deployment process.

At a systemic level, organizational readiness requires more than acquiring robotic hardware. Burden et al. (2022) emphasizes the necessity of conducting productivity evaluations to justify cobot investments and overcome long-standing industry inefficiencies. Similarly, Parascho (2023) points to a disciplinary disconnect between construction and robotics research that hinders effective translation and field adoption. Without deliberate efforts to align disciplinary vocabularies, workflows, and standards, technological potential may remain unrealized. Zhang et al. (2023) further caution that safety concerns and psychological stress related to novel human–robot relationships must be explicitly

managed. Meanwhile, Villani et al. (2018) and Onososen & Musonda (2022b) underscore the importance of intuitive programming interfaces and strategic planning for AI integration.

Collectively, these findings reinforce that the effective adoption of collaborative robots in construction demands a holistic, human-centered approach. Strategic alignment with existing organizational cultures, proactive engagement with worker concerns, and clear articulation of value beyond technical feasibility are all necessary to realize the benefits of HRC at scale.

Discussion

This narrative literature review examined human–robot collaboration (HRC) within the construction industry, highlighting five critical themes: safety risks and situational awareness, trust and worker perception, cognitive workload and ergonomics, immersive and augmented training environments, and organizational and adoption perspectives. Furthermore, synthesizing the current body of knowledge reveals several cross-cutting insights which will be necessary for human systems integration with robotic construction workflows.

Firstly, safety remains a unifying concern across all thematic areas. While traditional safety risks such as collisions and ergonomic strain are well recognized, issues related to attentional costs, mental fatigue, and psychological stress are increasingly acknowledged as pivotal to maintaining situational awareness and reducing incident risk (Liang et al., 2021; Shayesteh et al., 2023; Sun et al., 2023). Moreover, effective HRC necessitates not only mitigating physical risks through advanced sensing and control but also addressing attentional costs and psychological impacts on worker well-being and situational awareness. Secondly, worker perception and trust are foundational for successful HRC implementation (Begerowski et al., 2023; Chauhan et al., 2024; Kim et al., 2022; Obi-Rapu & Simmons, 2024). Positive perceptions, built on demonstrable safety and utility, foster trust, which in turn influences workers' willingness to collaborate and utilize robotic technologies effectively. Lastly, by leveraging technologies such as virtual reality (VR), augmented reality (AR), and physiological sensing,

researchers can now simulate risky scenarios, evaluate trust development, and measure mental workload in controlled yet realistic environments. These insights have informed new training methodologies and interface designs that align more closely with workers' needs and on-site conditions. However, just like most human systems integration efforts, the full potential of these tools remains contingent on broader organizational alignment and sustained support for workforce adaptation (Parascho 2023).

Despite these advances, several unresolved challenges and research gaps remain. Notably, there is a lack of standardized safety protocols tailored to the dynamic and mobile nature of robots in construction settings (Liang et al., 2021). While ISO standards exist for industrial applications, their applicability to unstructured and changing environments remains limited. Longitudinal studies are also scarce, leaving questions about the sustainability of worker trust and safety performance over time (Obi-Rapu & Simmons, 2024). In addition, although immersive training environments are promising, further validation is needed to ensure skill transfer and ecological validity in live construction settings (Shayesteh et al., 2023; Sun et al., 2023). The complexity of trust dynamics in construction-specific robots (often bulkier, noisier, and more autonomous than their industrial or social counterparts) needs to be better understood. Finally, bridging the divide between robotic technical capabilities and the organizational, cultural, and practical realities of construction remains a critical hurdle for widespread adoption.

Future research should prioritize interdisciplinary collaboration, integrating knowledge from human systems engineering, construction management, robotics, safety science, and psychology. A human-centered design philosophy must drive the development of collaborative systems, explicitly considering cognitive thresholds, perceptual limitations, and worker values. Field validation through case studies and deployment trials is essential to ensure HRC systems function reliably in authentic contexts. There is also a need for context-aware safety systems that can dynamically respond to

construction site scenarios without compromising productivity, further investigations into how trust, workload and safety are affected by robot interaction, the design of intuitive, multimodal human–robot interfaces and organizational change management strategies to support workforce reskilling to address concerns related to job displacement. Yet, to assess the true impact of human–robot collaboration (HRC), research must also establish robust evaluation metrics that capture productivity, safety, and overall system value in real-world contexts. Lastly, a deeper exploration of the ethical and societal implications of increasing automation in construction labor is necessary to ensure equitable and sustainable integration

In conclusion, HRC presents transformative opportunities for the construction industry, but these benefits can only be realized through holistic, ethically grounded, and human-centered design strategies. Future research must move beyond technical problem-solving to rigorously consider the human element at every stage of development and deployment. Through interdisciplinary insight and real-world validation, the industry can build safer, smarter, and more resilient partnerships between humans and machines.

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