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Development and Evaluation of an E-Tool for Human-Robot Interaction Safety Risk Assessment

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The construction industry faces significant challenges in ensuring worker safety, health, and productivity. To address these challenges, recent research has focused on innovative approaches, including the adoption of Robotics and Automation (RA) technologies such as wearable robots, remotely operated robots, and on-site automated systems. These technologies offer potential solutions to enhance safety and productivity. However, their integration into construction lags behind other industries, partly due to the absence of standardized guidelines and concerns surrounding human-robot interaction (HRI) safety risks. This study introduces an electronic tool (e-tool) specifically designed for safety risk evaluation in RA applications within construction. Developed through a mixed-methods approach, including a literature review and a modified Delphi process, this tool aims to identify and mitigate HRI safety risks. It encompasses various mitigation strategies and aids in pre-task planning. The tool, named "Assessment of Human-Robot Interaction Safety Risks in Construction Operations," has been tested by industry stakeholders, demonstrating its effectiveness, clarity, and practicality. This significant development not only advances worker safety in RA but also contributes to improving overall work environments and productivity in the construction sector through the strategic integration of robotic technologies.

Key Words: Human-robot interaction, Risk assessment, E-tool, Construction safety

Introduction

The construction industry, known for its dynamic, intricate, and hazardous nature, faces continuous challenges in productivity and the safety and health of workers, stemming from the intense interaction between humans and their work environment, as noted by Ryu et al. (2020). This complex interplay has been linked by construction professionals to a high rate of voluntary employee turnover (Ayodele et al. 2020), as workers seek to avoid an environment marked by decreasing productivity (Barbosa et al. 2017; BLS 2020a) and elevated risks of injuries, illnesses, and deaths (Oguz Erkal et al. 2021; BLS 2020b). In an effort to address these issues, there is an ongoing pursuit among researchers and practitioners for innovative approaches and preventative strategies to enhance both productivity and safety in construction settings (Okpala et al. 2020; Esmaeili and Hallowell 2012). This has led to a push for the adoption and implementation of novel solutions across various construction operations, encompassing safety and health management (Nnaji and Karakhan, 2020), intelligent contracting (McNamara and Sepasgozar, 2021), eco-friendly construction practices (Dewlaney et al. 2012),

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prefabrication techniques (Tam et al., 2007), and quality management initiatives (Ogunrinde et al. 2021). Among the technologies being utilized are virtual and augmented reality, building information modeling, and robotics and automation (RA) (Delgado et al., 2019; 2020; Samuelson and Björk, 2013).

RA technologies present new avenues to tackle the inherent safety and productivity challenges in construction trades (Delgado et al., 2019). In the construction sector, RA applications can be broadly categorized into three types: wearable robots (like exoskeletons), remotely operated robots (such as drones and autonomous vehicles), and on-site automated robotic systems [including single-task construction robots (STCRs) used for tasks like painting, bricklaying, welding, etc.] (Delgado et al., 2019). These categories, as illustrated in Figure 1, represent the varying levels of interaction between workers and robots, with wearable robots having the closest interaction with users, and STCRs featuring the least interaction as they are fully autonomous systems.

Figure 1. *Inter-play of Robotics and Automation in Construction*

Despite the potential advantages of Robotic Automation (RA), its implementation in the construction sector is relatively low compared to other fields, as identified in studies by Delgado et al. (2019) and Nnaji Karakhan (2020). This sluggish adoption is partly due to the absence of standardized guidelines for applying RA in construction, coupled with apprehensions about the safety risks of human-robot interactions (HRI), as indicated in research by Hwang et al. (2022) and Okpala et al. (2020). Hence, it is essential to pinpoint and mitigate negative HRIs, emphasizing worker safety in construction projects employing these technologies. In light of these safety concerns, the development of a tool for thorough safety risk evaluation is imperative, prioritizing the protection of construction workers' health and safety at all times.

Recognizing hazards and assessing safety risks are crucial for enhancing worker safety, as highlighted by Hallowell and Gambatese (2009) and Dharmapalan et al. (2015). Factors such as exposure, frequency, and severity are key in defining and assessing safety risks in construction, as detailed by Dharmapalan et al. (2015). To illustrate, researchers have conducted studies, both qualitative and quantitative, to evaluate various methodologies and measurement scales that reflect the positive or negative aspects of a trade, task, or system, as discussed by Karakhan and Gambatese (2017). For instance, Hallowell and Gambatese (2009) developed objective scales for different construction activities by scoring frequency, exposure, and severity levels to calculate the overall risk in concrete formwork construction. Similarly, Dharmapalan et al. (2015) conducted a quantitative study on the frequency and severity of risks associated with certain design features, leading to the creation of a design risk assessment tool for evaluating and comparing design safety risks.

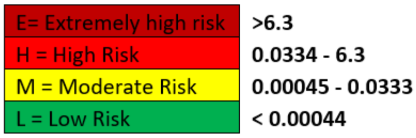
While existing studies on safety risk assessment are beneficial, they cannot be directly applied to RA due to the unique hazards and risks in this domain. Therefore, a systematic risk assessment approach, specifically tailored to assess task-based safety risks, is essential for integrating RA safely in the construction sector. An effective risk assessment tool for RA is vital to ensure controlled, safe, and efficient use of robots at construction sites. Presently, there is a lack of research focused on developing resources for worker safety in RA applications, as noted by Moud et al. (2022). This study aims to bridge this knowledge and practice gap by creating an electronic tool to facilitate the safe and effective utilization of robots in construction. The development of this practical tool is expected to complement existing job hazard analysis methods, empowering construction practitioners to identify and evaluate HRI safety risks associated with RA.

Research Method

The research team employed a mixed-methods approach that combined sequential steps to ensure the robustness of the study's results, as noted by Hallowell and Gambatese (2010). This approach included a comprehensive literature review and a modified Delphi process involving expert surveys for the collection, verification, and quantification of data relevant to the research goals. A specially designed survey questionnaire was developed and pre-tested, followed by the selection and engagement of experts for the Delphi panel, as suggested by Fellows and Liu (2015). Subsequently, the Delphi method was utilized to determine and quantify the safety risks associated with Human-Robot Interaction (HRI) and strategies for their prevention.

The expert panel then evaluated the hazards and safety risks associated with the use of RAs in tasks like bricklaying, concrete polishing and grinding, and dry-wall installation. The assessment of safety risks, or 'unit risk', was conducted in three distinct 'task-level groups', employing a frequency and severity scale drawn from earlier studies (Hallowell 2009; Dharmapalan et al. 2021). To clarify, 'Frequency' was defined as the likelihood of an incident occurring, and 'Severity' was the potential impact of an incident. The severity scale includes Near miss, Low severity, Medium severity, and High severity, while frequency indices were Once in 10 years = 0.000044, once per year = 0.00044, once per month = 0.0053, once per week = 0.0333, and once per day = 0.111 (Jazayeri and Dadi 2020; Dharmapalan et al. 2015. The unit risk calculation used Equation 1 (Eq.1), forming the basis for the risk classification thresholds in this study: "Extremely high risk", "High risk", "Moderate risk", and "Low risk" (as depicted in Figure 2), a classification method similarly employed in past research like Neubauer et al. (2015). Subsequently, participants were asked to assess the practicality and effectiveness of different HRI safety risk prevention strategies and pair these strategies with different safety risks.

Unit risk (S/w-h) = Frequency (incident/w-h) × Severity (S/incident) ……… (Eq.1)



E= Extremely high risk	**>6.3**
H = High Risk	**0.0334 - 6.3**
M = Moderate Risk	**0.00045 - 0.0333**
L = Low Risk	**< 0.00044**

Figure 2. *Safety risk levels*

The gathered data was then used to create an interactive, web-based application aimed at evaluating safety risks and mitigation tactics in the context of HRI. Finally, a survey was conducted to evaluate the effectiveness of the developed e-tool. Twenty-nine participants agreed to join the Delphi panel (12 from industry and 17 from academia), while nine participants participated in the survey focused on assessing the developed e-tool.

Results and Discussion

In the initial stage of the Delphi method, alongside demographic information for expert pre-qualification, the panelists were asked to discuss their knowledge regarding three types of Robotic Automation (RA) - wearable robots, remote-operated robots, and on-site automated robotic systems. The findings indicated a consistent trend of familiarity across experts from both academic and industrial backgrounds. Specifically, about 93% (27 out of 29) participants reported familiarity with wearable robots and on-site automated systems, and over 86% (25 out of 29 panelists) were knowledgeable about all three RA categories. This high familiarity level is crucial for ensuring that the expert inputs are relevant and reliable, aligning with insights from Bolger and Wright (2011).

Safety Risk Assessment

Tables 1 – 3 lists HRI safety risks rated "High risk." Some hazards were rated as high risk across activities and technologies. For wearable robots, key risks are improper tool use, restricted worker mobility, and mechanical part failure. Remote operated robots carry risks like operator mistakes, mechanical failures, weather issues, collisions, hazards from moving parts, and electrical dangers. With drones' growing role in construction, monitoring these risks is crucial for incident prevention (OSHA 2021). High risks for On-site Autonomous Robots (Single-task robots) include faulty equipment (like sub-controls) and entering a robot's protected zone. Mechanical part failure was rated as a high risk across the three technologies and the three tasks. Therefore, safety supervisors should develop, implement, and maintain a robot-specific inspection and maintenance plan. This plan should include critical information – such as maintenance frequency, inspectors' credentials, spare parts, support vendor contact information, etc. – that will ensure optimal performance of the robots.

Table 1.

Onsite Single-Task Robots HRI safety risks

	Bricklaying	**Dry-wall installation**	**Concrete grinding/polishing**
1	Faulty equipment (e.g., in the hydraulic sub-controls)	Malfunctioning control or transmission elements	Inadequate or incorrect work/task design
2	Entry into a robot's safeguarded area	Faulty equipment (e.g., in the hydraulic sub-controls)	Faulty equipment (e.g., in the hydraulic sub-controls)
3	Malfunctioning control or transmission elements	Entry into a robot's safeguarded area	Entry into a robot's safeguarded area
4	Mechanical part failure	Distrust in device	Autonomous moving parts
5	Electrical hazards	Autonomous moving parts	Mechanical part failure
6		Catching and dragging hazards	Catching and dragging hazards
7		Software error	Software error
8		Electrical hazards	Improper platform
9		Inadequate or incorrect work/task design	
10		Improper platform	

Table 2.

Remote-operated robots HRI safety risks

	Bricklaying	Dry-wall installation	Concrete grinding/polishing
1	Operator errors	Operator errors	Operator errors
2	Catching and dragging hazards (by moving parts)	Faulty equipment (e.g., in the hydraulic sub-controls)	Improper equipment / tool use by worker
3	Poor weather condition	Distrust in device	Software error
4	Collision in the workplace	Mechanical part failure	Mechanical part failure
5	Mechanical part failure	Poor weather condition	Distrust in device
6	Electrical hazards (e.g., faulty wire/plugs)	Electrical hazards (e.g., faulty wire/plugs)	Faulty equipment (e.g., in the hydraulic sub-controls)
7	Improper equipment layout	Catching and dragging hazards (by moving parts)	Poor weather condition (e.g., unstable flying conditions)
8		Collision in the workplace	Collision in the workplace
9			Catching and dragging hazards (by moving parts)
10			Electrical hazards (e.g., faulty wire/plugs)

Table 3.

Exoskeletons HRI safety risks

	Bricklaying	Dry-wall installation	Concrete grinding/polishing
1	Improper equipment / tool use by worker	Improper equipment / tool use by worker	Improper equipment / tool use by worker
2	Worker has limited mobility	Worker has limited mobility	Worker has limited mobility
3	Faulty equipment (e.g., in the hydraulic sub-controls)	Unworkable combination of robots and PPE	Faulty equipment (e.g., in the hydraulic, sub-controls)
4	Mechanical part failure	Mechanical part failure	Mechanical part failure
5		Dirt (e.g., grease) in work areas	Dirt (e.g., grease) in work areas
6		Inadequate or incorrect work/task design	Inadequate or incorrect work/task design
7		Technology discomfort	Adverse Indoor and outdoor climate
8			Unworkable combination of robots and PPE

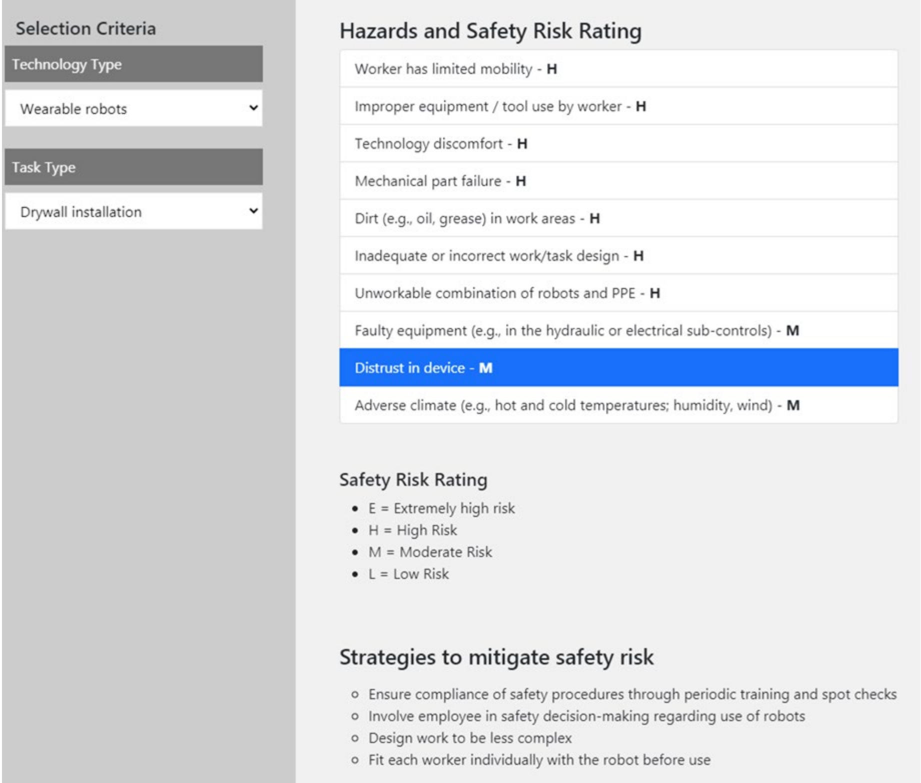
Safety Risk Mitigation Strategies

The expert panel, while achieving consensus of opinions, rated the following strategies as moderately to highly effective, and moderately to highly feasible: (1) ensuring compliance of safety procedures through periodic training and spot checks; (2) designing work to be less complex; (3) preventing unauthorized or improper maintenance and installation of robots; (4) involving an employee in safety decision-making regarding the use of robots; (5) providing clear, concise, available and up-to-date job aids, accepted by the intended user population; (6) incorporating manufacturer safety requirements into written company safety procedure; (7) use ergonomically designed wearable robots; (8) fit each worker individually with the robot before use; (9) have checks performed regularly by a skilled technologist/technician; (10) use only robots that are effective; and (11) Clean equipment regularly.

Although most of the highly rate strategies are implemented at the workface and project level, some strategies such as “designing work to be less complex” require dialog further upstream of the project (i.e., with the design team). Utilizing strategies that are higher on the hierarchy of controls will ensure that workers working with or close to robots are effectively protected.

Human-Robot Interaction Safety Risk Assessment E-Tool

After identifying and quantifying safety risks and mitigation strategies, the research team developed an interactive web-based tool to aid construction practitioners in recognizing potential safety risks and enhancing pre-task planning. This tool, named “Assessment of Human-Robot Interaction Safety Risks in Construction Operations”, is designed for use by individuals with task-specific knowledge, safety management, and the operation of robots (Figure 3). Specifically, the tool is ideal for safety professionals, foremen or other organization-appointed personnel responsible for job hazard analysis.



Selection Criteria

Technology Type: Wearable robots

Task Type: Drywall installation

Hazards and Safety Risk Rating

- Worker has limited mobility - **H**
- Improper equipment / tool use by worker - **H**
- Technology discomfort - **H**
- Mechanical part failure - **H**
- Dirt (e.g., oil, grease) in work areas - **H**
- Inadequate or incorrect work/task design - **H**
- Unworkable combination of robots and PPE - **H**
- Faulty equipment (e.g., in the hydraulic or electrical sub-controls) - **M**
- Distrust in device - **M**
- Adverse climate (e.g., hot and cold temperatures; humidity, wind) - **M**

Safety Risk Rating

- E = Extremely high risk
- H = High Risk
- M = Moderate Risk
- L = Low Risk

Strategies to mitigate safety risk

- Ensure compliance of safety procedures through periodic training and spot checks
- Involve employee in safety decision-making regarding use of robots
- Design work to be less complex
- Fit each worker individually with the robot before use

Figure 3. *HRI Safety Risk Assessment for Drywall Installation*

This tool's hazard listing and the pairing of safety risks with mitigation strategies, sourced from three rounds of the Delphi process, are intended to augment, not replace, engineering judgment or processes. In line with prior research, this tool serves as a supplement to other pre-task evaluation tools and methods (Dharmapalan et al., 2014). The research team focused on optimizing the tool’s layout and design for user convenience, menu clarity, and information transparency – essential features of effective tools. This focus ensures ease of use, accuracy, consistency in information provision, and straightforwardness in understanding (Stienen et al., 2015). Users can navigate the tool with ease, selecting from dropdown menus after clicking on the Technology or Task type tabs (refer to Figure 2) in the selection criteria section to specify their chosen construction task and robot. The tool then presents a list of safety risks related to the selected task and technology, with each risk linked to potential mitigation strategies upon selection.

To gather feedback from industry stakeholders on the tool's usage, a survey was distributed to construction practitioners with proficiency in project management, safety management, technology adoption, and implementation. Nine experienced construction and safety management professionals, each with over 10 years of experience and safety-related certifications (Authorized OSHA Trainer, Certified Safety Professional, etc.), tested and provided feedback on the tool.

Feedback was collected using a 1 to 9 scale (1 = very poor/totally disagree; 5 = average/neutral; 9 = excellent/totally agree). Overall, the participants rated the tool favorably (Table 4), with average scores ranging from 6.89 to 8.67, reflecting agreement on its layout, user-friendliness, clarity of menu and information, as well as its practicality and effectiveness. Some of the comments provided by construction professionals include: (1) *"It gives a clear and concise direction which is straightforward and understandable"* (2) "*It outlines specific instructions and direction to follow for individual operational activities available"*, (3) "*The strategies provided in the tool [are] quite insightful and will provide a second layer of checking as well as an understanding of the associated risks before performing any work"*.

Table 4.

Ratings after E-Tool Assessment (n = 9)

S/No	Description	Rating (Mean)
A	**Layout**	
1	The text in the app is clear	8.56
2	I am satisfied with the letter type and size	8.67
3	I am satisfied with the writing style	8.22
B	**User convenience**	
1	The e-tool would be easy to use on construction projects	6.89
2	The format of the e-tool is easy to understand	7.44
3	The e-tool is engaging (i.e., quite intuitive) while being used.	7.67
4	I am satisfied with the speed of the e-tool	8.56
C	**Menu clarity**	
1	The composition of the menu seems natural	7.78
2	I am satisfied with the navigation through the e-tool	7.22
3	It is easy to find the information I am looking for in the e-tool	7.44
D	**Information clarity**	
1	The information provided on the e-tool is easily understandable	8.11
2	The e-tool is adaptable (i.e., easy to integrate).	7.22
3	I could identify which mitigation strategies are recommended	7.33
4	I understand what mitigation strategies are recommended	7.11
E	**General Information**	
1	I will use this e-tool if it is made available to me	8.33
2	This e-tool is practical (i.e., provide accurate information).	7.67
3	The e-tool is effective (sufficient in breadth and depth).	7.11
4	The e-tool could help improve job hazard analysis	8.11

With the increasing presence of robots on construction sites, front line supervisors must account for the potential risks associated with these new technologies in their safety management plans. The results from this study indicate that the proposed tool could offer valuable insights when used in pre-task planning and job hazard analysis. This intuitive and user-friendly tool can enable workers to make data-driven decisions effectively, reducing reliance solely on personal experience.

Conclusion and Future Research

This study introduced "Assessment of Human-Robot Interaction Safety Risks in Construction Operations" as an electronic web-based application designed for evaluating safety risks in Robotics and Automation (RA) applications. Through a mixed-methods approach, information gathered from an exhaustive literature review and a modified three-round Delphi process involving experts from industry and academia enabled the identification and quantification of safety risks pertaining to different types of robots (i.e., onsite single-task robots, remote-operated robots, exoskeletons) used on construction jobsites. Mitigation strategies used to prevent safety risks associated with human-robot interactions on construction sites were also identified and quantified. The information collected informed the design of the interactive web-based application with the aim of assisting construction practitioners in recognizing potential safety risks associated with human-robot interactions on construction sites by enhancing their decision-making skills and pre-task planning activities. To evaluate the developed application, a survey questionnaire was administered to industry experts. The results showed that participants rated the tool favorably, indicating agreement on its layout, user-friendliness, clarity of menu and information, as well as its practicality and effectiveness.
Although the present study provides useful contributions to practice and research, the scope of the study was limited in several ways and could be expanded in future. For instance, future research should focus on expanding the scope of the e-tool to include risk ratings for additional technologies and tasks. The tool should be deployed and assessed on different types of construction project using case studies to ascertain the efficacy of the tool. Finally, future studies should capture insights from frontline workers on the safety risks associated with using robots on the job site. That way, a more comprehensive risk rating could be developed to facilitate safety management at the workface.

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