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Protocol for Assessing Human-Robot Interaction Safety Risks

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Abstract

Robotics and automation (RA)—such as exoskeletons, drones, and single-task construction robots (STCRs)—offer new possibilities to combat challenges facing the construction trades, including unsafe and dangerous working conditions. Despite RA's potential positive impacts, human-robot interaction (HRI) can introduce new hazards on the job site and elevate the potential impact of existing hazards. While some studies have assessed the effectiveness of RA technologies, none have evaluated the safety risks associated with implementing RA in the construction industry. There is also no HRI safety risk assessment protocol to assist practitioners conducting pre-task planning that involves RA.

This study developed a practical process and tools for practitioners to identify and quantify HRI safety risks when using RA in construction operations. Both the process and the tools could help reduce RA safety risks, increase the RA adoption, and improve construction safety performance.

Key Findings

The main products of this study are:

- A practical process for assessing and controlling HRI safety risk. The evaluation process comprises:
  - Safety Data Sheets (SDS) on the use of wearable robots (exoskeletons), remote-operated robots (e.g., drones and unmanned ground vehicles [UGVs]), and onsite automated robots (e.g., bricklaying robots).
  - Job Hazard Analysis (JHA) protocols for three tasks: drywall installation, bricklaying, and concrete grinding and polishing.
- A practical assessment manual containing:
  - Descriptions of available robotics and automation (RA) technologies.
  - Applications of RA technologies.
  - Factors that influence the use of RA technologies.
  - Current standards and procedures for RA.

The key findings of this study are:

- Identification of 40 hazards associated with the use of RA for construction operations.
- Classification of RA-related hazards into seven groups: Human; Control; Unauthorized Access or Operational Situation Awareness; Mechanical Concerns; Environmental Sources; Power Systems; and Improper Installation.
- Development of safety risk ratings for critical hazards in three categories of RA technologies (wearable robots, remote operated robots, and onsite automated robots) when used for three construction tasks (bricklaying, concrete grinding and polishing, and drywall installation).
- Identification of 22 preventive strategies for mitigating HRI safety risks during construction

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Introduction

While most industries have witnessed a significant improvement in productivity and worker safety over the last two decades, construction continues to report flat or declining productivity and high fatality rates (Barbosa et al., 2017; BLS, 2019). Construction also suffers from high injury rates. According to CPWR (2016), the rate of work-related musculoskeletal disorders (WMSDs) in the industry is about 9% higher than the rate across all industries combined. In fact, WMSDs account for approximately 77% of occupation-related injuries in the industry (Punnet and Wegman, 2004).

As practitioners strive for more efficient and safer methods of construction, they have started incorporating more technology in several aspects of their projects (Vähä et al., 2013). Researchers and practitioners believe that incorporating robotics and automation (RA)—including exoskeletons, drones, and single-task construction robots (STCRs)—offers new possibilities for combatting challenges such as workforce development (e.g., recruiting new skilled workers and retaining existing workers) as well as unsafe and dangerous working conditions (Li, 2018; Bock, 2015). Yet the adoption rate of technologies that can, for example, prevent WMSDs in the industry is slower than in other industries. (Delgado et al., 2019),

Regardless of the potential positive impact of RA, human-robot interactions (HRI) can introduce new hazards on the job site or increase the potential impact of existing hazards. For instance, drones could increase the level of distraction, while STCRs could have system failures leading to a caught in/between injury. Multiple agencies have identified this potentially damaging effect, and in a bid to respond to the challenges associated with HRI in construction, the National Institute for Occupational Safety and Health (NIOSH), as part of its Strategic Plan (2019−2023), is pushing for collaborative research dedicated towards the effective use of RA (NIOSH 2019)

While some studies have assessed the adoption level and effectiveness of RA technologies, limited studies have evaluated (quantified and rated) hazards associated with the implementation of RA in construction. Moreover, even fewer have developed assessment tools to assist practitioners using RA. Previous studies indicate that the lack of crucial resources, such as an HRI safety risk assessment protocol, could increase resistance to using these technologies in construction (Nnaji et al. 2019).

To fill this gap, the researchers developed a series of resources to assist practitioners conducting pre-task planning involving RA. These resources include: a Safety Data Sheets (SDS) for RA technologies; Job Hazard Analysis (JHA) for three construction tasks—drywall installation, bricklaying, and concrete grinding and polishing; and a manual that provides information on the use of different RAs for safety and health management. In developing these resources, the researchers used well-proven methodologies that meet standards of academic thoroughness. The results from this small study will assist practitioners identify and quantify HRI safety risks inherent in the use of RA in construction operations. The resources described in this report will augment and enhance existing JHA procedures and lead to a more effective use of RA, encouraging the successful adoption and diffusion of safety technologies in the construction industry.

Research Objectives

The goal of the present study is to provide practical resources that help practitioners in construction organizations identify and quantify human-robot interaction hazards inherent in the use of robotics and automation. The study focuses on the development of knowledge and resources that support the effective and safe application of RA in construction.

The specific objectives of this Small Study are to:

1. Identify HRI hazards associated with the use of RA;
2. Assess the safety risk level of each hazard across multiple RA levels and tasks;
3. Identify effective strategies for eliminating or reducing the impact of the safety risk on workers; and
4. Develop an HRI safety risk assessment protocol.

Research Methods And Tasks

The researchers adopted an academically rigorous multi-phase approach in executing this study. Their approach incorporated a mixed-methods research design that relied on a sequential investigation to ensure that the outcome of the study was robust. The researchers conducted a systematic literature review, a modified Delphi technique (an interactive, structured, and systematic data-collection technique relying on an expert panel), and interviews to collect, quantify, and verify relevant data needed to meet the research objectives. Previous studies have highlighted the benefit of using these methods to develop robust and practical tools (Hallowell and Gambatese, 2009; Fellows and Liu, 2015). The specific tasks conducted as part of this study are as follows:

1. Conduct a literature review on HRI hazards
2. Conduct a modified Delphi process using an expert panel
    a. Identify and select experts for Delphi panel
    b. Identify and quantify HRI hazards and preventive strategies
3. Develop assessment protocol for measuring and evaluating HRI hazards
4. Obtain industry feedback on the protocol
5. Develop and submit a final research report

Literature Review: Identification of HRI hazards associated with the use of RA

The research team conducted an exhaustive review of grey (e.g., non-academic reports, white papers, and newsletters) and academic literature to identify trades and activities with the most potential to gain from the implementation of RA and the hazards most associated with the use of RAs. The literature review focused on identifying practices, procedures, and policies that may be applicable to each RA category; RA implementation factors in construction practice; and strategies which could facilitate the safe implementation of RA. The researchers identified academic articles and industry reports using multiple databases such as Google Scholar, Web of Science, and Scopus. The literature reviews also included documents published by Construction Drive: Tech, CWPR, Engineering News-Record, National Safety Council, NIOSH, and other organizations focused on emerging technologies and safety management. The HRI safety risk factors and implementation strategies were presented to construction experts using a modified Delphi approach.

Modified Delphi Method: Identification and assessment of relevant and mitigation strategies

In order to identify and quantify HRI safety risk and preventive strategies, the researchers selected experts to participate in a 3-round, modified Delphi study process. The Delphi method provides an interactive, structured, and systematic data-collection process, based on strategic interactions with a group of experts, to obtain information and knowledge. The researchers executed the three-round Delphi process to ensure that the study generates both practical and theoretical insights. Since the research process involves human subjects, the research team obtained Institutional Review Board approval from The University of Alabama before commencing the Delphi process (see copy of approval letter in Appendix A). The Delphi process was managed using an online questionnaire survey platform (Qualtrics).

The first round of the Delphi process focused on assessing potential experts' qualifications and identifying the hazards associated with the use of RA. The research team invited 105 potential participants with relevant expertise to participate in the study, including faculty members, safety managers/directors, project/site engineers, and injury prevention specialists. Industry practitioner contacts were identified from the Associated General Contractors (AGC) and Associated Building Contractors (ABC) websites and listservs. Thirty-nine responses were received (66 invitees declined); as 10 responses were incomplete, 29 were ultimately analyzed. Each of the participants met the requirements listed in Table 1 to be considered an expert, in line with previous CPWR-supported research (Gambatese et al. 2020). Next, the research team analyzed participants' feedback on the list of hazards that was previously identified through the systematic literature review.

Table 1: Expert Qualification Requirement (adapted from Gambatese et al. 2020; AlOmari et al. 2020)

Academia	Industry
Faculty Member at an accredited Higher institution of Learning	Industry Professional (safety managers/directors, project/site engineers, and injury prevention specialists)
Construction industry experience (> 5 years)	Construction Industry Experience (> 3 years)
Holding a Ph.D with emphasis in construction management, innovation management and occupational health and safety	Holding a B.S closely related to AEC industry
Professional registration	Professional Registration
Membership of a construction safety engineering/management, workforce training and development, and technology integration committee	Led or presented at a work training, or standard operating procedure (SOP) review meeting, on a topic related to construction/safety management most especially risk assessment, work quality, and worker performance
Conference papers on the topic of construction engineering or safety management bordering technology implementation, technology development, implementation, quality, and worker performance (> 3 papers)	Job is mainly related to construction engineering and/or safety management
Journal articles on the topic of construction engineering or safety management bordering technology implementation, technology development, implementation, quality, and worker performance (> 3 articles)	Leadership position(s) or role(s) that you have filled within your current or previous organization(s) with respect to workforce training and development, safety management, and technology integration efforts (e.g., Human Resources/Workforce Development Manager, Construction Manager, etc.
Invited to Present at a conference with a focus on construction engineering, safety management, construction automation, risk assessment, work quality, and worker performance	
Book or Book chapter editing	

The next round of the process assessed the risks associated with hazards identified and verified in Round 1. Participants were asked to provide a risk rating (frequency and severity) for safety hazards for the following construction tasks: drywall installation, bricklaying, and concrete grinding and polishing, using the scales shown in Figure 1. Participants were to select 1 for severity and frequency if they believe that the hazard would occur once in 10 years and would likely result in a near miss when it occurs. Participants were asked to choose zero ("0") if the hazard did not apply to the technology or task. The research team separated the participants into three groups – one assessing the use of RA for each of the three tasks in the study (drywall installation, bricklaying, or concrete grinding and polishing). The primary reason for separating the participants into groups was to reduce survey fatigue. The research team ensured that each group had at least seven participants, meeting the minimum requirement of a Delphi panel (Hallowell and Gambatese 2009).

Frequency Scale: Average duration between incidents				
Never	1 year	1 month	1 week	1 day
1	2	3	4	5

Injury Severity Levels and Categories			
Near miss (1)	Low severity (2)	Medium severity (3)	High severity (4)
No injury or impact on work time - Near miss; Negligible	No impact on work time; worker returned to regular work within 1 day - Temporary discomfort; Persistent discomfort; Temporary pain; Permanent pain; Minor first aid	Worker could not return to regular work within 1 day - Major first aid; Medical case; Lost work time	Worker could not return to regular work at all - Permanent disablement Fatality

Figure 1: Frequency and Severity Scales

Round 3 provided participants with an opportunity to appraise the findings from the three groups in Round 2 using a Likert scale ("I agree" and "I disagree"). Participants were asked to provide new assessments/suggestions if they selected "I disagree." In addition, participants were asked to assess the potential impact of the identified strategies at risk mitigation. Consensus among the experts was evaluated using standard deviation and the Kendal W coefficient.

Development of an HRI safety risk assessment protocol

After identifying and assessing the impact of potential HRI hazards (obtaining safety risk ratings), the research team proposed potential strategies for reducing the impact of hazards associated with using RA in construction and verified these strategies using insights from the Delphi panel. Next, the research team developed practical tools for practitioners to use to assess and control HRI hazards associated with using RA for three construction tasks. The HRI hazard evaluation tools consist of: (1) Safety Data Sheets (SDS) for using wearable robots (exoskeletons), remote operated robots (e.g., drones and UGVs), and onsite automated robots (e.g., bricklaying robots); and (2) Job Hazard Analysis (JHA) protocols for three tasks: drywall installation, bricklaying, and concrete grinding and polishing. To develop the SDS and JHA in accordance with global standards easily understood by workers regardless of their levels of education, the team appraised SDS and JHA forms widely used in the industry, and especially those created from studies funded by CPWR and other practice-oriented organizations. In addition, the research team used example SDSs and JHAs received from industry collaborators. After developing these tools, the research team created a process to support their effective use. The availability of practical, easy-to-use tools should accelerate the transition of this research to practice, thereby aligning with CPWR's research-to-practice initiative.

Obtain industry feedback on the protocol

Following the development of the HRI resources, the researchers established a protocol for verifying the feasibility and effectiveness of the proposed tools. They began by contacting industry practitioners across the United States to assess the research products. These individuals have a combination of safety management expertise, construction management insight (project management and technology adoption/implementation), and familiarity with the operation of RA. Seven stakeholders (summarized in Table 2) assessed the tools' perceived effectiveness and applicability and proposed improvements. They provided their assessment of the research output (SDSs and JHA forms) using the verification statements, where: 1 = very poor/totally disagree; 5 = average/neutral, and 9 = excellent/totally agree. In addition, the practitioners received an accident case scenario and evaluated whether the JHA tool could have helped prevent, or reduce the impact of, an accident caused by HRI.

Table 2: Focus Group Demographics

No.	Experience (Years)	Highest Degree	Organization Type	Professional Registrations and Certifications
1	6 - 10	Graduate degree	Education	OSHA 30 or more (e.g., OSHA 510, OSHA 500)
2	6 - 10	Graduate degree	Education	OSHA 30 or more (e.g., OSHA 510, OSHA 500)
3	11 - 15	Graduate degree	Education	OSHA-authorized safety trainer
4	11 - 15	Graduate degree	Education	OSHA 10 Certification
5	11 - 15	Graduate degree	Owner Agency/ Client	- OSHA 30 Certification or more (e.g., OSHA 510, OSHA 500) - LEED Accredited Professional
6	6 - 10	Graduate degree	General Contractor	- Certified/Associate Safety Professional - OSHA 30 or more (e.g., OSHA 510, OSHA 500) - Safety Management Certificate
7	6 - 10	Graduate degree	Owner Agency/ Client	Certified/Associate Safety Professional

ACCOMPLISHMENTS AND RESULTS

The following activities were accomplished as part of the small study.

Literature Review

The researchers identified 40 hazards (Table 3) associated with the use of RA from multiple sources. These hazards are grouped into seven categories based on the OSHA robot hazard classification (OSHA, n.d).

Table 3: Safety Risks and Hazards associated with construction using RA

Cat/No.	Safety Risks and Hazards	Select References
A	**Human**	Bock (2015); Cho et al. (2018); IFA (2019); Delgado et al. (2019); Hasanzadeh et al. (2017); Kim et al. (2019); Namian et al. (2018); OSHA (2020); Tatum and Liu (2017); Xu et al, (2020)
1	Physical stress (e.g., impose additional load, fatigue)	
2	Operator errors	
3	Perceived safety (trust in robot)	
4	Work in an unfavorable body posture	
5	Technology comfort	
6	Mental stress (e.g., isolation, single workstation, forced to use device)	
7	Hygiene issue	
8	Improper equipment / tool use	
9	Distrust in device	
B	**Control**	Delgado et al. (2019); IFA (2019); Li (2018); OSHA (2020); Tatum and Liu (2017); Xu et al, (2020)
10	Software error	
11	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	
C	**Unauthorized Access or Operational Situation Awareness**	Bock (2015); De Looze et al. (2016); Delgado et al. (2019); IFA (2019); Kim et al. (2019); OSHA (2020); Xu et al, (2020)
12	Distraction	
13	Entry into a robot's safeguarded area	
D	**Mechanical Concerns**	Bock (2015); Delgado et al. (2019); IFA (2019); OSHA (2020); Xu et al, (2020)
14	Parts with dangerous surfaces	
15	Unguarded moving parts	
16	Autonomous moving parts	
17	Mechanical part failure	
18	Impalement hazards	
19	Worker has limited mobility	
20	Unpredicted movement or action by the robot	
21	Flammable materials	
22	Excessive vibration	
23	Hot surfaces / thermal burns	
E	**Environmental Sources**	Bock (2015); Delgado et al. (2019); IFA (2019); Kim et al. (2019); Perlman et al. (2014); Nnaji et al. (2019); OSHA (2020); Tatum and Liu (2017); Xu et al, (2020)
24	Electromagnetic or radio-frequency interference (transient signals)	
25	Poor weather condition (e.g., unstable flying conditions)	
26	Collision with infrastructure	
27	Catching and dragging hazards (by moving parts)	
28	Adverse Indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	
29	Uneven work surfaces / improper footing/changes in elevations	
30	Overhead/adjacent work/overhead loads	
31	Dirt (e.g., oil, grease) in work areas	
32	Introduces new source of noise	
F	**Power Systems**	Bock (2015; Delgado et al. (2019); IFA (2019); OSHA (2020); Tatum and Liu (2017); Xu et al, (2020)
33	Malfunctioning control or transmission elements	
34	Fire risks (due to electrical overloads or use of flammable hydraulic oil)	
35	Electrical hazards (e.g., rechargeable battery, faulty wire/plugs)	
G	**Improper Installation**	Bock (2015; Cho et al. (2018); Delgado et al. (2019); IFA (2019); OSHA (2020); Xu et al, (2020)
36	Inadequate or incorrect work/task design	
37	Absence of work/task requirements	
38	Improper equipment layout	
39	Improper platform (e.g., shoring/scaffold collapse)	
40	Unworkable combination of robots and PPE	

Based on the results from the literature review, the research team identified the following at-risk trades that could benefit from the application of at least one category of RA. As listed in Table 4, masonry workers, carpenters, drywall/ceiling/tile installers, and cement/concrete finishers suffer from higher rates on incidents that could be mitigated using RAs.

Table 4: Trades with the most potential to gain from the implementation of RA

No.	Trades	Specific hazards and trade-specific safety risk	Select References
1	Masonry workers (Brickmasons, Blockmasons, and Stonemasons)	• Slips, trips, and falls • Falling heavy objects • Collapsing or cave-in of excavations • Collapse or cave-in of walls • Electrical shocks • Risk of pain or injury from working in awkward positions, performing repetitive tasks, or lifting. • Moving, lifting, or carrying heavy objects	BLS (2020); CPWR (2016); CPWR (2020); Cho et al. (2018); Inyang et al. (2012)
2	Carpenters	• Exposure to loud noise from machinery and tools • Risk of pain or injury from working in awkward positions, performing repetitive tasks, or lifting • Risk of entanglement of body parts into rotating parts or machinery • Extreme temperatures when working outdoors. • Risk of eye injury from flying particles • Working at heights	
3	Drywall, Ceiling Tile Installers and Tapers	• Slips, trips, and falls • Falling heavy objects • Moving, lifting, or carrying heavy objects	
4	Cement and Concrete Finishers	• Skin Contact • Eye Contact • Inhalation • Skin problems caused by exposure to Portland cement • Risk of injury depends on duration and level of exposure and individual sensitivity	
5	Cement Masons and Terrazzo Workers	• Knee injuries (due to constant kneeling) • Hazards from silica • Skin problems caused by exposure to Portland cement	

The research team also identified several adoption drivers and strategies, policies, and regulations guiding or influencing the implementation of RAs, and this information is provided in the Practical Assessment Manual for RA use in Construction (see Appendix B).

Modified Delphi Process

The expert panel consisted of a total of 29 members: 17 were faculty members at U.S. universities within the United States, and 25 participants across industry and academia are actively involved in safety management (e.g., safety managers/directors, and injury prevention specialists). The panelists averaged 10.55 years of work experience in the construction industry. In addition, all of the participants have at least a bachelor’s degree, with 65.5% (19) having doctorates. Together the group holds a plethora of professional registrations and certifications related to construction engineering and/or safety management: there were three Professional Engineers (PE), 10 Certified/Associate Safety Professionals (CSP/ASP), 13 individuals with OSHA 30-hour Certification or more (e.g., OSHA 510, OSHA 500), and four LEED Accredited Professionals (LEED AP). Also, 96.55% of the experts (28) have given a presentation at a professional conference, workshop, or meeting on a topic related to construction engineering, safety management, construction automation, risk assessment, work quality, or worker performance.

Round 1 Survey

In Round 1 of the Delphi process, the research team evaluated participants’ familiarity with RAs and gave the panelists the list of RA-related hazards, asking them if each hazard is associated with the use of RA (i.e., if an RA technology worsens its impact or introduces a new hazard) across the three categories. Only

7% (2) of the experts were not familiar with either exoskeletons or on-site automated robotic systems. Although this value rose to 14% (4) when assessing remote-operated robots, the expert panel is overwhelmingly familiar (>86% of the panelists) with all three RA categories, which ensures that the responses received from the experts are relevant and reliable.

Responses from participants on the association between hazards listed in Table 3 and RA categories were collected using a binary scale (1 = Yes, 2 = No). Participants selected "YES" if they believe the hazard is associated with an RA technology and "NO" if the hazard is not introduced or impacted by the RA technology. To analyze the data for each RA category, the research team first flagged non-critical hazards--that is, those hazards that experts believe are not introduced or exacerbated by the use of RA. Hazards were considered "non-critical or irrelevant if more than 66% of participants flagged them. As seen in Table 4, no hazard received more than 66% "No" responses across the three RA categories, indicating that all hazards identified in this study could influence worker safety when using RA.

It is important to note that the research team conducted this assessment separately for experts in academia and practice groups. The research team observed a similar trend and high consistency within and between groups. Subsequently, the research team combined responses from both groups (see Table 5). At the RA category level, the research team removed hazards flagged within and across groups. For instance, the research team eliminated physical stress as a hazard when using on-site autonomous robots and remote operated robots but retained this hazard for wearable robots. This process was used to streamline the list of hazards analyzed by the experts in Round 2 of the Delphi process.

Table 5: Hazards Associated with RAs (N = 29)

No.	Hazards	Wearable Robots	Remote-operated robots	On-site autonomous robots
		No (%)	No (%)	No (%)
1	Physical stress (e.g., impose additional load, fatigue)	48.28%	82.76%	89.66%
2	Operator errors	41.38%	0.00%	24.14%
3	Perceived safety (trust in robot)	31.03%	27.59%	27.59%
4	Work in an unfavorable body posture	58.62%	82.76%	89.66%
5	Unpredicted movement or action by the robot	37.93%	20.69%	17.24%
6	Mental stress (e.g., isolation, forced to use device)	51.72%	34.48%	55.17%
7	Hygiene issue	48.28%	96.55%	96.55%
8	Improper equipment / tool use by worker	17.24%	13.79%	20.69%
9	Worker has limited mobility	27.59%	89.66%	86.21%
10	Software error	58.62%	6.90%	6.90%
11	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	17.24%	13.79%	3.45%
12	Distraction	31.03%	17.24%	20.69%
13	Entry into a robot's safeguarded area	68.97%	24.14%	3.45%
14	Technology discomfort	10.34%	24.14%	20.69%

Table 5: Hazards Associated with RAs (N = 29)

No.	Hazards	Wearable Robots	Remote-operated robots	On-site autonomous robots
15	Distrust in device	13.79%	13.79%	3.45%
16	Parts with dangerous surfaces	44.83%	27.59%	24.14%
17	Unguarded moving parts	58.62%	20.69%	13.79%
18	Autonomous moving parts	62.07%	27.59%	3.45%
19	Mechanical part failure	17.24%	6.90%	3.45%
20	Impalement hazards	55.17%	44.83%	27.59%
21	Flammable materials	68.97%	55.17%	51.72%
22	Excessive vibration	51.72%	75.86%	55.17%
23	Hot surfaces / thermal burns	55.17%	72.41%	58.62%
24	Electromagnetic or radio-frequency interference (transient signals)	65.52%	37.93%	44.83%
25	Poor weather condition (e.g., unstable flying conditions)	62.07%	10.34%	34.48%
26	Collision	75.86%	13.79%	13.79%
27	Catching and dragging hazards (by moving parts)	34.48%	6.90%	0.00%
28	Adverse Indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	27.59%	24.14%	41.38%
29	Uneven work surfaces / improper footing/changes in elevations	37.93%	44.83%	24.14%
30	Overhead/adjacent work/overhead loads	34.48%	20.69%	20.69%
31	Dirt (e.g., oil, grease) in work areas	27.59%	31.03%	27.59%
32	Introduces new source of noise	55.17%	27.59%	17.24%
33	Malfunctioning control or transmission elements	31.03%	20.69%	6.90%
34	Fire risks (due to electrical overloads or use of flammable hydraulic oil)	55.17%	34.48%	17.24%
35	Electrical hazards (e.g., rechargeable battery, faulty wire/plugs)	31.03%	17.24%	10.34%
36	Inadequate or incorrect work/task design	20.69%	24.14%	13.79%
37	Absence of work/task requirements	48.28%	41.38%	41.38%
38	Improper equipment layout	55.17%	37.93%	20.69%
39	Improper platform (e.g., shoring/scaffold collapse)	44.83%	41.38%	13.79%
40	Unworkable combination of robots and PPE	17.24%	44.83%	41.38%

Round 2 Survey

Before analyzing the data to determine the risk level of each hazard associated with the different tasks and technologies, the research team assessed the level of consensus within and between groups. Consensus within groups were assessed using Kendall's coefficient of concordance (W_k) and chi-square distribution (χ^2). Previous studies suggest that a W_k value (the level of agreement between experts by considering the differences between the mean rankings of the different variables) from 0.23 - 0.60 and a χ^2 result with p-value below 0.05 suggests consensus within a group (Gunduz and Elsherbeny 2020). The research team also checked the reliability of the survey tool within each group using Cronbach's alpha ($\propto$) – where $\propto$ above 0.7 indicates a reliable tool.

Table 6 shows the consensus and reliability results. The $\propto$ values are satisfactory (> 0.7), while the majority of the W_k values are between 0.23 and 0.60. There were three results where the RA technology with a specific task did not meet the consensus requirements: onsite STCR for dry-wall installation, and remote-operated robots for both bricklaying and concrete polishing. Although the W_k value was slightly below the recommended threshold for onsite STCR for concrete polishing and grinding, the p-value for $\chi 2$ was significant ($p\text{-value} < 0.05$), which signifies consensus. The team included the hazards that failed to achieve consensus in Round 3 of the Delphi process, providing participants with an opportunity to evaluate the mean safety risk ratings and adjust their rating, if they chose to.

Table 6: Group Agreement (Task-Based Classification)

Test Statistics	Groups								
	Dry-wall installation (n = 7)			Bricklaying (n = 8)			Concrete Polishing and Grinding (n =9)		
	Wearable Exo	Drones and Autonomous Vehicles	Onsite STCR	Wearable Exo	Drones and Autonomous Vehicles	Onsite STCR	Wearable Exo	Drones and Autonomous Vehicles	Onsite STCR
Cronbach's alpha (∝)	0.898	0.831	0.894	0.838	0.921	0.906	0.810	0.813	0.815
Kendall's coefficient (Wk)	**0.536**	**0.230**	0.182	**0.422**	0.188	0.199	**0.384**	0.144	**0.220**
Chi-square distribution ($\chi 2$)	71.301	30.643	22.967	64.156	28.539	33.356	65.727	24.546	41.544
Degrees of freedom (df)	19	19	21	19	19	21	19	19	21
P-Value	**0.000**	**0.044**	0.346	**0.000**	0.074	**0.042**	**0.000**	0.176	**0.005**

Bold Font denotes significance (p-value < 0.05)

Following these calculations to determine consensus, the research team calculated the safety risks for each hazard. First, they converted the linear rating provided by the participants in the survey (see 1 - 4 and 1 - 5 rating scales in Figure 1) into exponential safety risk values using a scale adapted from previous research (Hallowell 2008; Jazayeri and Dadi 2020). The adapted scale is provided in Table 7. An exponential scale provides a more realistic representation of the relationship between the different levels of severity and frequency (Hallowell 2008).

Table 7: Severity and Frequency Conversion (Adapted from Hallowell 2008; Jazayeri and Dadi 2020)

Severity scale conversion				
Near miss	Negligible	Minor first aid	Lost worktime	Permanent Disability, Fatality
0	1	17	158	14282
Frequency scale conversion				
1/10years	1/year	1/month	1/week	1/day
0.000044	0.00044	0.0053	0.0333	0.111

Next, the research team developed a process and threshold for determining the different safety risk levels - low risk to extremely high risk (Figure 2). The numbers presented in Figure 2 is derived from Equation 1:

$$\textit{Safety risk (S/w-h)} = \textit{Frequency (incident/w-h)} \times \textit{Severity (S/incident)} \qquad (1)$$

To determine the different safety risk levels, the research team relied on a safety risk assessment structure used in different industries (Neubauer et al. 2015). The research team included the proposed thresholds for "Extremely high risk," "High risk," "Moderate risk," and "Low risk" in Round 3 to provide participants the opportunity to validate it.

		Severity				
		0	1	17	158	14282
	0.000044	0	0.000044	0.000748	0.006952	0.628408
	0.00044	0	0.00044	0.00748	0.06952	6.28408
Frequency	0.0053	0	0.0053	0.0901	0.8374	75.6946
	0.0333	0	0.0333	0.5661	5.2614	475.5906
	0.111	0	0.111	1.887	17.538	1585.302

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

<u>Round 3 Survey</u>

In Round 3, the research team focused on:

i. Assessing the thresholds used for the safety risk levels;
ii. Confirming the safety risk ratings derived from Round 2 that failed to meet the consensus requirements; and
iii. Establishing strategies for preventing or reducing the impact of hazards attributed to human-robot interaction.

Before Round 3 commenced, the research team paired identified/verified strategies with hazards that they (the strategies) could affect positively (reduce frequency/impact of the hazard). The pairing was presented to participants to provide feedback to help achieve the third focus (iii above).

Participants were first asked if they agree with the safety risk levels and thresholds shown in Figure 2 using three questions (I agree, I am not certain, and I disagree). Ninety-six percent of the expert panelists (25 completed responses) agreed with the safety risk assessment rating scale used in this study. The only respondent who did not expressed a preference that "Extremely high risk" be assigned to any safety risk and hazard assigned a *Permanent Disability/Fatality* severity rating irrespective of frequency selected.

Next, the research team verified that consensus was achieved for safety risk associated with using an on-site autonomous robot for drywall installation and remote-operated robots for bricklaying and concrete polishing and grinding. These activities and RAs were re-evaluated because results from the consensus analysis indicated that consensus was not reached (Table 5). Results from the safety risk reassessment indicate that consensus was achieved for each reassessed RA technology and task (p-value > 0.05; W_k from 0.23 - 0.60).

Finally, participants were asked to rate the risk reduction capability of a group of strategies using a 10-point Likert scale where:

- 0 - 1 points = Strategies could have little to no impact on safety risk reduction;
- 2 - 4 = Strategies could reduce Moderate Risk (M) to Low Risk (L);
- 5 - 7 = Strategies could reduce High Risk (H) to Moderate Risk (M);
- 8 - 10 = Strategies could reduce High Risk (H) to Low Risk (L).

For instance, participants were asked to select 0 or 1 on the Likert scale if they believe a particular combination of strategies would have no impact on safety risk reduction. On the other hand, participants were expected to select 8, 9, or 10 if a combination of strategies could control a significant risk (reducing a safety risk from High Risk to Low Risk).

The median ratings shown in Table 7 indicate that the strategies could reduce or prevent the impact of the associated hazards to different degrees. Since their effectiveness rate ranges from 5 to 8, the suggested strategies would likely have a significant impact on risk reduction [ranging from reducing high risk to moderate risk, and high risk to low risk].

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	• Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population • Ensure compliance of safety procedures through periodic training and spot checks; • Ensure proper ventilation and lightening (natural or forced) in rooms/work location • Incorporate manufacturer safety requirements into written company safety procedures	5	5.05	2.36
Autonomous moving parts	• Wear appropriate personal protective equipment • Clean equipment regularly • Use only robots that have been shown to be effective • Procure robots with low vibration intensity	7	6.86	1.49
Catching and dragging due to moving parts	• Check for visible defects on robots before starting work • Ensure compliance of safety procedures through periodic training and spot checks	7	7	1.58
Collision in the workspace	• Provide clear, concise, available and up-to-date job aids accepted by the intended user population • Observe and adhere to the manufacturer's information on the scope of use • Obtain and review safety data sheets from the RA manufacturer • Use only robots that have been shown to be effective • Design work to be less complex	6	6.86	2.06
Dirt (e.g., oil, grease) in work areas	• Clean equipment regularly	7	6.67	1.71

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
Distrust in device	• 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	8	7.86	1.42
Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	• Prevent unauthorized or improper maintenance and installation of robots • Observe and adhere to the manufacturer's information on the scope of use • Obtain and review safety data sheets from the RA manufacturer	7	6.8	1.88
Entry into a robot's safeguarded area	• Observe and adhere to the manufacturer's information on the scope of use • Ensure compliance of safety procedures through periodic training and spot checks • Involve employee in safety decision-making regarding use of robots • Observe safety distances; Design work to be less complex • Ensure proper ventilation and lightening (natural or forced) in rooms/work location • Fit each worker individually with the robot before use	7	6.24	2.34
Errors made by operator	• Wear appropriate personal protective equipment • Provide clear, concise, available and up-to-date job aids accepted by the intended user population • Incorporate manufacturer safety requirements into written company safety procedures • Select suitable hearing protection and make available/use • Ensure compliance with safety procedures through periodic training and spot checks • Have checks performed regularly by a skilled technologist/technician • Involve employee in safety decision-making regarding use of robots	7	6.95	2.13

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
	• Observe safety distances • Fit each worker individually with the robot before use			
Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	• Clean equipment regularly • Prevent unauthorized or improper maintenance and installation of robots • Check for visible defects on robots before starting work • Ensure compliance of safety procedures through periodic training and spot checks • Have checks performed regularly by a skilled technologist/technician	8	7.33	1.96
Improper equipment / tool use by worker	• Wear appropriate personal protective equipment • Provide clear, concise, available and up-to-date job aids accepted by the intended user population • Observe and adhere to the manufacturer's information on the scope of use; Observe safety distances • Obtain and review safety data sheets from the RA manufacturer; Use ergonomically designed wearable robot • Use only robots that have been shown to be effective • Ensure that only robots without sharp edges, crushing points or other dangerous surfaces are used • Fit each worker individually with the robot before use	8	6.9	2.81
Improper platform (e.g., shoring/scaffold collapse)	• Provide clear, concise, available and up-to-date job aids accepted by the intended user population • Incorporate manufacturer safety requirements into written company safety procedures • Obtain and review safety data sheets from the RA manufacturer; Design work to be less complex	7	7.05	2.2

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
Inadequate or incorrect work/task design	• Incorporate manufacturer safety requirements into written company safety procedures • Observe and adhere to the manufacturer's information on the scope of use • Involve employee in safety decision-making regarding use of Robots • Use only robots that have been shown to be effective • Ensure that only robots without sharp edges and crushing points or other dangerous surfaces are used	7	6.85	2.06
Malfunctioning control or transmission elements	• Prevent unauthorized or improper maintenance and installation of robots • Check for visible defects on robots before starting work • Observe and adhere to the manufacturer's information on the scope of use • Ensure compliance of safety procedures through periodic training and spot checks • Obtain and review safety data sheets from the RA manufacturer	7	6.38	2.09
Mechanical part failure	• Clean equipment regularly; • Prevent unauthorized or improper maintenance and installation of robots; • Check for visible defects on robots before starting work • Ensure compliance of safety procedures through periodic training and spot checks • Have checks performed regularly by a skilled technologist/technician	6	5.52	2.42
Poor weather condition (e.g., unstable flying conditions)	• Provide clear, concise, available and up-to-date job aids, accepted by the intended user population • Observe and adhere to the manufacturer's information on the scope of use • Involve employee in safety decision-making regarding use of Robots • Ensure proper ventilation and lightening (natural or forced) in rooms/work location	7	6.33	2.56

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
Software error	• Prevent unauthorized or improper maintenance and installation of robots • Observe and adhere to the manufacturer's information on the scope of use • Obtain and review safety data sheets from the RA manufacturer	7	7.24	1.87
Technology discomfort	• Wear appropriate personal protective equipment • Provide clear, concise, available and up-to-date job aids, accepted by the intended user population • Incorporate manufacturer safety requirements into written company safety procedures • Select suitable hearing protection and make available/use • Observe and adhere to the manufacturer's information on the scope of use • Involve employee in safety decision-making regarding use of robots • Obtain and review safety data sheets from the RA manufacturer • Use only robots that have been shown to be effective • Ensure that only robots without sharp edges, crushing points or other dangerous surfaces are used • Procure robots with low vibration intensity • Design work to be less complex • Fit each worker individually with the robot before use	8	7.29	1.68
Unworkable combination of robots and PPE	• Wear appropriate personal protective equipment • Provide clear, concise, available and up-to-date job aids, accepted by the intended user population • Incorporate manufacturer safety requirements into written company safety procedures	8	6.76	2.61

Table 8: Impact of strategies on safety risk reduction (n = 25)

Hazard	Strategies	Effectiveness of strategy on risk reduction		
		Median	Mean	SD
	• Select suitable hearing protection and make available/use • Ensure compliance of safety procedures through periodic training and spot checks; • Use only robots that have been shown to be effective • Ensure that only robots without sharp edges, crushing points or other dangerous surfaces are used • Procure robots with low vibration intensity • Design work to be less complex • Fit each worker individually with the robot before use			
Worker's mobility is limited	• Provide clear, concise, available and up-to-date job aids accepted by the intended user population • Incorporate manufacturer safety requirements into written company safety procedures • Observe and adhere to the manufacturer's information on the scope of use • Observe safety distances • Use only robots that have been shown to be effective • Ensure that only robots without sharp edges, crushing points or other dangerous surfaces are use • Design work to be less complex • Fit each worker individually with the robot before use	8	7.62	1.72

<u>HRI safety risk assessment protocol</u>

In developing a protocol for evaluating HRI hazards (see Appendix C), the intent was for the protocol to complement other traditional pre-task evaluation tool (task-based JHA, for instance). This tool would assist contractors in identifying potential hazards based on the construction task and the type of RA. The protocol was designed using data (hazards, risk scores, and mitigation strategies) acquired from the three rounds of the Delphi process. The research team recognizes the importance of optimizing ease of use, comprehensiveness, and visual appeal – critical elements of effective tools that achieve broad dissemination to the target audience. Therefore, sections, notations, and color codes were used to ensure the documents are easy to understand. Although only three tasks were evaluated in this study, the protocol will provide safety professional/foreman/superintendent leading a job hazard analysis a process for assessing the safety risks associated with a specific activity or task involving RA. Based on the result of that assessment (the safety risk matrix outcome), the individual leading the JHA could reference strategies that align with the hazards rated as moderate, high, and extremely high risk.

Although the outcome of the safety risk assessment may be subjective due to potential bias of the individual conducting the assessment, the assignment of recommended strategies will be largely objective. Users of the tool should have a combination of task-specific knowledge, safety management expertise, and familiarity with the operation of the RA. An organization could develop additional JHAs for multiple tasks using the process and products presented in this study and insights gained from performing JHAs on projects using these resources.

Feedback on the Research Products

As explained previously in "Obtain industry feedback on the protocol" section (Page 6), the research team asked seven practitioners and researchers to provide their assessment of the research output (JHA forms and SDS) using the verification statements provided to a 1 to 9 scale where 1 = very poor/totally disagree; 5 = average/neutral, and 9 = excellent/totally agree.

Results from the research product feedback analysis indicate that most participants believe that the resources developed (SDSs and JHAs) are very practical, adaptable, engaging, effective, and easy to use and understand. As seen in Table 8, the minimum median score assigned for all items regarding a variety of tool characteristics was 7.5, indicating a very high acceptability level.

Table 8: Assessment of Safety Data Sheet (SDS) and Job Hazard Analysis (JHA) Forms (n = 7)

Tool Assessment		**SDS**	**JHA**
Ref	**Verification Statement**	**Median**	**Median**
Q1	Information is easy to understand.	8	8
Q2	Tool is practical (i.e., provide accurate and consistent information).	8	9
Q3	Tool would be easy to use on projects.	7.5	8
Q4	Tool is adaptable (i.e., easy to integrate into existing sheets/forms).	8	9
Q5	Tool is engaging (prompts) while being used.	7.5	9
Q6	Tool is effective (sufficient in breadth and depth).	9	9

In addition to the Likert scale response, participants provided open-ended feedback. They were generally pleased with the structure and level of detail provided in the products. Below are examples of comments received from stakeholders who reviewed the research products:

> "*Integral adaptability is cogent while introducing wearable devices for workers in high risk, or precision-related work environment. They must have been able to practice using the device in a stable, non-hazardous environment. The development of muscle alignment and coordination while wearing this device is pivotal to workplace safety".*

> *"The safety data sheets that you have created is excellent and comprehensive. These will definitely be useful as technological solutions are increasingly adopted in construction workplaces."*

> *"The developed JHA tool is an excellent and well-thought-out tool that can be used to effectively identify the hazards associated with the use of RA"*

> *"The tool is also very user-friendly and intuitive to use."*

Deviations (Timeline/methodology)

There was no major deviation from the timeline as initially projected. However, regarding the research methodology, the Delphi process was slightly modified. In the second round of the 3-round Delphi process, the experts were divided into three groups to assess information per construction task type. This modification was designed to avoid attrition that could occur if the information presented to the experts is too lengthy. To maintain the initial objective, a statistical analysis assessed the level agreement within and between groups. Only once consensus was achieved did the researchers proceed to subsequent survey rounds. In addition, the research team opted for an online assessment/feedback process instead of an in-person focus-group meeting to achieve the goal of Task 4, a change necessary due to the restrictions caused by COVID-19.

Future Funding Plans

Data from the small study will be used in the submission of grant proposals on related topics to the National Institute of Health, National Science Foundation, and the Construction Industry Institute.

Dissemination Plan

Journal articles and a conference paper that describe the research study and findings will be written and submitted for publication and presentation. All manuscripts will be written such that the names of the industry partners, Delphi panel members, and other participating firms are not identified.

List of Presentations/Publications, Completed and/or Planned

Accepted for Publication

1. Okpala, I.U, Nnaji, C., Ogunseiju, O., and Akanmu, A. (*in press*). "Assessing the Role of Wearable Robotics in the Construction Industry: Potential Safety Benefits, Opportunities and Implementation Barriers." Automation and Robotics in the Architecture, Engineering, and Construction Industry. Springer.

Submitted for Review

1. Okpala, I.U., Nnaji, C., and Gambatese, J. (2021) "Investigating Hazards and Safety Risks inherent in Human-Robot Interactions." Submitted to ASCE Construction Institute/Construction Research Congress 2022.

Planned Publications

1. Okpala, I. U., Nnaji, C. (2022) "Identification of Safety Risks for Robotics and Automation Use during Construction Operations." To be Submitted to Journal of Safety Science in September 2022.

2. Okpala, I.U., Nnaji, C., and Gambatese, J. (2022) "Development of Safety Risk Assessment Tool for Implementing Robotics and Automation in Construction Operations." To be Submitted to Journal of Construction Engineering and Management in September 2021.

3. Okpala, I.U., Nnaji, C., and Gambatese, J. (2022) "Assessment of Wearable Robot Safety Risks during Construction Operations." To be Submitted to Journal of Management in Engineering in October 2021.

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APPENDICES

Appendix A – Research Project Approval by UA Internal Review Board (IRB)

THE UNIVERSITY OF ALABAMA® | *Office of the Vice President for* Research & Economic Development Office for Research Compliance

July 14, 2020

Ifeanyl Okpala
Department of Civil Construction Environmental Engineering
College of Engineering
Box 870205

Re: IRB # 20-06-3663: "Protocol for Assessing Human-Robot Interaction Safety Risks"

Dear Ifeanyl Okpala:

The University of Alabama Institutional Review Board has granted approval for your proposed research. Your application has been given exempt approval according to 45 CFR part 46. Approval has been given under exempt review category 2 as outlined below:

(2) Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) if at least one of the following criteria is met:

(iii) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by §46.111(a)(7).

The approval for your application will lapse on July 13, 2021. If your research will continue beyond this date, please submit the annual report to the IRB as required by University policy before the lapse. Please note, any modifications made in research design, methodology, or procedures must be submitted to and approved by the IRB before implementation. Please submit a final report form when the study is complete.

Please use reproductions of the IRB approved informed consent form to obtain consent from your participants.

Sincerely,

Carpantato T. Myles, MSM, CIM, CIP
Director & Research Compliance Officer

Jessup Building | Box 870127 | Tuscaloosa, AL 35487-0127
205-348-8461 | Fax 205-348-7189 | Toll Free 1-877-820-3066

Appendix B

Robotic Systems Assessment Manual

Chukwuma Nnaji, John Gambatese, and Ifeanyi Okpala

The University of Alabama

Oregon State University

CPWR Small Study No. 20-4-PS

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Wearable Exoskeletons

Wearable robots, wearable robotics, and wearable exoskeletons (also referred to as ”exos”) are a class of machines (mechanical devices) that enhance human worker performance when physically attached to a person’s body while performing work. During construction, they can be used during lifting operations, or for tasks involving the use of tools in awkward positions thereby reducing strains and sprains as well as fatigue.

Some active exoskeletons include: Hybrid Assisted Limb (HAL) for Care Support; MeBot-EXO; MK2b; Eco-Pick Lift Assist; Lucy; MuscleSuite; Angel-Suit; UMEx-oLEA; and FORTIS™. Some passive exoskeletons include: BackX; Bending Non- Demand Return (BNDR) Device; Laevo; Personal Lift - Assist Device (PLAD); SPEXOR; EksoVest; H-VEX (Hyundai Vest Exoskeleton); Fawcett Exsovest™ with a zeroG2 arm; shoulderX; PAEXO; EXHAUSS Stronger; SkelEx; LegX; and Chairless-Chair.

Exoskeletons Applicable in Construction

No.	Wearable Robot	Tasks	Body Location	Cost	Category*
1	FLx ErgoSkeleton	Pick and carry	Upper body	$298.87	Passive
2	Hilti EXO-01	Elevated arms and repetitive arm motions	Upper body	$1,599.00	Passive
3	SuitX MAX	Bending, lifting, squatting, elevated arms, and prolonged standing	Full body	-	Passive
4	Flex Lift	Bending, lifting, and standing	Full body	-	Passive
5	Ekso Vest	Elevated arms, static arms, and repeated arm motions	Upper body	$5,000	Passive
6	Iron Hand	Grasping	Upper body (Wrist)	$6,500	Active
7	FORTIS	Heavy tool and static arms	Semi-full body	$7,149	Passive
8	ATOUN Model Y	Bending and lifting	Upper body	-	Active
9	Levitate Airframe	Elevated arms, static arms, and repeated arm motions	Upper body	$5000	Passive
10	Laevo	Bending, lifting, and reaching	Upper body	-	Passive
11	BackX	Bending, lifting, reaching, and stooping	Upper body	$4000	Passive

* Passive exos do not have any electrical power source (non-motorized); Active exos use batteries or electric cable connections to run sensors and actuators

Key Safety Risks and Hazards

- Worker could have limited mobility
- Improper use of exoskeleton by worker
- Technology could cause some discomfort
- Mechanical part failure could lead to injury
- Dirt (e.g., oil, grease) in work areas
- Inadequate or incorrect work/task design fit
- Unworkable combination of robots and PPE
- Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)
- Distrust in device
- Adverse indoor and outdoor climate (e.g., hot/cold temperatures; humidity, wind)

Key Trades for which Exos could Improve Safety and Performance

- Masonry workers (Brickmasons, Blockmasons, and Stonemasons)
- Carpenter
- Drywall, Ceiling Tile Installers and Tapers
- Cement and Concrete Finisher
- Cement Masons and Terrazzo Workers
- Electricians
- Roofers
- Hazardous Materials Removal Workers

Current Standards, Committees, Procedures, and Policies

- Committee F48 on Exoskeletons and Exosuits
- 2015 European Union (EU) research and development project

Other Useful Resources on Wearable Robots

- Construction Junkie
- Exoskeleton Report
- Examples of Industrial Exoskeletons for Return to Work Consideration

Remote-operated Robots

Remote-operated robots, consisting of unmanned aerial systems (UASs) and unmanned ground vehicles (UGVs), are either aircrafts (UAS) or ground machines (UGV) with a ground-based controller and a system of communications for piloting movement. These robotic systems can be applied in construction project performance and management.

Some unmanned aerial systems include: DJI Phantom 4 V2.0; DJI Phantom 4 RTK; senseFly eBeeX; Freefly Alta 8; Flyabilty Elios 2; DJI Agras MG-1; Skydio 2; Autel EVO II Series; Autel Robotics EVO; and Parrot Anafi. Unmanned ground vehicles include Robotic Roadworks and Excavation System (RRES); APT Automated Pressure Testing Technology; and Husky Unmanned Ground Vehicle.

Remote-operated Robots Applicable in Construction

No.	Remote-operated robot	Key Functionality	Flight Time	Cost
1	Freefly's Astro Drone	Compatible with various cinema cameras	Flight time varies with payload	$17,495.00
2	DJI's Inspire 2 with X7 camera	Compatible with various Zenmuse cameras	Flight time is 23-27 minutes	$3,099.00
3	Wingtra One Drone	Has 42 MP camera, and can fly higher than drones limited to 20 MP cameras	Flies at 16 m/s (36 mph) for up to 59 minutes per flight.	$20,000
4	DJI's Phantom 4 Pro Version 2.0	Has a 1-inch CMOS sensor that can shoot 4K/60fps videos and 20MP photos,	30-min Flight Time	$2,049
5	Mini 2	Has a 1-inch CMOS sensor that 12MP photos	31 min Flight time	$449
6	Robotic Roadworks and Excavation System (RRES)	Combines below-ground locating sensors, artificial intelligence, and machine learning for safer, faster, and smarter roadworks	End-To-End Process	-
7	Husky Unmanned Ground Vehicle	Suitable for research and rapid prototyping application	Runtime of 3 hours	$5,750.00

Key Safety Risks and Hazards

- Errors made by operator
- Improper equipment / tool use by worker
- Software error
- Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)
- Distrust in device
- Mechanical part failure
- Poor weather condition (e.g., unstable flying conditions)
- Collision in the workspace
- Catching and dragging due to moving parts

- Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)

Key Trades and Activities which can be Improved

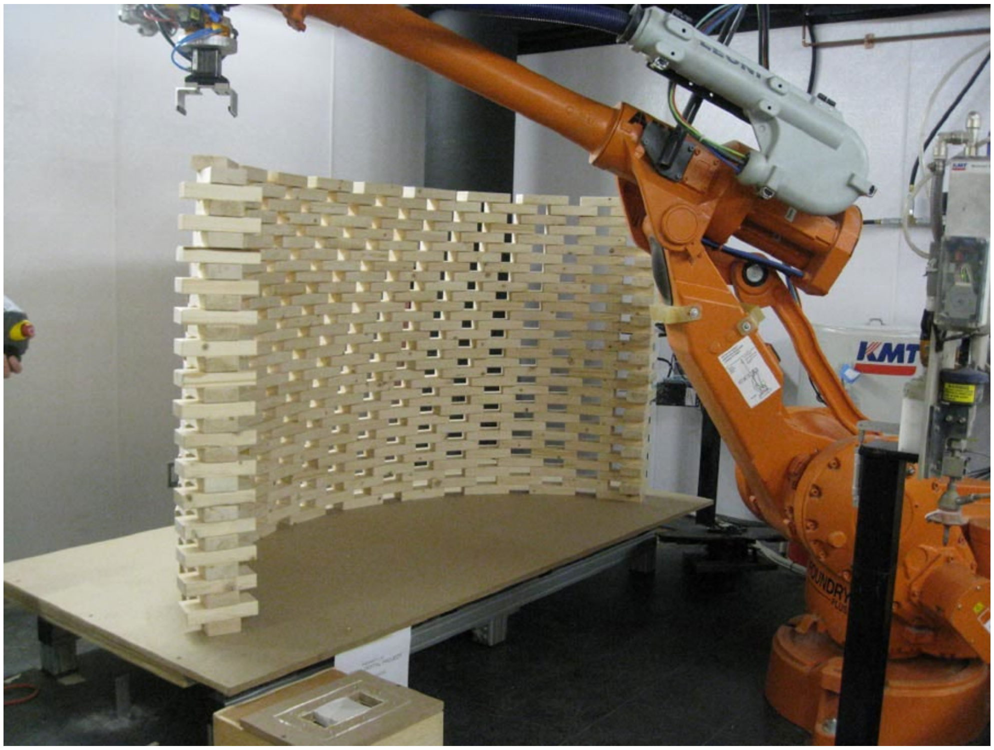
- Roofers
- Glaziers
- Painters, Construction and Maintenance
- Masonry workers (Brickmasons, Blockmasons, and Stonemasons)
- Carpenter
- Drywall, Ceiling Tile Installers and Tapers
- Cement and Concrete Finisher
- Cement Masons and Terrazzo Workers

Current Standards, Committees, Procedures, and Policies

- Autonomy Levels for Unmanned Systems (ALFUS) developed by NIST
- Small UAS rule as a new part 107 to Title 14 Code of Federal Regulations (14 CFR)
- 14 CFR Part 107 Small Unmanned Aircraft Systems

Other Useful Resources on Remote-operated Robots

- Drones in Construction: A Guide to Launching Your Program
- Tech 101: Construction drones
- Why and how to use drones in construction and infrastructure
- 2021 ‘s Best Drones in Construction
- The Best Drones for 2021
- 6 Benefits of Incorporating Drone Technology into the Construction Workflow
- OSHA’s memo formalizing its use of drones for inspection activities



On-site Automated Robotic Systems

On-site automated robotic systems are machines used directly on the construction site to create structures and buildings. These systems include single task construction robots (STCRs) which are utilized in bricklaying, steel welding, steel-truss assembly, façade installation, wall painting, and concrete laying.

Current on-site automated robotic systems include Hadrian X®; SAM100 (Semi-Automated Mason); HRP-5P; TyBot (rebar tying robot); Baubot; Terminator; Spot; SkyTy; and IronBot.

On-site Automated Robotic Systems Applicable in Construction

No.	On-site automated robotic system	Tasks	Application and Productivity	Cost
1	Hadrian X®	Precision construction Bricklaying Robot; Intelligent controls system; and dynamic stabilization technology	200 bricks an hour	About $2 million
2	SAM100 (Semi-Automated Mason)	For onsite masonry construction	3,000 bricks per day	About $500,000
3	TyBot	Rebar tying robot	Self-locates, self-positions and self-ties up to 1,100 rebar intersections per hour	$795,000
4	Baubot	Fully mobile robotic systems to perform various tasks on construction sites	Multiple applications	Approx. $176,830
5	IronBot	Rebar carrying and placing robot	Self-placing up to 5,000-pound bundles of both transverse and longitudinal rebar	-

Key Safety Risks and Hazards

- Software error
- Faulty equipment (e.g., in the hydraulic, electrical sub-controls)
- Entry into a robot's safeguarded area
- Distrust in device
- Autonomous moving parts
- Catching and dragging due to moving parts
- Malfunctioning control or transmission elements
- Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)
- Inadequate or incorrect work/task design
- Improper platform (e.g., shoring/scaffold collapse)

- Mechanical part failure

Key Trades and Activities which can be Improved

- Flooring Installers and Tile and Stone Setters
- Carpenters
- Sheet Metal Workers
- Construction Equipment Operators
- Masonry workers (Brickmasons, Blockmasons, and Stonemasons)
- Drywall and Ceiling Tile Installers
- Tapers
- Cement and Concrete Finisher
- Cement Masons
- Terrazzo Workers

Current Standards, Committees, Procedures, and Policies

- American National Safety Standard ANSI/RIA R15.06-1992. Industrial Mobile Robots - Safety Requirements - Part 1: Requirements for The Industrial Mobile Robot
- National Institute for Occupational Safety and Health (NIOSH) Alert Publication No. 85103. Request for Assistance in Preventing the Injury of Workers by Robots
- National Institute for Occupational Safety and Health (NIOSH) Technical Report Publication No. 880108. Safe Maintenance Guidelines for Robotic Workstations
- National Safety Council Data Sheet 1-717-85. Robots.
- Occupational Safety and Health Administration Publication No. 3067. Concepts and Techniques of Machine Safeguarding. U.S. Department of Labor, 1980
- Occupational Safety and Health Administration Publication No. 2254 (Revised). Training Requirements in OSHA Standards and Training Guidelines
- OSHA Instruction Publication No. 8-1.3. 1987. Guideline for Robotics Safety

Other Useful Resources on On-site automated robotic systems

- A realistic look at the advantages of robotics in construction in 2020
- Robots, AI, and the road to a fully autonomous construction industry
- 6 Paths to the Automated Construction Site
- Robotics - OSHA
- Robotics, Automation, and Employee Safety for the Future Employer

Factors Influencing Successful Implementation of Robotic Systems

Organization

- Operations/IT/Safety department robotic systems competence level
- Level of support in workplace environment (management and owner)
- Cost effectiveness (ROI)
- Initial acquisition, setup, operating and maintenance costs of robotic systems
- Available research efforts on practical benefits of robotic systems
- Worker retention
- Impact on productivity (e.g., labor, time)
- Acceptance by workers (e.g., workforce level of acceptance to change)
- Having direct competitors or partners who adopt similar robots
- Availability of robotic systems decision support tools

Technology

- Versatility of robotic systems
- Durability of robotic systems
- Safety and health impacts (effectiveness)
- Inherent safety risks (e.g., snag and fall risks; mechanical failure; a false sense of safety)
- Ease of Use
- Adaptability
- Level of trust in on-site automated robotic systems (performance)
- Availability of and to access to robotic systems
- Level of interoperability with current systems (e.g., safety management system)
- Operating conditions (e.g., project size, location, weather)

External

- Presence of government regulation for use
- Presence of appropriate industry standards for use
- Availability of operation guidelines and vendor support for use
- Extent of governmental support for robotics applications in construction (e.g., financial, guidance, public procurement, legal issues for robots)
- Restrictions within regulatory environment (air traffic restrictions, etc.)
- Industry-level change requiring robotic systems adoption

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Construction technology should be implemented in a manner which enhances AND preserves worker safety and health

Appendix C

Safety Protocol

Assessing Human-Robot Interaction Safety Risks

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4. References

1. Introduction

This protocol is a human-robot interaction assessment tool which:

- Provides guidance for the application of robotics and automation during construction operations
- Applies to the use of wearable robots, remote operated robots, and onsite robotic systems during construction tasks
- Supports the execution of construction tasks including dry wall installation, bricklaying, and concrete grinding and polishing

The protocol Does not replace current applicable safety processes and hierarchy of controls

Applying this tool during pre-task planning involves:

- Multiple parties including construction superintendent, foreman, and safety personnel
- A safety plan complete with specific procedures for correct execution

The assessment of safety risks and hazards should follow an onsite hazard identification process, adapted from OSHA (2002), using safety data sheets (SDS) and Job Hazard Analysis (JHA) forms. The crew conducting the assessment should:

- Identify the specific job task to be carried out
- Determine where the task is to be performed (task location)
- Find out who is exposed (worker)
- Identify which technology will be used to execute the task
- Review the safety data sheet (SDS) applicable to the technology
- Utilize the appropriate JHA form to determine the hazards' preliminary risk rating
- Determine the final risk rating perceived after strategies have been selected and implemented

Note: The safety risk ratings provided in this document are based on consensus of an expert panel

2. Safety Data Sheets

A. Wearable Robots

SECTION 1: TECHNOLOGY DESCRIPTION

Wearable robots, wearable robotics, or wearable exoskeletons are a class of machines (mechanical devices) that enhance human workers' performance when physically attached to the body during work. During construction, they can be used during lifting operations, or for tasks involving the use of tools in awkward positions, thereby preventing strains and sprains, and reducing fatigue.

SECTION 2: TECHNOLOGY IMAGES

Figure 1: Subject adorning an Exoskeleton (back and side views)

SECTION 3: SAFETY HAZARD CATEGORY

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
Frequency	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

"Frequency" is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.

"Severity" is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

SECTION 4: HAZARDS AND SAFETY RISKS

The hazards listed below are those introduced or increased when using wearable robots.

ID #	Hazards
HR1	Worker has limited mobility
HR2	Improper equipment / tool use by worker
HR3	Technology discomfort
HR4	Mechanical part failure
HR5	Dirt (e.g., oil, grease) in work areas
HR6	Inadequate or incorrect work/task design
HR7	Unworkable combination of robots and PPE
HR8	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)
HR9	Distrust in device
HR10	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)
HR11	Physical stress (e.g., impose additional load, fatigue)
HR12	Operator errors
HR13	Perceived safety (trust in robot)
HR14	Work in an unfavorable body posture
HR15	Unpredicted movement or action by the robot
HR16	Hygiene issue
HR17	Worker has limited mobility
HR18	Distraction
HR19	Parts with dangerous surfaces
HR20	Catching and dragging hazards (by moving parts)
HR21	Uneven work surfaces / improper footing/changes in elevations
HR22	Overhead/adjacent work/overhead loads
HR23	Malfunctioning control or transmission elements
HR24	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)
HR25	Absence of work/task requirements
HR26	Improper platform (e.g., shoring/scaffold collapse)

SECTION 5A: HAZARDS AND SAFETY RISK ANALYSIS - DRY WALL INSTALLATION

Below is a list of moderate and high-risk hazards introduced or increased when using wearable robots for drywall installation.

ID #	Hazards	Safety Risk Rating
HR1	Worker has limited mobility	H = High Risk
HR2	Improper equipment / tool use by worker	H = High Risk
HR3	Technology discomfort	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR5	Dirt (e.g., oil, grease) in work areas	H = High Risk
HR6	Inadequate or incorrect work/task design	H = High Risk
HR7	Unworkable combination of robots and PPE	H = High Risk
HR8	Faulty equipment (e.g., in the hydraulic or electrical sub-controls)	M = Moderate Risk
HR9	Distrust in device	M = Moderate Risk
HR10	Adverse climate (e.g., hot and cold temperatures; humidity, wind)	M = Moderate Risk

SECTION 5B: HAZARDS AND SAFETY RISK ANALYSIS – BRICKLAYING

Below is a list of moderate and high-risk hazards introduced or increased when using wearable robots for bricklaying.

ID #	Hazards	Safety Risk Rating
HR1	Worker has limited mobility	H = High Risk
HR2	Improper equipment / tool use by worker	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR8	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H = High Risk
HR3	Technology discomfort	M = Moderate Risk
HR5	Dirt (e.g., oil, grease) in work areas	M = Moderate Risk
HR6	Inadequate or incorrect work/task design	M = Moderate Risk
HR9	Distrust in device	M = Moderate Risk
HR7	Unworkable combination of robots and PPE	M = Moderate Risk
HR10	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	M = Moderate Risk

SECTION 5C: HAZARDS AND SAFETY RISK ANALYSIS – CONCRETE GRINDING AND POLISHING

Below is a list of moderate and high-risk hazards introduced or increased when using wearable robots for concrete grinding and polishing.

ID #	Hazards	Safety Risk Rating
HR1	Worker has limited mobility	H = High Risk
HR2	Improper equipment / tool use by worker	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR8	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H = High Risk
HR5	Dirt (e.g., oil, grease) in work areas	H = High Risk
HR6	Inadequate or incorrect work/task design	H = High Risk
HR7	Unworkable combination of robots and PPE	H = High Risk
HR10	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	H = High Risk
HR3	Technology discomfort	M = Moderate Risk
HR9	Distrust in device	M = Moderate Risk

Section 6: Strategies for mitigating safety risk and hazards

The table below provides a list of strategies (S) and corresponding hazards (HR). Each strategy is paired with hazards (listed in Section 4) that the strategy could assist in preventing or controlling.

ID#	STRATEGY	HAZARDS
S1	Wear appropriate personal protective equipment when using wearable robots (protective gloves safety googles, additional protective clothing, etc.)	HR2, HR3, HR7
S2	Clean wearable robot regularly	HR8, HR4, HR5
S3	Prevent unauthorized or improper maintenance and installation of wearable robot	HR8, HR4
S4	Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR1, HR2, HR3, HR10, HR7
S5	Incorporate wearable robot manufacturer's safety requirements into written company safety procedures	HR1, HR3, HR10, HR6, HR7
S6	Check for visible defects on wearable robot before starting work	HR8, HR4
S7	Select suitable hearing protection and make available/use	HR3, HR7
S8	Observe and adhere to the manufacturer's information on the scope of use	HR1, HR2, HR3, HR6
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR8, HR9, HR4, HR10, HR7
S10	Have checks performed regularly by a skilled technologist/technician	HR8, HR4
S11	Involve employee in safety decision-making regarding use of wearable robot	HR3, HR9, HR6
S12	Obtain and review safety data sheets from the wearable robot manufacturer	HR2, HR3
S13	Use ergonomically designed wearable robots	HR2
S14	Use shading/sunscreen protection to reduce impact of the sun when using wearable robot	HR3, HR10
S15	Use only wearable robots that have been shown to be effective	HR1, HR2, HR3, HR6, HR7
S16	Ensure that only wearable robots without sharp edges, crushing points or other dangerous surfaces are used	HR1, HR2, HR3, HR6, HR7
S17	Procure wearable robots with low vibration intensity	HR3, HR6, HR7
S18	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR1, HR3, HR9, HR7
S19	Ensure proper ventilation and lightening (natural or forced) in work area	HR10
S20	Fit each worker individually with the wearable robot before use	HR1, HR2, HR3, HR9, HR6, HR7

B. Remote-Operated Robots

Section 1: Technology description

Remote-operated robots, consisting of unmanned aerial systems (UASs) and unmanned ground vehicles (UGVs), are either aircrafts (UAS) or ground machines (UGV) with a ground-based controller and a system of communications for piloting movement. These robotic systems can be applied in construction project performance and management. UASs introduce new risks on the job site or elevate the potential impact of existing risks. These risks should not be overlooked; hence, a complete understanding of the safety risk factors associated with the use of UASs and UGVs can permit users to execute appropriate responses that reduce potential negative outcomes.

Section 2: Technology images

Figure 1: Unmanned Aerial Vehicle (UAV), and Unmanned Ground Vehicle (UGV).

Section 3: Safety hazard category

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
Frequency	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

"Frequency" is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
"Severity" is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

SECTION 4: HAZARDS AND SAFETY RISKS

The hazards listed below are those introduced or increased when using remote-operated.

ID #	Hazards
HR1	Errors made by operator
HR2	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)
HR3	Distrust in device
HR4	Mechanical part failure
HR5	Poor weather condition (e.g., unstable flying conditions)
HR6	Collision in the workspace
HR7	Catching and dragging due to moving parts
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)
HR9	Improper equipment / tool use by worker
HR10	Software error
HR11	Perceived safety (trust in robot)
HR12	Unpredicted movement or action by the robot
HR13	Mental stress (e.g., isolation, single workstation, forced to use device)
HR14	Distraction
HR15	Entry into a robot's safeguarded area
HR16	Technology discomfort
HR17	Parts with dangerous surfaces
HR18	Unguarded moving parts
HR19	Autonomous moving parts
HR20	Impalement hazards
HR21	Electromagnetic or radio-frequency interference (transient signals)
HR22	Poor weather condition (e.g., unstable flying conditions)
HR23	Adverse Indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)
HR24	Uneven work surfaces / improper footing/changes in elevations
HR25	Overhead/adjacent work/overhead loads
HR26	Dirt (e.g., oil, grease) in work areas
HR27	Introduces new source of noise
HR28	Malfunctioning control or transmission elements
HR29	Fire risks (due to electrical overloads or use of flammable hydraulic oil)
HR30	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)
HR31	Inadequate or incorrect work/task design
HR32	Absence of work/task requirements
HR33	Improper platform (e.g., shoring/scaffold collapse)
HR34	Unworkable combination of robots and PPE
HR35	Dirt (e.g., oil, grease)

SECTION 5A: HAZARDS AND SAFETY RISK ANALYSIS - DRY WALL INSTALLATION

Below is a list of moderate and high risks hazards introduced or increased when using remote-operated robots for drywall installation.

ID #	Hazard	Risk Rating
HR1	Errors made by operator	H = High Risk
HR2	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H = High Risk
HR3	Distrust in device	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR5	Poor weather condition (e.g., unstable flying conditions)	H = High Risk
HR6	Collision in the workspace	H = High Risk
HR7	Catching and dragging due to moving parts	H = High Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H = High Risk
HR9	Improper equipment / tool use by worker	M = Moderate Risk
HR10	Software error	M = Moderate Risk

SECTION 5B: HAZARDS AND SAFETY RISK ANALYSIS – BRICKLAYING

Below is a list of moderate and high-risk hazards introduced or increased when using remote-operated robots for bricklaying.

ID #	Hazard	Risk Rating
HR1	Errors made by operator	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR5	Poor weather condition (e.g., unstable flying conditions)	H = High Risk
HR6	Collision in the workspace	H = High Risk
HR7	Catching and dragging due to moving parts	H = High Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H = High Risk
HR9	Improper equipment / tool use by worker	H = High Risk
HR2	Faulty equipment (e.g., in the hydraulic, electrical sub-controls)	M = Moderate Risk
HR10	Software error	M = Moderate Risk

SECTION 5C: HAZARDS AND SAFETY RISK ANALYSIS – CONCRETE GRINDING AND POLISHING

Below is a list of moderate and high-risk hazards that are introduced or increased when using remote-operated robots for concrete grinding and polishing.

ID #	Hazard	Risk Rating
HR1	Errors made by operator	H = High Risk
HR2	Faulty equipment (e.g., in the hydraulic or electrical sub-controls)	H = High Risk
HR3	Distrust in device	H = High Risk
HR4	Mechanical part failure	H = High Risk
HR5	Poor weather condition (e.g., unstable flying conditions)	H = High Risk
HR6	Collision in the workspace	H = High Risk
HR7	Catching and dragging due to moving parts	H = High Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H = High Risk
HR9	Improper equipment / tool use by worker	H = High Risk
HR10	Software error	H = High Risk

SECTION 6: STRATEGIES FOR MITIGATING SAFETY RISK AND HAZARDS

The table below provides a list of strategies (S) and corresponding hazards (HR). Each strategy is paired with hazards (listed in Section 4) that the strategy could assist in preventing or controlling.

ID #	STRATEGY	HAZARDS
S1	Wear appropriate personal protective equipment (protective gloves safety googles, additional protective clothing, etc.)	HR1, HR3
S2	Clean equipment regularly	HR2, HR4
S3	Prevent unauthorized or improper maintenance and installation of robots	HR2, HR4
S4	Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR10, HR2, HR4, HR8
S5	Incorporate manufacturer safety requirements into written company safety procedures	HR1
S6	Check for visible defects on robots before starting work	HR2, HR4, HR7
S7	Select suitable hearing protection and make available/use	HR1
S8	Observe and adhere to the manufacturer's information on the scope of use	HR9, HR10, HR5, HR6, HR8
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR1, HR2, HR3, HR7
S10	Have checks performed regularly by a skilled technologist/technician	HR1, HR2, HR4
S11	Involve employee in safety decision-making regarding use of Robots	HR1, HR5, HR6
S12	Observe safety distances (nearby workers/from equipment)	HR1, HR9, HR6
S13	Obtain and review safety data sheets from the RA manufacturer	HR9, HR10, HR8
S14	Use ergonomically designed wearable robot	HR2
S15	Use shading/sunscreen products/protection against the sun when using robot	HR2
S16	Use only robots that have been shown to be effective	HR9, HR6
S17	Ensure that only robots (e.g., exoskeletons, single-task robots) without sharp edges, crushing points or other dangerous surfaces are used	HR2
S18	Procure robots with low vibration intensity	HR9
S19	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR3, HR6
S20	Ensure proper ventilation and lightening (natural or forced) in rooms/work location	HR5
S21	Fit each worker individually with the robot before use	HR1, HR9, HR3

C. On-site Automated Robotic Systems

SECTION 1: TECHNOLOGY DESCRIPTION

On-site automated robotic systems are machines used directly on the construction site to create structures and buildings. They include single task construction robots (STCRs) which are utilized in bricklaying, steel welding, steel-truss assembly, façade installation, wall painting, and concrete laying

SECTION 2: TECHNOLOGY IMAGE

Figure 1: Single-task robotic systems. (Skanska 2016; Wilcox, 2021)

SECTION 3: SAFETY HAZARD CATEGORY

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
Frequency	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

"Frequency" is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
"Severity" is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

SECTION 4: HAZARDS AND SAFETY RISKS

The hazards listed below are those introduced or increased when using on-site automated robotic systems.

Ref.	Hazards
HR1	Software error
HR2	Faulty equipment (e.g., in the hydraulic, electrical sub-controls)
HR3	Entry into a robot's safeguarded area
HR4	Distrust in device
HR5	Autonomous moving parts
HR6	Catching and dragging due to moving parts
HR7	Malfunctioning control or transmission elements
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)
HR9	Inadequate or incorrect work/task design
HR10	Improper platform (e.g., shoring/scaffold collapse)
HR11	Mechanical part failure
HR12	Operator errors
HR13	Perceived safety (trust in robot)
HR14	Unpredicted movement or action by the robot
HR15	Improper equipment / tool use by worker
HR16	Distraction
HR17	Technology discomfort
HR18	Parts with dangerous surfaces
HR19	Unguarded moving parts
HR20	Impalement hazards
HR21	Electromagnetic or radio-frequency interference (transient signals)
HR22	Poor weather condition (e.g., unstable flying conditions)
HR23	Collision in the workplace
HR24	Adverse Indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)
HR25	Uneven work surfaces / improper footing/changes in elevations
HR26	Overhead/adjacent work/overhead loads
HR27	Dirt (e.g., oil, grease)
HR28	Introduces new source of noise
HR29	Fire risks (due to electrical overloads or use of flammable hydraulic oil)
HR30	Absence of work/task requirements
HR31	Improper equipment layout
HR32	Unworkable combination of robots and PPE

SECTION 5A: HAZARDS AND SAFETY RISK ANALYSIS - DRY WALL INSTALLATION

Below is a list of moderate and high-risk hazards introduced or increased when using on-site automated robotic systems for drywall installation.

Ref.	Safety risk/hazard	Risk Rating
HR1	Software error	H = High Risk
HR2	Faulty equipment (e.g., in the hydraulic, electrical sub-controls)	H = High Risk
HR3	Entry into a robot's safeguarded area	H = High Risk
HR4	Distrust in device	H = High Risk
HR5	Autonomous moving parts	H = High Risk
HR6	Catching and dragging due to moving parts	H = High Risk
HR7	Malfunctioning control or transmission elements	H = High Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H = High Risk
HR9	Inadequate or incorrect work/task design	H = High Risk
HR10	Improper platform (e.g., shoring/scaffold collapse)	H = High Risk
HR11	Mechanical part failure	M = Moderate Risk

SECTION 5B: HAZARDS AND SAFETY RISK ANALYSIS – BRICKLAYING

Below is a list of moderate and high-risk hazards introduced or increased when using on-site automated robotic systems for bricklaying.

Ref	Safety risk/hazard	Risk Rating
HR2	Faulty equipment (e.g., in the hydraulic, or electrical sub-controls)	H = High Risk
HR3	Entry into a robot's safeguarded area	H = High Risk
HR7	Malfunctioning control or transmission elements	H = High Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H = High Risk
HR11	Mechanical part failure	H = High Risk
HR6	Catching and dragging due to moving parts	M = Moderate Risk
HR4	Distrust in device	M = Moderate Risk
HR5	Autonomous moving parts	M = Moderate Risk
HR9	Inadequate or incorrect work/task design	M = Moderate Risk
HR10	Improper platform (e.g., shoring/scaffold collapse)	M = Moderate Risk

SECTION 5C: HAZARDS AND SAFETY RISK ANALYSIS – CONCRETE GRINDING AND POLISHING

Below is a list of moderate and high risks hazards introduced or increased when using on-site automated robotic systems for concrete grinding and polishing.

Ref	Safety risk/hazard	Risk Rating
HR1	Software error	H = High Risk
HR2	Faulty equipment (e.g., in the hydraulic, or electrical sub-controls)	H = High Risk
HR3	Entry into a robot's safeguarded area	H = High Risk
HR5	Autonomous moving parts	H = High Risk
HR6	Catching and dragging due to moving parts	H = High Risk
HR9	Inadequate or incorrect work/task design	H = High Risk
HR10	Improper platform (e.g., shoring/scaffold collapse)	H = High Risk
HR11	Mechanical part failure	H = High Risk
HR4	Distrust in device	M = Moderate Risk
HR7	Malfunctioning control or transmission elements	M = Moderate Risk
HR8	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	M = Moderate Risk

SECTION 6: STRATEGIES FOR MITIGATING SAFETY RISK AND HAZARDS

The table below provides a list of strategies (S) and corresponding hazards (HR). Each strategy is paired with hazards (listed in Section 4) that the strategy could assist in preventing or controlling.

ID #	STRATEGY	HAZARDS
S1	Wear appropriate personal protective equipment (protective gloves safety googles, additional protective clothing, etc.)	HR2, HR5, HR11
S2	Clean equipment regularly	HR2, HR16, HR11
S3	Prevent unauthorized or improper maintenance and installation of robots	HR2, HR11
S4	Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR1, HR18
S5	Incorporate manufacturer safety requirements into written company safety procedures	HR9, HR10
S6	Check for visible defects on robots before starting work	HR2, HR6, HR7
S8	Observe and adhere to the manufacturer's information on the scope of use	HR1, HR3, HR7, HR8, HR10
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR2, HR3, HR4, HR11, HR14, HR7
S10	Have checks performed regularly by a skilled technologist/technician	HR2, HR11
S11	Involve employee in safety decision-making regarding use of Robots	HR3
S12	Observe safety distances (nearby workers/from equipment)	HR3
S13	Obtain and review safety data sheets from the RA manufacturer	HR1, HR18, HR8, HR10
S15	Handle equipment with dampers or sprung handles	HR9
S16	Use shading/sunscreen products/protection against the sun when using robot	HR5
S17	Use only robots that have been shown to be effective	HR5
S18	Ensure that only robots (e.g., exoskeletons, single-task robots) without sharp edges, crushing points or other dangerous surfaces are used	HR11
S19	Procure robots with low vibration intensity	HR5
S20	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR4, HR9, HR10
S21	Ensure proper ventilation and lightening (natural or forced) in rooms/work location	HR3
S22	Fit each worker individually with the robot before use	HR4, HR9

3. Job Hazard Analysis Forms

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SECTION 1: PROJECT (JOB) DATA

Activity/Job:

Preliminary Risk Rating (Before):

Project Location:

Final Risk Rating (After):

Date Prepared:

Work Area:

Preparer (Name/Title):

Reviewed by (Name/Title):

Notes:

- Prior to the start of work, a pre-job brief will be held with employees to review and discuss this Job Hazard Analysis (JHA) and safe work practices. Any questions or concerns that arise shall be directed to the Safety Manager or designated Field Superintendent or QC Representative.
- JHA shall be reviewed and revised as necessary if new hazards are discovered during the course of the particular activity or the entire project.

SECTION 2: RISK ASSESSMENT MATRIX

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
Frequency	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

Step 1: Review each "Hazard" with the identified Job Strategy "Controls" and determine the Risk Rating.

- **"Frequency"** is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
- **"Severity"** is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

Step 2: Enter the Safety Risk Rating (Frequency against Severity) as L, M, H, or E for each "Hazard" in the JHA table. Annotate the overall highest Risk Rating at the top of the JHA form.

SECTION 3: HAZARDS AND SAFETY RISK ASSESSMENT

Technology Used	Hazard Ref.	Hazard	Preliminary Safety Risk Assessment (L, M, H, or E)	Present? ("Y" or "N")	Strategies for Mitigating Safety Risk and Hazards	Final Safety Risk Assessment (L, M, H, or E)

Bricklaying JHA

Section 1: Project (Job) Data - Bricklaying

Activity/Job:

Project Location:

Date Prepared:

Preparer (Name/Title):

Reviewed by (Name/Title):

Preliminary Risk Rating (Before):

Final Risk Rating (After):

Work Area:

Notes:

- Prior to the start of work, a pre-job brief will be held with employees to review and discuss this Job Hazard Analysis (JHA) and safe work practices. Any questions or concerns that arise shall be directed to the Safety Manager or designated Field Superintendent or QC Representative.
- JHA shall be reviewed and revised as necessary if new hazards are discovered during the course of the particular activity or the entire project.

Section 2: Risk Assessment Matrix

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
Frequency	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

Step 1: Review each "Hazard" with the identified Job Strategy "Controls" and determine the Risk Rating.

- **"Frequency"** is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
- **"Severity"** is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

Step 2: Enter the Safety Risk Rating (Frequency against Severity) as L, M, H, or E for each "Hazard" in the JHA table. Annotate the overall highest Risk Rating at the top of the JHA form.

SECTION 3: HAZARDS AND RISKS

Technology Used	Hazard Ref.	Hazard	Preliminary Safety Risk Assessment (L, M, H, or E)	Present? ("Y" or "N")	Strategies for Mitigating Safety Risk and Hazards	Final Safety Risk Assessment (L, M, H, or E)
Wearable robot	HR1	Worker has limited mobility	H			
	HR2	Improper equipment / tool use by worker	H			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR6	Mechanical part failure	H			
	HR4	Technology discomfort	M			
	HR5	Distrust in device	M			
	HR7	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	M			
	HR8	Dirt (e.g., oil, grease) in work areas	M			
	HR9	Inadequate or incorrect work/task design	M			
	HR10	Unworkable combination of robots and PPE	M			
Remote-operated robot	HR11	Errors made by operator	H			
	HR2	Improper equipment / tool use by worker	H			
	HR6	Mechanical part failure	H			
	HR13	Poor weather condition (e.g., unstable flying conditions)	H			
	HR14	Collision in the workspace	H			
	HR15	Catching and dragging due to moving parts	H			

	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H			
	HR12	Software error	M			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	M			
On-site autonomous robot	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR17	Entry into a robot's safeguarded area	H			
	HR6	Mechanical part failure	H			
	HR19	Malfunctioning control or transmission elements	H			
	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H			
	HR20	Improper platform (e.g., shoring/scaffold collapse)	H			
	HR9	Inadequate or incorrect work/task design	M			
	HR15	Catching and dragging due to moving parts	M			
	HR5	Distrust in device	M			
	HR18	Autonomous moving parts	M			

SECTION 4: STRATEGIES FOR MITIGATING SAFETY RISK AND HAZARDS

In the table below, the strategies have been paired with the individual safety hazards that the strategy mitigates. The list of hazards could be found in the JHA or Safety Data Sheet.

Strategy Ref.	Strategy	Hazards
S1	Wear appropriate personal protective equipment (protective gloves safety googles, additional protective clothing, etc.)	HR2, HR4, HR10, HR3, HR1, HR5
S2	Clean equipment regularly	HR3, HR6, HR8
S3	Prevent unauthorized or improper maintenance and installation of robots	HR3, HR6
S4	Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR1, HR2, HR4, HR7, HR10, HR3, HR6
S5	Incorporate manufacturer safety requirements into written company safety procedures	HR1, HR4, HR7, HR9, HR10
S6	Check for visible defects on robots before starting work	HR3, HR6
S7	Select suitable hearing protection and make available/use	HR4, HR10
S8	Observe and adhere to the manufacturer's information on the scope of use	HR1, HR2, HR4, HR9
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR3, HR5, HR6, HR7, HR10
S10	Have checks performed regularly by a skilled technologist/technician	HR3, HR6
S11	Involve employee in safety decision-making regarding use of Robots	HR4, HR5, HR9
S12	Observe safety distances (nearby workers/from equipment)	HR1, HR2
S13	Obtain and review safety data sheets from the RA manufacturer	HR2, HR4
S14	Use ergonomically designed wearable robot	HR2, HR5
S15	Handle equipment with dampers or sprung handles	HR9
S16	Use shading/sunscreen products/protection against the sun when using robot	HR3
S17	Use only robots that have been shown to be effective	HR1, HR2, HR4, HR9, HR10
S18	Ensure that only robots (e.g., exoskeletons, single-task robots) without sharp edges, crushing points or other dangerous surfaces are used	HR1, HR2, HR4, HR3, HR9, HR10
S19	Procure robots with low vibration intensity	HR4, HR2, HR9, HR10
S20	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR1, HR4, HR5, HR10, HR9
S21	Ensure proper ventilation and lightening (natural or forced) in rooms/work location	HR7
S22	Fit each worker individually with the robot before use	HR1, HR2, HR4, HR5, HR9, HR10

DRY WALL INSTALLATION JHA

SECTION 1: PROJECT (JOB) DATA – DRY WALL INSTALLATION

Activity/Job:

Project Location:

Date Prepared:

Preparer (Name/Title):

Reviewed by (Name/Title):

Preliminary Risk Rating (Before):

Final Risk Rating (After):

Work Area:

Notes:

- Prior to the start of work, a pre-job brief will be held with employees to discuss and review this Job Hazard Analysis (JHA) and safe work practices. Any questions or concerns that arise shall be directed to the Safety Manager or designated Field Superintendent or QC Representative.
- JHA shall be reviewed and revised as necessary if new hazards are discovered during the course of the particular activity or the entire project.

SECTION 2: RISK ASSESSMENT MATRIX

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
Frequency	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

Step 1: Review each "Hazard" with the identified Job Strategy "Controls" and determine the Risk Rating.

- **"Frequency"** is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
- **"Severity"** is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

Step 2: Enter the Safety Risk Rating (Frequency against Severity) as L, M, H, or E for each "Hazard" in the JHA table. Annotate the overall highest Risk Rating at the top of the JHA form.

SECTION 3: HAZARDS AND RISKS

Technology Used	Hazard Ref.	Hazard	Preliminary Safety Risk Assessment (L, M, H, or E)	Present? ("Y" or "N")	Strategies for Mitigating Safety Risk and Hazards	Final Safety Risk Assessment (L, M, H, or E)
Wearable robot	HR1	Worker has limited mobility	H			
	HR2	Improper equipment / tool use by worker	H			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	M			
	HR4	Technology discomfort	H			
	HR5	Distrust in device	M			
	HR6	Mechanical part failure	H			
	HR7	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	M			
	HR8	Dirt (e.g., oil, grease) in work areas	H			
	HR9	Inadequate or incorrect work/task design	H			
	HR10	Unworkable combination of robots and PPE	H			
Remote-operated robot	HR11	Errors made by operator	H			
	HR2	Improper equipment / tool use by worker	M			
	HR12	Software error	M			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR5	Distrust in device	H			
	HR6	Mechanical part failure	H			

	HR13	Poor weather condition (e.g., unstable flying conditions)	H			
	HR14	Collision in the workspace	H			
	HR15	Catching and dragging due to moving parts	H			
	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H			
On-site autonomous robot	HR12	Software error	H			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR17	Entry into a robot's safeguarded area	H			
	HR5	Distrust in device	H			
	HR18	Autonomous moving parts	H			
	HR6	Mechanical part failure	M			
	HR15	Catching and dragging due to moving parts	H			
	HR19	Malfunctioning control or transmission elements	H			
	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H			
	HR9	Inadequate or incorrect work/task design	H			
	HR20	Improper platform (e.g., shoring/scaffold collapse)	H			

SECTION 4: STRATEGIES FOR MITIGATING SAFETY RISK AND HAZARDS

In the table below, the strategies have been paired with the individual safety hazards that the strategy mitigates. The list of hazards could be found in the JHA or Safety Data Sheet.

Ref	Strategy	Hazard
S1	Wear appropriate personal protective equipment (protective gloves safety googles, additional protective clothing, etc.)	HR2, HR4, HR10, HR3, HR18, HR6, HR11, HR1, SHR5
S2	Clean equipment regularly	HR3, HR6, HR8, HR18
S3	Prevent unauthorized or improper maintenance and installation of robots	HR3, HR6
S4	Provide clear, concise, available and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR1, HR2, HR4, HR7, HR10, HR12, HR19, HR3, HR6, HR16
S5	Incorporate manufacturer safety requirements into written company safety procedures	HR1, HR4, HR7, HR9, HR10, HR20, HR11
S6	Check for visible defects on robots before starting work	HR3, HR6, HR15, HR19
S7	Select suitable hearing protection and make available/use	HR4, HR10, HR11
S8	Observe and adhere to the manufacturer's information on the scope of use	HR1, HR2, HR4, HR9, HR12, HR17, HR19, HR16, HR20, HR13, HR14, HR16
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR3, HR5, HR6, HR7, HR10, HR17, HR15, HR19, HR11
S10	Have checks performed regularly by a skilled technologist/technician	HR3, HR6, HR11
S11	Involve employee in safety decision-making regarding use of Robots	HR4, HR5, HR9, HR17, HR11, HR13, HR14
S12	Observe safety distances (nearby workers/from equipment)	HR1, HR2, HR17, HR11, HR14
S13	Obtain and review safety data sheets from the RA manufacturer	HR2, HR4, HR12, HR19, HR16, HR20
S14	Use ergonomically designed wearable robot	HR2, HR5
S15	Handle equipment with dampers or sprung handles	HR9
S16	Use shading/sunscreen products/protection against the sun when using robot	HR18, HR3
S17	Use only robots that have been shown to be effective	HR1, HR2, HR4, HR9, HR10, HR18, HR14
S18	Ensure that only robots (e.g., exoskeletons, single-task robots) without sharp edges, crushing points or other dangerous surfaces are used	HR1, HR2, HR4, HR3, HR9, HR10, HR6
S19	Procure robots with low vibration intensity	HR4, HR2, HR9, HR10, HR18
S20	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR1, HR4, HR5, HR10, HR9, HR20, HR14
S21	Ensure proper ventilation and lightening (natural or forced) in rooms/work location	HR7, HR17, HR13
S22	Fit worker individually with the robot before use	HR11, HR1, HR2, HR4, HR5, HR9, HR10

CONCRETE GRINDING AND POLISHING JHA

SECTION 1: PROJECT (JOB) DATA – CONCRETE GRINDING AND POLISHING

Activity/Job:

Project Location:

Date Prepared:

Preparer (Name/Title):

Reviewed by (Name/Title):

Preliminary Risk Rating (Before):

Final Risk Rating (After):

Work Area:

Notes:

- Prior to the start of work, a pre-job brief will be held with employees to review and discuss this Job Hazard Analysis (JHA) and safe work practices. Any questions or concerns that arise shall be directed to the Safety Manager or designated Field Superintendent or QC Representative.
- JHA shall be reviewed and revised as necessary if new hazards are discovered during the course of the particular activity or the entire project.

SECTION 2: RISK ASSESSMENT MATRIX

		Severity				
		Near miss	Negligible	Minor first aid	Lost worktime	PD, Fatality
Frequency	1/10 years	L	L	L	M	H
	1/year	L	L	M	H	H
	1/month	L	M	H	H	E
	1/week	L	M	H	H	E
	1/day	L	H	H	E	E

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

PD = Permanent Disability

Step 1: Review each "Hazard" with the identified Job Strategy "Controls" and determine the Risk Rating.

- **"Frequency"** is the likelihood of an incident or accident occurring and is categorized as: once a day (1/day), once a week (1/week), etc.
- **"Severity"** is the outcome/degree of impact of an incident that could occur and is categorized as: Near miss, Negligible, Minor first aid, etc.

Step 2: Enter the Safety Risk Rating (Frequency against Severity) as L, M, H, or E for each "Hazard" in the JHA table. Annotate the overall highest Risk Rating at the top of the JHA form.

SECTION 3: HAZARDS AND RISKS

Technology Used	Hazard Ref.	Hazard	Preliminary Safety Risk Assessment (L, M, H, or E)	Present? ("Y" or "N")	Strategies for Mitigating Safety Risk and Hazards	Final Safety Risk Assessment (L, M, H, or E)
Wearable robot	HR1	Worker has limited mobility	H			
	HR2	Improper equipment / tool use by worker	H			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR4	Technology discomfort	M			
	HR5	Distrust in device	M			
	HR6	Mechanical part failure	H			
	HR7	Adverse indoor and outdoor climate (e.g., hot and cold temperatures; humidity, wind)	H			
	HR8	Dirt (e.g., oil, grease) in work areas	H			
	HR9	Inadequate or incorrect work/task design	H			
	HR10	Unworkable combination of robots and PPE	H			
Remote-operated robot	HR11	Errors made by operator	H			
	HR2	Improper equipment / tool use by worker	H			
	HR12	Software error	H			
	HR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR5	Distrust in device	H			
	HR6	Mechanical part failure	H			

	HR13	Poor weather condition (e.g., unstable flying conditions)	H			
	HR14	Collision in the workspace	H			
	HR15	Catching and dragging due to moving parts	H			
	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	H			
On-site autonomous robot	HR12	Software error	H			
	SHR3	Faulty equipment (e.g., in the hydraulic, pneumatic, or electrical sub-controls)	H			
	HR17	Entry into a robot's safeguarded area	H			
	HR5	Distrust in device	M			
	HR18	Autonomous moving parts	H			
	HR6	Mechanical part failure	H			
	HR15	Catching and dragging due to moving parts	H			
	HR19	Malfunctioning control or transmission elements	M			
	HR16	Electrical malfunction (e.g., rechargeable battery, faulty wire/plugs)	M			
	HR9	Inadequate or incorrect work/task design	H			
	HR20	Improper platform (e.g., shoring/scaffold collapse)	H			

SECTION 4: STRATEGIES FOR MITIGATING SAFETY RISK AND HAZARDS

In the table below, the strategies have been paired with the individual safety hazards that the strategy mitigates. The list of hazards could be found in the JHA or Safety Data Sheet.

Ref	Strategy	Safety risk/hazard
S1	Wear appropriate personal protective equipment (protective gloves safety googles, additional protective clothing, etc.)	HR2, HR4, HR10, HR3, HR18, HR6, HR11, HR1, HR5
S2	Clean equipment regularly	HR3, HR6, HR8, HR18
S3	Prevent unauthorized or improper maintenance and installation of robots	HR3, HR6
S4	Provide clear, concise, and up-to-date job aids (procedures, instructions on using robots), accepted by the intended user population	HR1, HR2, HR4, HR7, HR10, HR12, HR19, HR3, HR6, HR16
S5	Incorporate manufacturer safety requirements into written company safety procedures	HR1, HR4, HR7, HR9, HR10, HR20, HR11
S6	Check for visible defects on robots before starting work	HR3, HR6, HR15, HR19
S7	Select suitable hearing protection and make available/use	HR4, HR10, HR11
S8	Observe and adhere to the manufacturer's information on the scope of use	HR1, HR2, HR4, HR9, HR12, HR17, HR19, HR16, HR20, HR13, HR14, HR16
S9	Ensure compliance of safety procedures through periodic training and spot checks	HR3, HR5, HR6, HR7, HR10, HR17, HR15, HR19, HR11
S10	Have checks performed regularly by a skilled technologist/technician	HR3, HR6, HR11
S11	Involve employee in safety decision-making regarding use of Robots	HR4, HR5, HR9, HR17, HR11, HR13, HR14
S12	Observe safety distances (nearby workers/from equipment)	HR1, HR2, HR17, HR11, HR14
S13	Obtain and review safety data sheets from the RA manufacturer	HR2, HR4, HR12, HR19, HR16, HR20
S14	Use ergonomically designed wearable robot	HR2, HR5
S15	Handle equipment with dampers or sprung handles	HR9
S16	Use shading/sunscreen products/protection against the sun when using robot	HR18, HR3
S17	Use only robots that have been shown to be effective	HR1, HR2, HR4, HR9, HR10, HR18, HR14
S18	Ensure that only robots (e.g., exoskeletons, single-task robots) without sharp edges, crushing points or other dangerous surfaces are used	HR1, HR2, HR4, HR3, HR9, HR10, HR6
S19	Procure robots with low vibration intensity	HR4, HR2, HR9, HR10, HR18
S20	Design work to be less complex (procedures to avoid tasks which involve very complex decisions, diagnoses or calculations)	HR1, HR4, HR5, HR10, HR9, HR20, HR14
S21	Ensure proper ventilation and lightening (natural or forced) in rooms/work location	HR7, HR17, HR13
S22	Fit each worker individually with the robot before use	HR11, HR1, HR2, HR4, HR5, HR9, HR10

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