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Virtual Boundaries: Investigating the Ethical and Social Risks of Exoskeletons in the Construction Industry

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Abstract

Construction continues to be one of the most dangerous industries, with workers constantly exposed to physically demanding and repetitive activities. Exoskeletons are emerging as ergonomic interventions that amplify human strength and agility while reducing muscle fatigue and discomfort. However, like any robotic technology, exoskeletons may have unintended consequences. While studies have examined the health and safety risks of exoskeletons in construction, there is a significant gap in the literature regarding their ethical and social risks. Issues related to privacy concerns, exoskeletons' design, and discrimination, among many others, are housed in the ethical risks, and social risks often include questions regarding exoskeletons' affordability, accessibility and impact on social identity and communication, among others. This study addresses that gap by investigating the ethical and social risks associated with exoskeleton use in construction, assessing their impact on workers' health and safety and exploring how they can be designed to minimize these risks. This study further developed a comprehensive and practical worker-centric guide aimed at advancing the safe and ethical implementation of exoskeletons in the construction industry.

Key Findings

The study developed a practical, worker-centric guide that examines exoskeleton preferences for construction trades, ethical and social risks of exoskeletons, the impacts of these risks on construction workers' health and safety, the impact of these risks on the implementation of exoskeletons in the construction industry, and strategies to mitigate these identified ethical and social risks. The study further highlights barriers to implementing the identified strategies.

1. **Ethical and Social Risks:** A total of 34 ethical and social risks were identified from the literature review. Out of the 34, 18 were verified by experts in the construction industry and used in this study. These risks are categorized under design, autonomy, dehumanization, stigmatization, vulnerability, affordability, and accessibility.

2. **Risk Criticality:** Experts rated the identified risks on a Likert scale of 1 to 5 (with 1 being not critical, 2 less critical, 3 moderately critical, 4 very critical, and 5 extremely critical). Results show inaccessibility and unaffordability are examples of Very Critical risks, and stigmatization and loss of identity are examples of Less Critical risks.

3. **Exoskeleton Suitability:** Passive exoskeletons are suitable for repetitive overhead work and awkward postures, while active exoskeletons are better for heavy lifting. Back-support exoskeletons are most suitable for trades such as plumbers and carpenters, while full-body exoskeletons suit laborers.

4. **Risk Impact on Workers' Health and Safety:** The findings revealed that ethical and social risks related to design, autonomy, privacy, unauthorized access, dependency, exoskeleton weight, and overdependence pose significant health and safety concerns to workers.

5. **Mitigating Strategies:** Seventy strategies to mitigate identified ethical and social risks were proposed and evaluated.

6. **Barriers to proposed strategies:** Fifteen barriers to effective risk mitigation were identified.

7. **Worker-Centric Guide:** A comprehensive guide was developed to facilitate the implementation of exoskeletons such that the ethical and social risks are minimized.

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Introduction

The construction industry has long been plagued with high rates of work-related musculoskeletal disorders (WMSDs) [1, 2]. The high occurrence of WMSDs among construction workers not only results in staggering healthcare expenses and permanent disabilities but also in indirect costs from delays, productivity loss, and early exit from the workforce [3]. To address this, several scholars and some construction companies have started exploring the use of exoskeletons, wearable mechanical devices that augment construction workers' strength and agility while reducing muscle fatigue and discomfort when performing any construction-related tasks. [4, 5, 6]. There has been a proliferation of studies on exoskeletons in recent years reporting their potential and benefits. For instance, Ogunseiju, Gonsalves [7] quantified the impact of exoskeletons on workers' health, finding that exoskeletons reduced discomfort in the lower leg, lower back, and thigh by 28%, 21.74%, and 3.13%, respectively. Bennett, Adamczyk [8] also found that the ability of exoskeletons to reduce exertion and fatigue could enhance productivity levels in the construction industry, while Lindhard, Lassen [9] reported that exoskeletons could also lead to lower costs from workers' injuries, as exoskeletons prevent WMSDs.

The documented benefits of exoskeletons have prompted several construction companies to incorporate them into their jobsites [10]. However, as with any other robotic device, such technology can have unintended consequences, leading to ethical and social concerns. There needs to be a continual evaluation of benefits against risks and concerns to protect the construction workers who will be end users of exoskeletons. As posited by the principle of beneficence and non-maleficence, early detection of risks and concerns resulting from the use of exoskeletons is important to protect construction workers. Ethical concerns about exoskeletons may arise, such as overworking a worker, making them feel like a robot, reducing their privacy and autonomy. Because users' perceptions of the ethical and social risks of technology influence their trust and acceptance of that technology, it becomes critical to investigate the risks of exoskeletons to facilitate their adoption in construction.

To date, however, there have been few or no studies about construction workers that document the ethical and social risks associated with exoskeletons. This study aims to fill this gap by investigating those risks; their impact on workers' health and safety; and how exoskeletons can be designed so these risks are minimized, workers are protected, and adoption is facilitated. The study developed a practical, easy-to-use guide to facilitate an understanding of the ethical implementation of exoskeletons so workers are protected. This research contributes to advancing the design and implementation of exoskeletons in the construction industry while protecting the health and safety of its workers. This research also contributes to NIOSH Activity Goal 4.2.3 and NIOSH Strategic Plan: FYs 2019−2026, which seeks research that investigates the barriers to implementing technologies for MSD interventions.

Objectives

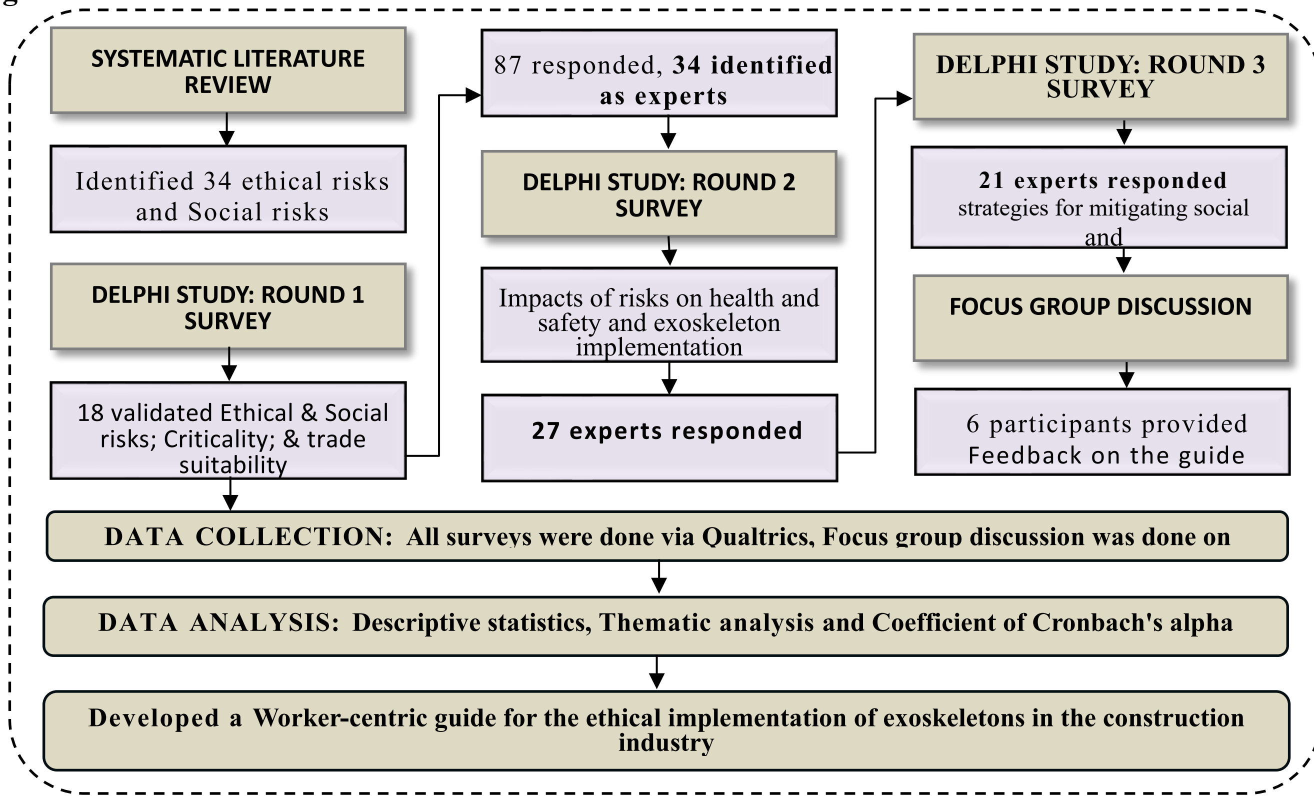
This research leverages a systematic literature review, a Delphi technique (consisting of three rounds of surveys), and a focus group discussion to achieve the research objectives, which are to:

1. Identify the ethical and social risks of exoskeletons in the construction industry;
2. Identify the suitability of different exoskeleton types for construction trades;
3. Assess the impacts of exoskeletons' ethical and social risks on the health and safety of construction workers;
4. Identify effective strategies for mitigating the impacts of ethical and social risks of exoskeletons; and
5. Develop a worker-centric guide to minimize the ethical and social risks of exoskeletons.

Methods

To fulfill the aforementioned objectives, a multi-phase approach incorporating mixed-methods research design was used. This method facilitated a systematic investigation, guaranteeing that the study's outcomes were robust. Figure 1 illustrates an overview of the tasks undertaken to achieve the objectives, which are further elaborated to detail how each objective was met.

Figure 1: Research Overview



<u>Systematic Review of Ethical and Social Risks</u>

The researchers conducted a systematic literature review on the ethical and social risks of exoskeletons, as well as strategies for mitigating these risks, through Google Scholar. Additionally, grey papers, such as trade journals and published guides on exoskeletons, were reviewed. This research helped identify specific ethical and social risks of exoskeletons for construction workers and strategies for mitigating these risks.

<u>Delphi Study</u>

The researchers conducted a Delphi study with three rounds of surveys to produce robust findings. The research team secured Institutional Review Board approval from the Georgia Institute of Technology before initiating the Delphi study, as the study involves human subjects (*Please refer to Appendix C for the approval letter*). The Delphi study was conducted using an online survey platform (Qualtrics).

Round 1 of the Delphi Study

This first round of the Delphi study was designed to identify experts and procure data for the first survey. Participants completed the expert criteria portion before proceeding with the first survey.

Expert Selection

The first round of the Delphi study was distributed to construction professionals and academia through different professional platforms, such as Associated General Contractors of America (AGC), Associated Schools of Construction (ASC), National Association of Women in Construction (NAWIC), and LinkedIn to identify potential experts for the study. The expert selection criteria (see Table A in Appendix A for highlights of the expert qualification criteria) followed qualifications requirements in similar Delphi studies [11-13] Among the 87 participants who responded, 16 did not consent to or complete the survey, and only 34 qualified as experts. These 34 included several industry practitioners with a wealth of industrial experience and professors who lecture at reputable higher education institutions (these categories will be identified as experts in academia). Please refer to Table B of Appendix A for an overview of participant demographics.

First survey

The first survey required participants to provide (1) to what extent they agreed with each ethical and social risks identified from the systematic literature review, (2) the construction trade impacted mainly by these risks, (3) the level of the criticality of the identified risks; and (4) additional risks not identified from the literature. The experts were also required to ascertain the suitability of different exoskeleton types for various construction trades and why these exoskeleton types are suitable. More than 82% of the experts were familiar with exoskeletons, increasing the reliability and relevance of this study's findings.

Round 2 of the Delphi Study

The second round of the Delphi study was a survey distributed to the 34 experts to assess the impacts of the risks identified in Survey 1 on workers' health and safety, using a 4-point Likert scale of very high, high, medium, or low. In this round, the expert panel also assessed the impact of ethical and social risks on the implementation of exoskeletons in the construction industry using a Likert scale and confirmed the suitability of exoskeleton types for different construction trades. Out of 34 experts, 27 responded in this round.

Round 3 of the Delphi Study

During the third round of the Delphi study, the 27 experts who completed Round 2 were presented with another survey, this one on strategies to alleviate risks, and were required to indicate their level of agreement (from strongly agree to strongly disagree) with these strategies. During this round, the experts also assessed the effectiveness of these strategies and identified potential barriers to implementing the strategies. Out of the 27, 21 responded.

Developing a Worker-Centric Guide to Minimize the Ethical and Social Risks of Exoskeletons

After using the Delphi method for identifying exoskeletons' ethical and social risks and their impacts, the suitability of exoskeletons for construction, and mitigation strategies for those risks, the research team developed a worker-centric guide for implementing exoskeletons to minimize their ethical and social risks. This kind of guide places the needs and interests of workers at the center of implementing such technologies. To strengthen the guide, existing policy guidelines, such as the American Society for Testing and Materials (ASTM) for exoskeletons [14, 15], were incorporated into it.

Focus Group Discussion on Worker-Centric Guide

To validate the guide, the study conducted a focus group discussion with construction industry practitioners. This discussion evaluated the study's research outcomes. Six experts were recruited, four of whom had previously participated in the three rounds of the Delphi study. A sample size of six is consistent with previous studies [16]. Each participant was familiar with exoskeletons and had more than three years of experience in the construction industry (see Table C of Appendix A for the demographics of the focus group participants). Participants were provided with the guide one week before the focus group. On the day of the focus group, participants provided comments and additional feedback on the guide. Additionally, the focus group participants were required to complete a brief survey on their level of agreement with the risks identified in the guide. This helped in providing quantitative validation of the worker-centric guide.

Data Analysis

The responses of the experts during the Delphi study were analyzed via Microsoft Excel: the mean, mode, and standard deviation were provided to garner insight into the most common perception of the risk among experts. The study evaluated the level of agreement among the experts during each round of the study, with a higher percentage indicating a stronger consensus among the experts [17]. Additionally, the extent of group agreement on each objective was assessed using the coefficient of Cronbach alpha.

The study used a different type of analysis for the focus group. This discussion was recorded and transcribed. Participants' identities were protected by de-identifying the transcript. The de-identified data were analyzed using the Braun and Clarke coding procedure [18]. Emerging themes were extracted (thematic analysis) using qualitative analysis software (i.e. Nvivo) to identify common themes based on the experts' levels of agreement, while the survey results (obtained after the focus group discussion) were analyzed using descriptive statistics. After data analysis, the worker-centric guide was updated to reflect the findings, additions, and opinions obtained from the focus group discussion.

Accomplishments And Results

The following activities were accomplished as part of this research.

Literature Review

The use of exoskeletons poses several risks that need to be considered carefully before use and implementation [19]. The first step is to understand the different types of risks associated with the exoskeletons. To achieve this, the research team conducted a systematic literature review on ethical and social risks and strategies for mitigating these risks through Google Scholar. The literature review identified 34 categories of ethical and social risks of exoskeletons, (in no specific order) including design, autonomy, privacy, unauthorized access, dependency, mandatory use, movement restrictions, trust, stigmatization, maintenance, vulnerability, standard regulation, cost, misuse, accessibility, and priority. The researchers proposed conceptual frameworks as a foundational guide in addressing the ethical and social considerations inherent in the utilization of exoskeletons (see Figures II and III of Appendix A). These frameworks combine interconnected elements, illustrating the intricate relationship between ethical consideration, associated risks, and proposed mitigation strategies, as well as its social dimensions.

<u>Round 1 of the Delphi Study</u>

Objective 1: Identify ethical and social risks of exoskeletons in the construction industry.

Participants provided their agreement with the risks identified from the literature review, using a 5-point Likert scale, where 5 – strongly agree and 1 – strongly disagree. The ethical and social risks agreed upon by experts during this round are broadly classified under design, dehumanization, autonomy, trust, stigmatization, affordability, and accessibility. Each risk had at least a 75% level of agreement ratings among the experts (Table 1) and a mean rating of at least 3.0 for each identified risk to ensure that all important risks were identified and considered in the next survey round. Based on the inclusion protocol suggested by similar Delphi studies, risks not meeting these criteria did not proceed to the next round of surveys (Holman [8], Von der [9], and Sourani and Sohail [10]). For example, Sourani and Sohail [10] and Kilner [11] posited that agreement in Delphi studies can range between 55%-100%. A group agreement of 87% was achieved across the survey sections using Cronbach's alpha, implying high internal consistency and reliability [7].

Table 1: Ethical and Social Risks of Exoskeletons in the Construction Industry

Category	Risks	Description	*%Agreement*	*Mean*	SD
Design Related Risks	Gender Unsuitability	Exoskeletons may not fit all genders.	86.32	3.44	1.02
	Weight Issues	Heavy exoskeletons can lead to discomfort and fatigue	83.19	3.32	1.09
	Weather incompatibility	Exoskeletons may not be suitable for all weather.	76.42	3.12	1.07
	Movement Restriction	Exoskeletons can restrict natural movement.	85.96	3.35	0.92
Dehumanization Related Risks	Appearance	Robot-like appearance.	80.37	3.15	1.02
	Overdependence	Workers may become overly dependent on exoskeletons.	90.68	3.47	0.99
Trust Related Risks	Data Privacy	Embedding health monitoring sensors in exoskeletons can pose ethical risks regarding privacy and data security.	76.85	3.18	1.14
	Data Misuse	Unauthorized use of biometric data (e.g., heart rate, movement)	90.16	3.59	0.96
	Lack of Transparency	Create distrust among workers.	96.06	3.74	0.96
	Safety Concerns	Concern whether the usage would be safe for workers.	92.06	3.71	0.97
	Acceptance	Affects the acceptance among users.	75.76	2.91	1.00
Autonomy Risk	Mandatory Use	It can reduce worker autonomy and cause discomfort.	92.00	3.68	0.94
Stigmatization Risk	Perceived Weakness	Perception as physically weak.	75.76	2.91	1.00
Affordability-Related Risks	High Cost	Financial burden on construction companies.	91.74	3.56	0.93
	Financial barrier	A significant barrier to widespread adoption.	82.30	3.32	1.17
	Cost Justification	Significant safety and productivity improvements.	97.10	4.06	0.85

Table 1: Ethical and Social Risks of Exoskeletons in the Construction Industry (continued)

Category	Risks	Description	%Agreement	Mean	SD
Accessibility-Related Risks	Gender Preferences	Limit accessibility for some users.	77.48	3.26	1.16
	Health Prioritization	Workers with pre-existing health conditions prioritized for exoskeleton use	83.93	3.29	1.14

Criticality of the Ethical and Social Risks with Exoskeleton

The study further assessed the level of criticality (highest importance and value) of the identified ethical and social risks. Understanding the criticality of these risks is a first step to mitigating the potential negative impacts on workers' health and safety. Experts rated the identified risks on a Likert scale of 1 to 5 (with 1 being not critical, 2 less critical, 3 moderately critical, 4 very critical and 5 extremely critical). Table 2 categorizes various ethical and social risks associated with exoskeleton use based on the percentage rate of criticality. Risks with a criticality rating above 89% are classified as Very Critical, or of high concern. For instance, the inaccessibility and unaffordability of exoskeletons were rated as Very Critical. Critical risks (e.g., Design of exoskeletons, Risk of overworking exoskeleton users) have percentages ranging from approximately 75% to 89%, indicating significant ethical or social concerns. Lower-rated risks, such as stigmatization and loss of identity, are considered Less Critical based on their lower percentage rates (below 75%) and are considered less severe but still important to address.

Table 2: Criticality of Ethical and Social Risks Associated with Exoskeleton

Ethical and Social risks	% rate of Criticality	Mean	SD	Criticality
Inadequate maintenance of the exoskeleton	96.83	3.71	1.00	Very Critical
Unaffordability of exoskeletons	93.75	3.76	1.18	Very Critical
Inaccessibility of exoskeletons	90.09	3.26	1.05	Very Critical
Prioritizing exoskeleton use for workers	89.22	3.00	0.92	Very Critical
Design of exoskeletons	88.60	3.35	1.04	Critical
Risk of overworking exoskeleton users	84.62	3.06	1.15	Critical
Need to regulate exoskeleton use	84.31	3.00	1.13	Critical
Lack of trust in exoskeletons	83.48	3.38	1.21	Critical
Misuse by the users of exoskeletons	82.83	2.91	1.16	Critical
Vulnerability to accidents from exoskeleton use	81.98	3.26	1.21	Critical

Table 2: Criticality of Ethical and Social Risks Associated with Exoskeleton (continued)

Ethical and Social risks	% rate of Criticality	Mean	SD	Criticality
Mandating exoskeleton use for workers	81.55	3.03	1.34	Critical
Loss of privacy from exoskeleton users	77.32	2.85	1.26	Critical
Violating worker rights using exoskeletons	76.70	3.03	1.29	Critical
Risk of autonomy from exoskeleton use	76.09	2.71	1.14	Critical
Risk of physical restriction from exoskeleton use	75.51	2.88	1.17	Critical
Risk of job displacement from exoskeleton use	73.86	2.59	1.10	Less Critical
Loss of self-identity from exoskeleton use	72.53	2.68	1.20	Less Critical
Risk of discrimination from exoskeleton use	71.59	2.59	1.13	Less Critical
Risk of job insecurity from exoskeleton use	69.77	2.53	1.19	Less Critical
Stigmatization of exoskeleton use	68.18	2.59	0.96	Less Critical
Risk of losing human identity due to exoskeleton use	67.07	2.41	1.13	Less Critical
Loss of social communications due to exoskeleton use	66.67	2.47	1.13	Less Critical
Impact on physical appearance	63.53	2.50	1.13	Less Critical
Dehumanization of exoskeleton users	61.36	2.59	1.21	Less Critical

Less critical		***critical***		***Very critical***	

Potential Ethical and Social Risks Identified in Focus Group Discussion

Potential risks not identified in the literature (*see Table D of Appendix A*) were provided by focus group participants during their discussion. These include overestimating exoskeletons' capabilities, where workers may lift beyond their limits, potentially leading to injury. Another risk involves employer-employee legal implications, as over-expectation of exoskeleton performance could result in dissatisfaction and even legal disputes. Additionally, accidents or health issues arising from exoskeleton use could create a negative perception of exoskeletons within the workforce.

Objective 2: Identify the suitability of different exoskeleton types for construction trades

Task-Specific Exoskeleton Preferences

The study investigated the type of exoskeleton (passive or active) required for specific construction activities. Passive exoskeletons use mechanical components like springs and dampers, rather than powered systems, to provide support and load distribution, while active exoskeletons use powered systems, such as motors, sensors, and actuators, to assist the wearer's movements. Table 3 outlines the type of exoskeleton used for selected construction activities. Passive exoskeletons are suitable for repetitive overhead work, as they provide support to the shoulders and arms, reducing muscle fatigue. In contrast, active exoskeletons are more effective for heavy lifting activities, reducing strain on the lower back and legs. For tasks that involve awkward postures or frequent bending and twisting, passive exoskeletons are ideal due to their lighter weight and less robotic, thereby stabilizing the body during non-standard movements.

Table 3: Activity-Specific Exoskeleton Preferences

Activity	Exoskeleton type
Repetitive overhead work	Passive
Heavy lifting	Active
Awkward postures	Passive
Frequent bending and twisting	Passive

Construction Task-Specific Exoskeleton Recommendations

The study further specifies the most suitable exoskeleton type for various construction trades, ensuring that workers receive the appropriate level of support for their tasks (See Table F of Appendix A, Suggested type of exoskeleton that best suits the work required in construction). During the first survey, the experts were provided with a list of trades, and for each trade, they selected the most appropriate exoskeleton types. These selections were further validated in the second round of the survey. The experts were given the selected trades and the exoskeleton types, and on a Likert scale of strongly agree to strongly disagree, validated these choices. The process indicated that plumbers, electricians, plasterers, HVAC technicians, and painters are better suited for passive exoskeletons, with agreement amongst experts ranging from 70% to 76%. Only rebar workers and construction labor are better suited for active exoskeletons, with 52% and 55% ratings, respectively.

Potential for Exoskeleton Use Based on Support Needed for Construction Tasks

The experts also provided their level of agreement (based on a Likert scale of strongly agree to strongly disagree) on the optimal type of exoskeleton support for each construction task. Table 4 highlights the specific body parts that would benefit from exoskeleton support, helping workers receive targeted assistance where it is needed most. The findings revealed the most common need is for back support.

Key findings include:

- **Back-Support exoskeletons** are highly suitable for plumbers, carpenters, rebar workers, and masons, with suitability ranging from 82% to 85%. Trades like roofers, drywallers, and plasterers show a suitability range of 73% to 81%. Painters, electricians, HVAC technicians, and construction laborers exhibit a suitability range of 63% to 71%, while heavy equipment operators have lower suitability for back-support exoskeletons (rating = 42%).
- **Full-body support exoskeletons** are better suited for construction laborers, with a 67% agreement amongst the experts.
- The findings also revealed that **Shoulder support exoskeletons** are less suitable for roofers, heavy equipment operators, and construction laborers.
- **Leg support exoskeletons** are suitable for carpenters and masons, with suitability rates of 73% and 58%, respectively.
- Lastly, the findings revealed that **Neck support exoskeletons** are highly suitable for electricians, with a suitability rate of 58%.

Table 4: Exoskeleton Support by Construction Trades

Construction Trades	Back-support	Full-body support	Leg support	Neck support	Shoulder support	Wrist support
Drywaller	76%	52%	36%	36%	61%	52%
Electricians	61%	27%	12%	58%	61%	61%
Plumbers	82%	27%	33%	42%	58%	52%
Carpenters	85%	36%	73%	30%	64%	64%
Rebar worker	82%	42%	48%	33%	55%	58%
Masons	82%	39%	58%	36%	58%	58%
Roofers	73%	42%	48%	21%	36%	42%
Painters	70%	24%	30%	42%	48%	48%
HVAC technicians	70%	33%	36%	45%	61%	39%
Heavy equipment operators	42%	27%	18%	27%	30%	39%
Plasterer	73%	27%	48%	30%	61%	64%
Construction Labor	67%	67%	39%	36%	48%	45%

Most suitable									Least suitable

The findings from Table 4 were used to put exoskeleton support recommendations for various construction trades into three categories: *Optimal* (ratings above 60%), *Suggested* (ratings between 40%-59%), and *Least Suitable* (ratings below 40%). These thresholds helped provide practical recommendations for exoskeleton use (see Table G in Appendix A). For example, the back support exoskeleton was agreed to be optimal for all construction trades except for heavy equipment operators.

Focus Group Recommendations for Exoskeleton Types for Construction Trades

Focus group participants suggested other construction trades that can greatly benefit from the use of exoskeletons (*see Table E of Appendix A* for the highlighted suggestions provided for using exoskeletons in various construction trades). For example, tile workers could use passive exoskeletons that provide support to the back, legs, shoulders, and neck, helping to reduce fatigue during prolonged tasks. Pipefitters, particularly in mechanical roles, may find passive exoskeletons offer back support when lifting and welding heavy equipment and pipes.

Second Round of the Delphi Study

Objective 3: Impacts of ethical and social risks of exoskeletons.

Impacts of ethical and social risks of exoskeletons on the health and safety of construction workers

The Delphi study experts assessed the impacts of ethical and social risks associated with exoskeletons on the health and safety of construction workers using a Likert scale, categorizing risks as very high, high, medium, or low *(*see Table H of Appendix A for the detailed ratings, which indicate a strong consensus among experts on several risks*)*. Key findings include a very high agreement on the risks associated with insufficient training (100% agreement) and the consequences of overreliance on exoskeletons, which could lead to ignoring safety protocols (98.82% agreement). Additionally, high agreement was noted regarding the implications of exoskeleton weight (94.37% agreement) and the influence of unequal access (95.24% agreement). Conversely, risks related to users appearing less human received a medium rating, indicating varied perceptions.

Impacts of ethical and social risks on the implementation of exoskeletons in the construction industry

The ethical and social risks associated with these technologies can profoundly impact their adoption and integration. These impacts were evaluated using a mode-based analysis (Table 5). For example, both the risk of losing human identity due to exoskeleton use and workers' vulnerability to accidents were identified as having a very high impact on implementation. Factors such as inaccessibility due to gender preferences and cost implications also has significant impacts on the implementation of exoskeletons. However, experts believed that the risks of exoskeleton users appearing robotic or of inadequate maintenance were less impactful on implementation.

Table 5: Impact of Ethical and Social Risks on Exoskeleton Implementation

Risks	Impact on implementation	Mean	% agreement	Mode
Risk of losing human identity due to exoskeleton use	**Very High**	4.07	100%	4
Workers' vulnerability to accidents from exoskeleton use	**Very High**	4.15	100%	4
Prioritizing workers with preexisting health conditions	**Very High**	3.74	100%	4
Lack of regulation policies	**Very High**	3.74	100%	4
Exoskeleton-induced physical restriction	**Very High**	3.56	100%	4
Potential misuse of exoskeletons	**Very High**	3.41	100%	4
Inaccessibility due to gender preference	**Very High**	3.59	100%	3
Design-related risks	**High**	3.52	98.95%	4
Cost implications	**High**	3.15	98.82%	4
Potential stigmatization of exoskeleton users	**High**	3.11	98.81%	3
Autonomy risks, including mandatory use	**High**	3.15	98.82%	3
Risk of inadequate maintenance	**Moderate**	3.07	97.59%	3
Potential overworking of exoskeleton users	**Moderate**	2.78	96%	3
Risks of exoskeleton users appearing robotic	**Moderate**	3.37	97.80%	3
Perception of exoskeleton users as physically weak	**Moderate**	3.15	97.65%	3

Table 5: Impact of Ethical and Social Risks on Exoskeleton Implementation (continued)

Risks	Impact on implementation	Mean	% agreement	Mode
Weight of exoskeletons	Low	2.63	94.37%	2
Workers' distrust in exoskeletons	Low	2.70	95.89%	2
Workers' over-dependency on exoskeletons	Low	2.41	93.85%	2

Third Round of the Delphi Study

Objective 4: Identify effective strategies for mitigating the impacts of ethical and social risks of exoskeletons

Effective strategies for mitigating these ethical and social concerns of exoskeleton

Experts then responded to a series of strategies for mitigating the ethical and social risks associated with exoskeleton use. These measures aim to ensure that exoskeleton technology remains effective, inclusive, safe, and ethical. Table 6 outlines various strategies to address specific ethical and social risks, including their respective percentage agreements, mean scores, and mode values. Additionally, Tables I and J in Appendix A detail strategies suggested by the focus group participants to mitigate these risks. By implementing these strategies, construction companies can manage the challenges associated with exoskeleton adoption, ensuring that the technology benefits users.

Table 6: Effective strategies for mitigating the ethical and social risks of exoskeleton

S/N	Effective Strategies	% Agreement	Mean	Mode	Ratings
A	**Gender Biased**				
1	Develop exoskeletons that suit various body types (one-size-fits-all exoskeletons)	87.1	3.73	4	Effective
2	Utilize lighter materials in designing exoskeletons while maintaining the strength of the exoskeleton	81.82	4.09	4	Effective
3	Design exoskeletons with adjustable features for women.	91.67	4.40	5	Effective
B	**Weight of Exoskeleton**				Effective
4	Add adjustable features for a balanced weight distribution.	89.71	4.36	4	Effective
5	Use light-weight materials in designing exoskeletons while maintaining the exoskeleton's strength	98.91	4.55	5	Highly Effective
6	Use lighter power systems like advanced batteries for active exoskeletons	87.69	4.38	5	Effective
C	**Feeling Like Robot**				
7	Incorporate user feedback in the design process.	93.42	4.44	5	Highly Effective

Table 6: Effective strategies for mitigating the ethical and social risks of exoskeleton (continued)

S/N	Effective Strategies	% Agreement	Mean	Mode	Ratings
8	Provide options of less robotic (soft) exoskeletons for users.	81.82	4.09	4	Effective
9	Provide frequent training on exoskeleton capabilities and limitations.	85.48	4.42	5	Effective
D	**Health Monitoring Sensors**				
10	Obtain consent from users.	91.89	4.53	5	Highly Effective
11	Test exoskeletons extensively for accurate sensor data to avoid misinformation	95	4.47	5	Highly Effective
12	Educate workers on the benefits of health monitoring sensors for exoskeletons	93.51	4.50	5	Highly Effective
E	**Overdependency on exoskeletons**				
13	Monitor and schedule the use of the exoskeleton	94.81	4.29	5	Highly Effective
14	Provide frequent training on exoskeletons' capabilities and limitations	82.76	4.36	5	Effective
15	Provide a Platform for getting frequent feedback on the use of exoskeleton	88.06	4.54	5	Effective
F	**Movement restrictions risks**				Effective
16	Design exoskeletons with ergonomic features to improve natural movement	100	4.52	5	Effective
17	Provide frequent training on the use of exoskeletons.	78.85	4.10	4	Moderate
18	Use feedback from users' movements to refine the exoskeleton's functionality.	93.24	4.31	4	Highly Effective
G	**False sense of security risks**				
19	Provide a brief guide on the capabilities of exoskeletons before every use	87.3	4.23	5	Effective
20	Offer frequent training on the proper use of exoskeletons.	89.23	4.14	4	Effective
21	Set up feedback systems to identify and correct any user misconceptions	96.3	4.33	5	Highly Effective

Barriers to Implementing Mitigation Strategies

It is essential to understand not just the strategies for mitigating related risks but also the barriers that may limit the effective implementation of exoskeletons. Round 3 of the Delphi study entailed a list of barriers to the implementation of the afore-discussed strategies. The expert identified these barriers and were encouraged to suggest additional ones. These potential barriers are categorized according to the risk types they most relate to (*please refer to Figure 1 of Appendix A*). Earlier in this report, findings about design risks identified issues like the high cost of lighter power systems (81%) and limited user training (86%) as significant barriers, with time constraints and knowledge restrictions also being prevalent. For autonomy, privacy, and stigmatization risks, the complexity of data protection regulations (86%) and restrictions from exoskeleton manufacturers (67%) posed significant obstacles, particularly data privacy and software updates. In terms of affordability and accessibility, high costs and a lack of specialized expertise were noted as prominent barriers. These barriers were noted as particularly impeding strategies such as partnerships with exoskeleton manufacturers and government agencies. By examining these barriers, stakeholders can better prepare for and address these challenges, ensuring a smoother integration of exoskeletons into the construction sector.

Worker-Centric Guide

Objective 5: Develop a worker-centric guide to minimize the ethical and social risks of exoskeletons.

Based on the findings from objectives 1 to 4, the researchers developed a worker-centric guide that describes how exoskeletons should be implemented in the construction industry to minimize ethical and social concerns. The developed guide is attached to Appendix B of this report and includes all the objectives of this study, alongside an introduction to different types of exoskeletons.

Focus Group Discussion

The focus group also discussed the worker-centric guide, providing the participating experts' valuable insights. Participants, who all have at least three years of experience and familiarity with exoskeletons (*see Table C of Appendix A for focus group participant demographics*), engaged in a structured dialogue that was analyzed using thematic analysis via NVivo. Also, at the end of the discussion the experts filled out a feedback survey (designed on a Likert scale that ranged from strongly agree to strongly disagree), on their impression of the guide (*see Table K of Appendix A for the level of agreement*). The survey included questions on the comprehensiveness, understandability, practicality and likelihood of recommending the guide.

Quantitative feedback on the worker-centric guide

The Delphi study results complemented the focus group findings, demonstrating a robust level of agreement across most questions (*see Table K of Appendix A for feedback from experts).* For example, the guide's effectiveness in addressing risk impacts on health and safety received unanimous support (100%), and the likelihood of recommending the guide was similarly rated at 100%. The focus group found the guide highly usable. The practicality and actionability of the recommendations in the guide, the balance of technical details, and understandability of the guide received an agreement of 97%, 98%, and 100%, respectively, from the participants.

Qualitative feedback on the worker-centric guide

The focus group participants received the worker-centric guide so they could provide qualitative feedback (*see Table L of Appendix A for findings from thematic analysis*). The experts agreed that active exoskeletons are appropriate for heavy lifting tasks, while passive exoskeletons are suitable for overhead work due to their lightweight nature. Experts emphasized the importance of task-specific exoskeletons, particularly highlighting the back as a consistently affected body part across various trades. However, experts noted that active exoskeletons may be impractical for certain trades due to their high cost and weight. The group suggested combining exoskeleton types (such as combining a shoulder-support and a back-support exoskeleton) to optimize performance based on specific trade tasks, such as using neck and shoulder support for painters or back support for heavy equipment operators. Ethical and social risks, such as dehumanization and trust issues, were acknowledged, with a strong emphasis on the need for gender-specific customization to ensure safety and comfort.

However, in terms of their impact on workers' health and safety, experts highlighted dehumanization and design risks as priorities, as well as using training to build trust and prevent injuries. This finding suggests that frequent, task-specific training should be an effective mitigation approach. Finally, barriers to implementing these strategies were seen as adequately addressed, with no significant additional concerns raised. The expert suggested areas of future research should involve trade workers directly to better tailor exoskeleton designs to real-world construction tasks. Overall, the guide was well-received, with experts agreeing that it comprehensively covered of issues and barriers related to exoskeleton use in construction trades.

Discussion and Relevance of Accomplishments

This research sought tto understand exoskeletons' ethical and social risks in the construction industry by investigating (1) the ethical and social risks that influence the adoption and sustainable use of these exoskeletons; (2) the impact of the ethical and social risks on workers' health and safety; and (3) how exoskeletons can be designed, such that these risks are minimized, workers are protected, and adoption is facilitated. The findings from this research are a first step to facilitating the implementation of exoskeletons in the construction industry, which can consequently impact the safety and productivity of the 7.5 million US workers in the construction industry. For example, while exoskeletons are known to facilitate safety, little is known about which exoskeleton type is suitable for each construction trade, which this study has addressed. The knowledge of the suitability of different exoskeleton types for various trades is crucial for ensuring a safe and effective implementation. Even with the growing adoption of exoskeletons in construction, there is a lack of training guides to prepare the construction workforce for their use. While some believe adopting exoskeletons can improve workers' safety, there is a lack of awareness about the ethical and social risks involved in their implementation and how these risks can be effectively mitigated. This study has developed a comprehensive guide that is intended to help key stakeholders, such as designers, manufacturers, employers, and policymakers, in embedding human values into the design requirements of exoskeletons specifically for the construction industry. By focusing on ethical principles and prioritizing workers' well-being, this study encourages, fostering a safer construction environment. As a result, the findings of this research may facilitate a systemic shift towards advancing the design and implementation of exoskeletons in the construction industry in a way that protecting the health and safety of construction workers.

Changes/Problems

Despite the research team's efforts to recruit females in the construction industry, most females invited for the study did not qualify as experts. However, 35% of the recruited experts were females, as opposed to 50% proposed. This can be directly attributed to the fact that according to the Bureau of Labor Statistics (BLS), women in construction only make up 10.8% of the total workforce, with women in construction trades at 4.3% [20]. Likewise, the research planned for 50% of the recruited experts to come from small and medium-scale companies; in the end, 44% of the experts were from these two categories, where Small-sized companies are categorized as having 1 – 100 employees, Medium-sized companies as 101 – 500 employees, and Large-sized companies as having above 500 employees. These were the only deviations from the study goals, objectives, approach, method, and projected timeline.

Future Funding Plans

Based on the findings from this study, the Investigators (Dr. Omobolanle Ogunseiju and Dr. Yong Kwon Cho) have recently received a grant from the U.S. Occupational Safety and Health Administration (OSHA) to train workers on 'preventing and controlling ergonomic risks of construction workers through the implementation of exoskeletons'. Based on the findings of this small study, the research team also plans to submit grant proposals to the National

Institute of Health, the National Science Foundation, and the Construction Industry Institute so we can further investigate how human-wearable robot interactions in the construction industry can be safely implemented.

List of Presentations/Publications

The authors have submitted a review paper titled "Ethical and Social Risk of Exoskeleton in Construction Industry: a Systematic Literature Review" to the *Journal of Information Technology in Construction*.

The authors also have planned journal publications, which are listed below:

1. The ethical and social risks of exoskeletons in the construction industry: A Delphi study
2. Assessing the impacts of ethical and social risks of exoskeletons in the construction industry
3. Strategies for mitigating the ethical and social risks of exoskeletons in the construction industry
4. Suitability of exoskeletons types for different construction trades: A Delphi study

Dissemination Plan

The research team intends to disseminate the research findings through journal and conference papers and training workshops. The planned publications will be submitted to leading journals such as ASCE Journal of Construction Engineering and Management, Journal of Information Technology in Construction, Automation in Construction, and Safety Science. Findings will also be presented as part of training supported by the new grant received by the Investigators.

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Appendix A: Supplementary Data/Findings

Table A. Expert Qualifications for the Delphi technique

Academia	Industry professional
Faculty Member at an accredited institution	Industry Professionals (such as safety managers/directors, project/site engineers, project managers, and injury prevention specialists)
Construction industry experience (at least 5 years)	Construction Industry Experience (at least 3 years)
Registered as a professional body e.g. Professional Engineer (PE), Licensed Architect (AIA), Certified Safety Professional (CSP), Associated Risk Manager (ARM)	Registered as a professional body, e.g., Professional Engineer (PE), Licensed Architect (AIA), Certified Safety Professional (CSP), Associated Risk Manager (ARM)
Belongs to a construction safety committee, workforce training committee, and technology integration committee	Participants should have presented at a work training or standard operating procedure (SOP), or review meeting on a topic related to construction/safety management most especially risk assessment, work quality, and worker performance
Published at least 3 conference and journal papers on construction safety, technology implementation and development, workers' performance and quality control	Held leadership positions in workforce training, construction safety management, and technology implementation
At least PhD in construction related domain Writer or editor of a book or book chapter on the topic of construction safety and health, or risk management	At least a BSc in fields related to Construction, Architecture and Engineering

Table B: Participants demographics for the Round 1 Delphi study

Demographic Feature	Category	Count (N=34)
Gender	Male	21
	Female	12
	Prefer not to answer	1
Age Range	25-34 years	15
	35-44 years	9
	45-54 years	6

Table B: Participants demographics for the Round 1 Delphi study (continued)

Demographic Feature	Category	Count (N=34)
	55-64 years	3
	65 years or older	1
Education Level	Bachelor's Degree	14
	Graduate Degree (Master's)	7
	Doctorate Degree (PhD)	13
Specialization	Construction-related/ Engineering	34
Occupation	Construction Practitioner	27
	Academic/Faculty	7
Practitioner Role	Project Manager	7
	Safety Manager	3
	Estimator, Scheduler	3
	Construction Technologist	1
	Virtual Design and Construction (VDC)	3
	Company Directors	4
	Senior Construction Manager	3
	Other (please specify)	3
Experience in Industry	3-5 years	11
	6-10 years	10
	11-15 years	2
	16-20 years	5
	21+ years	2
	26 years and above	4
Company Size	Large (500+ employees)	19
	Medium (100-500 employees)	7
	Small (1-99 employees)	8

Table B: Participants demographics for the Round 1 Delphi study (continued)

Demographic Feature	Category	Count (N=34)
Construction Sector	Heavy and Civil Engineering Construction	6
	Others (Please specify)	7
	Mixed-use Construction	6
	Infrastructure Construction	4
	Residential Construction	2
Familiarity with Exoskeleton	1 - Not Familiar	5
	2 - Slightly Familiar	6
	3 - Moderately Familiar	7
	4 - Very Familiar	12
	5 - Extremely Familiar	4
Contributed to Safety Book	Yes	3
Publications/Conference	Yes	7
Participation in Construction Safety Training	Yes	33
	No	1
Participation in Review Meetings (Safety/Risk/Quality)	Yes	23
	No	4
Led in Workforce/Safety Training	Yes	17
	No	10
Membership in Professional Bodies	Yes (ASSP-7); (CSP - 5); (PE - 3); (ARM - 1); (BCSP - 3); others - 9)	19
	No	15
Belong to Technology Committees	Construction Safety Committee	10
	Workforce Training Committee	4
	Technology Integration Committee	3
	Others (Please specify)	6
	None	11

Table C: Demographics of the Construction Practitioners Experts for the Focus Group

Demographic Feature	Category	Count (N=6)
Gender	Male	4
	Female	2
Practitioner Role	Safety Manager	1
	Construction/Civil Engineer	2
	Construction Technologist	2
	Other (please specify)	1
Experience in Industry	3-5 years	1
	6-10 years	3
	16-20 years	2
Familiarity with Exoskeleton	Very Familiar	4
	Moderately Familiar	2
Knowledge about Exoskeleton	A Great deal of Knowledge	4
	Little Knowledge	2
Experience on Exoskeleton	A Great deal of Experience	4
	Little Experience	2
Participation in Safety Training (OSHA, Fall Protection, PPE, etc.)	30 hours of training	1
	50 hours of training	1
	60 hours or more of training	4

Table D: Additional Ethical and Social Risks Identified during Focus Group Discussion

Risk	Description
Feeling Overpowered	Workers may feel overconfident and attempt to lift beyond their natural limits, potentially leading to injury.
Employer-Employee Legal Implications	Over-expectation of exoskeleton capabilities could lead to dissatisfaction and legal issues.
Negative Perception Due to Health Issues	Accidents or health problems may arise from exoskeleton use, affecting workforce perceptions negatively.
Perception as just another tool	Some workers may view exoskeletons as a tool, like other machinery (like a loader, or a duct lift, or a man lift)

Table E: Expert Recommendation Exoskeleton Types and Support for Construction Trades

Construction Trades	Exoskeleton by Type	Exoskeleton by Support
Tile Workers	Passive	Back, leg, shoulder, neck
Pipe Fitters (Mechanical)	Passive	Back support for lifting and welding heavy equipment and pipes
Iron Workers	Active	Scaffold erector, task-specific exoskeleton use
Concrete Finishers	Active	Full-body support
Structural Iron Workers	Not specified	Back, wrist, leg support
Facade Workers / External Painting Workers	Not specified	Leg exoskeletons, along with back and shoulder support

Table F: Construction Task-Specific Exoskeleton Preferences

Task	Active	Passive	Suitable
Drywaller	45%	55%	Passive
Electricians	30%	70%	Passive
Plumbers	21%	79%	Passive
Carpenters	30%	70%	Passive
Rebar worker	52%	48%	Active

Table G: Optimal Exoskeleton-Support by Construction Trades

	Preferrable Exoskeleton support					
Construction Trades	**Back**	**Full-Body**	**Leg**	**Neck**	**Shoulder**	**Wrist**
Drywallers	**Optimal**	**Suggested**	**Least suitable**	**Least suitable**	**Suggested**	**Suggested**
Electricians	**Optimal**	**Least suitable**	**Least suitable**	**Suggested**	**Optimal**	**Optimal**
Plumbers	**Optimal**	**Least suitable**	**Least suitable**	**Suggested**	**Suggested**	**Suggested**
Carpenters	**Optimal**	**Suggested**	**Optimal**	**Least suitable**	**Suggested**	**Suggested**
Rebar Workers	**Optimal**	**Suggested**	**Medium**	**Least suitable**	**Suggested**	**Suggested**

Table H: Impact of Exoskeletons' Ethical and Social Risks on Workers Health and Safety

S/N	Ethical and Social Risks	% Agreement	Mean	SD	Mode	Impact
A	**Design-Related**					
R1	Impact of non-gender-neutral exoskeleton designs on Health and Safety	89.66	2.15	0.80	2	High
R2	Consequences of exoskeleton weight on workers	94.37	2.63	0.91	3	High
R3	Implications of exoskeleton malfunctions on workers' health and safety	98.68	2.81	0.72	3	High
R4	Effects of health sensor data breaches on workers' psychological well-being	86.21	2.15	0.89	3	High
R5	Influence of unequal access to exoskeleton	95.24	2.33	0.72	2	High
R6	Risks from overdependency on exoskeleton support	92.54	2.48	0.96	3	High
R7	Risks from exoskeletons' interference with workers' natural movement.	95.59	2.52	0.92	2	High
R8	Risks from insufficient exoskeleton training	100	2.96	0.74	3	Very High
R9	Risks from ignoring safety protocols due to exoskeleton overreliance	98.82	3.15	0.80	3	Very High
B	**Dehumanization-Related**					

Table H: Impact of Exoskeletons' Ethical and Social Risks on Workers Health and Safety (con't)

S/N	Ethical and Social Risks	% Agreement	Mean	SD	Mode	Impact
R10	Risks from exoskeleton users appearing less human	71.11	1.67	0.72	1	Medium
R11	Risks from exoskeleton-induced dehumanization	78.43	1.89	0.83	1	Medium

Table I: Effective strategies for mitigating these ethical and social concerns of exoskeleton

S/N	Effective Strategies	% Agreement	Mean	Mode	Rating
H	**Unauthorized access risks**				
22	Implement multi-factor authentication to ensure system access is limited to authorized users	91.55	4.33	5	Highly Effective
23	Regularly update software to guard against vulnerabilities.	89.55	4.29	4	Effective
24	Establish and enforce access control policies that restrict access to only necessary users	96.34	4.39	4	Highly Effective
I	**Misusing Exoskeleton users' data**				Effective
25	Offering comprehensive training on proper usage in mitigating the Misuse of Exoskeleton users' data?	82.76	4.36	4	Effective
26	Establishing and communicating clear policies on acceptable uses in mitigating the misuse of Exoskeleton users' data	92.96	4.13	4	Highly Effective
27	strict access controls to authorized personnel only in mitigating the misuse of Exoskeleton users' data	97.62	4.32	4	Highly Effective

Table J: Suggested strategies for mitigating these ethical and social concerns of exoskeleton

S/N	Suggested Strategies	
A.	**Gender Biased**	
1	Features for wide ranges of heights and weights	Suggested
2	Design for adjustability for all body types	Suggested
3	Design for different body types	Suggested
4	Inclusive Design for all – Ergonomically customizable with continuous improvement and development	Suggested
B.	**Weight of Exoskeleton**	
5	Ensure engineering/design maximizes ideal load points (like hips)	Suggested
C.	**Movement Restriction Risks**	
6	Build in adjustment to get the correct fit	Suggested
D.	**Feeling Like Robot**	
7	Make them cool looking – Iron Man	Suggested
8	Make designers use exoskeletons to see firsthand how their designs impact users	Suggested
E.	**Overdependency on Exoskeletons**	
S/N	**Suggested Strategies**	
9	Provide exercise options so muscles don't deteriorate from non-use	Suggested
F.	**Mandatory Exoskeleton Use**	
10	Include in training: benefits to users of exoskeletons	Suggested
11	Don't make it mandatory, it's a tool to make work safer, easier, faster, and more efficient	Suggested

Figure I: Barriers to Implementing Mitigation Strategies

Section A: Design-Related Barriers to the Ethical and Social Risk of Exoskeletons

Feature	High Expenses	User Restrictions	Health & Safety Regulations	Manufacturer Restrictions	Time Constraints	Knowledge Restriction
Custom Features	52%	48%	43%	48%	33%	48%
Less Robotic Exo Choices	33%	24%	24%	48%	24%	48%
Lighter Power Systems	81%	10%	10%	48%	19%	19%
Obtaining Consent	10%	62%	71%	24%	24%	19%
User Training	24%	81%	57%	43%	86%	76%
Using Lighter Materials	76%	14%	24%	38%	24%	24%

Section B: Additional Barriers to Autonomy, Privacy, Stigmatization & Trust Risks of Exoskeleton

Feature	High Expenses	Knowledge Restriction	Data Protection Regulations	Manufacturer Restrictions	Lack of Online Support
Data Privacy	24%	38%	86%	67%	38%
Procuring Feedbacks	48%	52%	33%	43%	71%
Software Update	52%	43%	48%	57%	48%
Strict Access	38%	38%	67%	52%	43%
Transparency on Exo Impacts	24%	62%	29%	33%	48%

Section C: Additional Barriers to Affordability and Accessibility Risks of Exoskeleton

Feature	High Costs	Lack of Expertise	Time Constraints	Compliance Complexity	Slow Partnerships	Lack of Motivation	Multiple Decision Makers
Monitoring Exo Use	24%	48%	65%	24%	0%	14%	33%
One-Size-Fits-All Exo	62%	33%	53%	14%	10%	24%	14%
Partnering with Exo	62%	67%	29%	67%	81%	38%	62%
Partnering with Govt Agencies	62%	19%	35%	48%	76%	81%	81%

Table K. Focus Group Discussion: Feedback from experts on the worker-centric guide

Questions	E 1	E 2	E 3	E 4	E 5	Mean	Mode	% Agreement
Exoskeleton types are suitable for trades.	6	3	6	5	5	5	6	97.48
Agree with ethical and social risks.	6	5	6	5	4	5.2	6	100
Agree with the criticality of the risks.	6	5	5	5	4	5	5	100
Focus group suggests additional risks.	1	3	6	3	5	3.6	3	94.62
Guide identifies impacted trades.	6	5	5	4	3	4.6	5	97.44
Guide addresses risk impacts on health/safety.	6	5	6	4	4	5	6	100
Risk impacts on workers' health/safety are identified.	6	5	3	4	3	4.2	3	94.78
Risk impacts on exoskeleton implementation are assessed.	6	5	5	5	3	4.8	5	97.45

Table K. Focus Group Discussion: Feedback from experts on the worker-centric guide (con't)

Questions	E 1	E 2	E 3	E 4	E 5	Mean	Mode	% Agreement
Strategies are sufficient for mitigating risks.	6	5	5	4	4	4.8	5	100
Strategies will be effective for mitigating concerns.	6	5	5	5	5	5.2	5	100
Guide addresses barriers to implementing strategies.	5	5	5	5	5	5	5	100
Agreement on identified ethical/social risks.	5	5	6	5	5	5.2	5	100
Understandability of the guide.	5	5	6	5	6	5.4	5	100
Practicality and actionability of recommendations.	4	4	5	3	4	4	4	97.41
Guide covers all aspects of exoskeleton use.	3	4	4	4	3	3.6	4	97.39
Balance of technical details and accessibility.	4	4	4	4	2	3.6	4	98.06
Likelihood of recommending the guide	6	6	6	6	4	5.6	6	100

Note: E represents Expert (Focus group participants)

Table L: Focus Group Discussion Themes, Subthemes, and Codes of Expert Feedback on the Guide

Theme	Subtheme	Code	Excerpt
Suitability for Trades	Active Exoskeleton	Suitability for lifting	"I mean this Table looks good, like active for lifting heavy things and passive for other things. Makes sense."
	Passive Exoskeleton	Suitability for overhead tasks Lightness	"Those are extremely light, almost weightless, in a way. It's just, it's just your hands are just overhead for a long time, so coming from like an employer point of view, the passive exoskeleton is easy all day long for those activities."
		Preference for specific trades	"I totally agree with the guide saying that passive would be suitable for those types of trade specifically."
	Exoskeleton by Support Types	Optimal support for back	"My biggest takeaway is that for every particular trade, like since back is the most affected body part, and I think that's why we see it's consistently optimal for all of the different trades."

Table L: Focus Group Discussion Themes, Subthemes, and Codes of Expert Feedback on the Guide (continued)

Theme	Subtheme	Code	Excerpt
			"Yeah, I mean I have to say the fact that optimal for back that makes a lot of sense."
Ethical and Social Risks	Dehumanization Trust and Design Agreement		"I think most of them, I do definitely agree with them. Especially dehumanization. Trust is one big thing, and design for male and female would be different."
	Movement Restriction	Risk Assessment	"I'm not sure if the movement restriction necessarily would be an ethical risk, but it is definitely a risk."
	Affordability	Economic Impact	"Affordability is again a grey area in the sense that if we are looking at people of the companies buying these exoskeletons, then it might become an ethical issue."
Mitigating Strategies	Customizable for body types	Strategy Effectiveness	"Your strategy of developing an exoskeleton just to suit various body types, that strategy in itself is effective. Yeah, because if you take care of movement restrictions, you won't have gender issues."
	Effectiveness	Assessment of outlined strategies	"I agree with all of these. They are covering all aspects of gender, weight, or movement. I think all are effective, not just moderate."
Barriers	Agreement on barriers	Summary of Barriers	"After reviewing these, I don't think there is any additional comment. They summarize different perspectives and barriers very well. Every barrier is OK as listed in the Table."
Impact on Health and Safety	Relevance and Importance	High Impact	"Most of them here are very high, It summarizes the effectiveness of the points identified in this study. They are very relevant and important, so I agree with this Table."
	Customization	Need for gender-specific designs	"I would like to stress the design part of the risk because there should be more customization required on the gender of the person who is using it. The passive exoskeleton didn't fit my body properly, and the upper part was choking my neck, which can be hazardous."

Conceptual Frameworks

The researchers developed conceptual frameworks that serve as a foundational guide in addressing the ethical and social considerations surrounding the utilization of exoskeletons in the construction industry. *Figure*s II and III visually represent the interconnected elements of this framework, illustrating the intricate relationship between ethical principles, associated risks, and proposed mitigation strategies, as well as its social dimensions.

Figure II: Conceptual framework for social risks and proposed mitigating strategies.

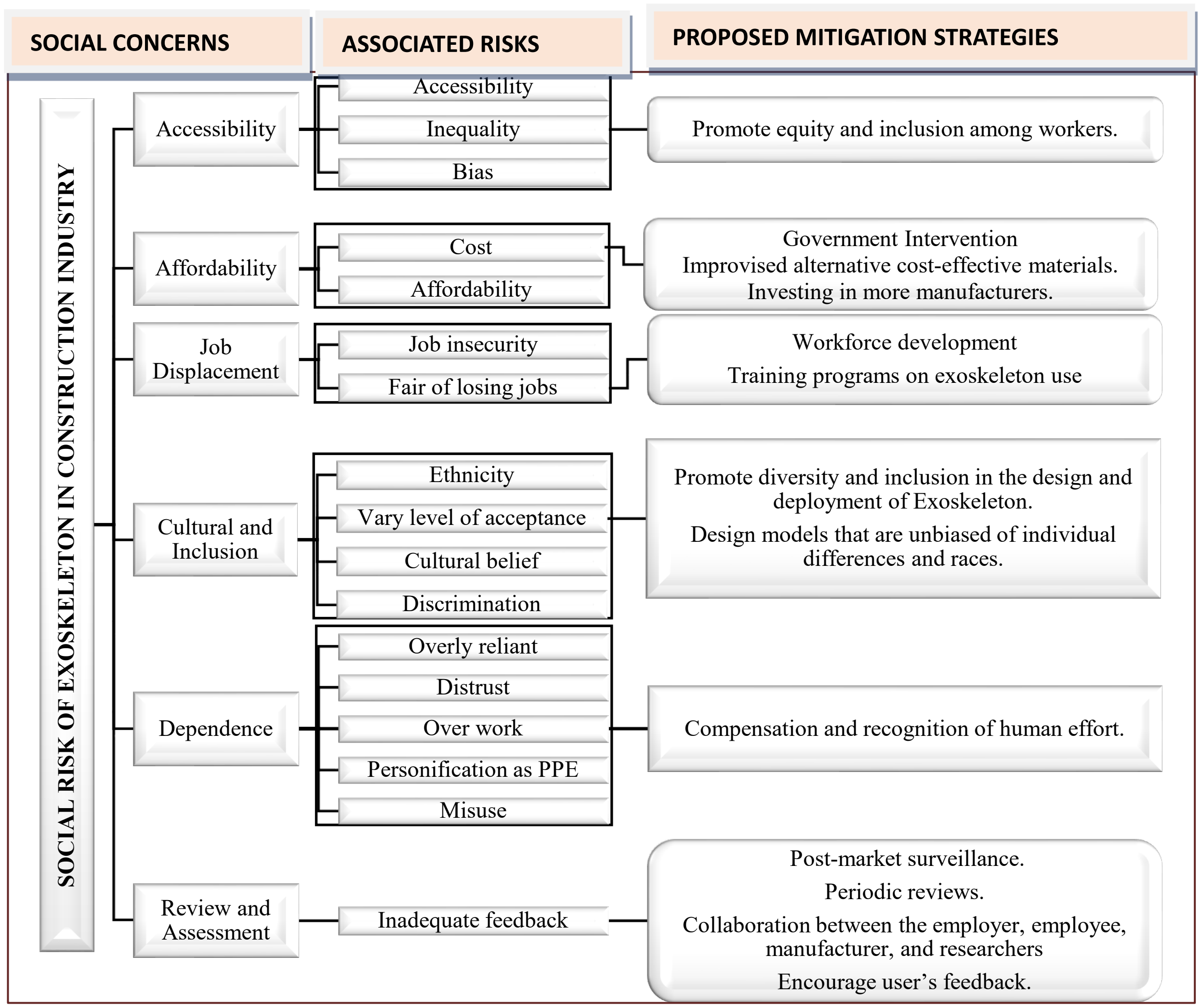
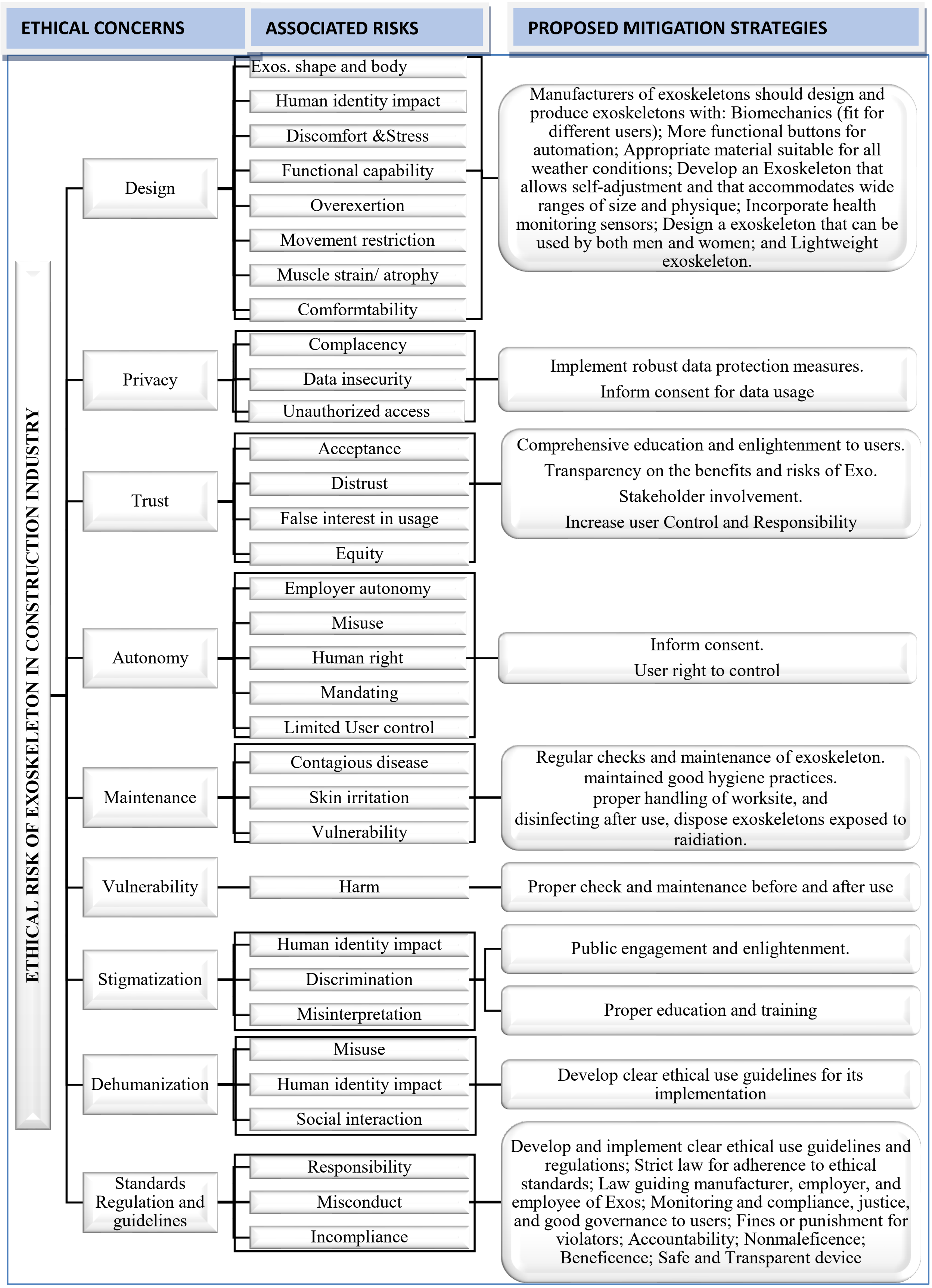


Figure III: Conceptual framework for ethical risks and proposed mitigating strategies.



Appendix B:

A Worker-Centric Guide On The Ethical And Social Risks Of Exoskeleton

A Guide to Mitigating the Ethical and Social Risks of Exoskeletons in the Construction Industry

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FOREWORD

Exoskeletons are emerging as a transformative technology in the construction industry, offering potential benefits in terms of enhanced worker safety, productivity, and efficiency. However, using exoskeletons also comes with some ethical and social concerns. This guide aims to address the ethical and social risks of exoskeletons and propose strategies for mitigating them. Overall, the goal of this guide is to promote the safe and ethical implementation of exoskeletons such that workers are protected and adoption is facilitated in the construction industry.

OBJECTIVES OF THE GUIDE

The objectives of the guide are to:

- Provide an understanding of exoskeletons and their applications in construction.
- Analyze the ethical and social risks associated with using exoskeletons.
- Create awareness of how these ethical and social risks can impact workers' health and safety.
- Provide an understanding of how these ethical and social risks impact the implementation of exoskeletons in the construction industry.
- Create awareness of strategies for mitigating the ethical and social risks of exoskeletons in the construction industry.
- Present the possible barriers to implementing the identified strategies.

INTRODUCTION TO EXOSKELETONS

- Exoskeletons are mechanical devices that aid and augment the wearer's physical strength through mechanical torque or powered motors. They work by providing extra support and strength, either through mechanical parts or powered motors, making it easier to lift heavy objects or perform repetitive tasks without getting tired as quickly.
- They are designed to enhance human capabilities by providing additional support and strength, reducing strain and fatigue.
- Two major types of exoskeletons:

1. **Active exoskeletons:**

Fig 1: Active Exoskeleton

- The exoskeleton uses actuators powered by electric motors (Fig 1).
- The actuators generate mechanical force, which helps the wearer perform tasks with less effort.
- Active exoskeletons are commonly used in applications where significant physical assistance is needed, such as lifting heavy objects, enhancing endurance in walking or standing, and aiding mobility for people with disabilities.

2. **Passive exoskeletons:**

Fig 2: Passive Exoskeleton

- Unlike active exoskeletons, passive exoskeletons do not have powered actuators. Instead, they use mechanical components like springs or elastic bands to store and release energy. (Fig 2).

- These are often used for tasks that involve repetitive motions or sustained postures, helping to reduce fatigue and the risk of injury.

APPLICATIONS OF EXOSKELETONS IN THE CONSTRUCTION INDUSTRY

In the construction industry, exoskeletons can be used to assist in a variety of tasks.
For example:

- **Lifting and Carrying:** Exoskeletons can provide support for lifting heavy materials, reducing the risk of back injuries and fatigue.
- **Overhead Work:** Exoskeletons can help workers hold tools and materials overhead for longer periods.
- **Repetitive Tasks:** Exoskeletons can reduce the physical toll of repetitive tasks, such as carpentry, painting, drilling, hammering, or screwing, by providing support and assisting with the movements of different body parts.

Common Types of Exoskeleton Support:

1. **Full-body Support:**
    - Full-body exoskeletons (Fig 3) provide complete assistance, supporting the entire body from the legs to the arms and back.
    - These systems are useful in construction tasks that require lifting, carrying, or holding heavy materials.
    - They help distribute weight more evenly across the body, reducing the risk of injury and fatigue, particularly in tasks involving significant physical exertion.

Fig 3: Full-body Support

2. **Back Support:**
    - Back support exoskeletons (Fig 4) are designed to reduce the strain on the lower back during lifting, carrying, or bending activities.
    - They are especially beneficial for tasks like loading and unloading materials or any work that involves frequent lifting or bending for prolonged periods.

Fig 4: Back Support

3. **Leg Support:**
   - Leg support exoskeletons (Fig 5) assist with walking, standing, or performing squatting movements.
   - These are particularly beneficial for workers who spend long hours on their feet or those recovering from lower limb injuries.
   - In construction, these exoskeletons are valuable for tasks that require prolonged standing work, such as scaffolding work, or operating equipment that requires constant standing. They help reduce leg fatigue and support joint stability.

Fig 5: Leg Support

4. **Neck Support:**
   - Neck support exoskeletons (Fig 6) support the neck and head, often used in professions that require holding the head in a particular position for extended periods.
   - This support helps to reduce the strain on neck muscles and prevent discomfort or injury.
   - They are used in construction tasks where workers need to look up or hold their heads in an upward position for extended periods, such as during overhead installations or inspections.

Fig 6: Neck Support

5. **Shoulder Support:**
   - Shoulder support exoskeletons (Fig 7) are designed for tasks that involve repetitive overhead work, such as painting, construction, or electrical work.
   - They help support the arms and shoulders, reducing the physical burden on these areas and lowering the risk of injuries.
   - By supporting the arms and shoulders, these exoskeletons reduce muscle strain and fatigue, helping to prevent shoulder injuries and increase productivity.

Fig 7: Shoulder Support

6. **Wrist Support:**
   - Wrist support exoskeletons (Fig 8) are used to assist with repetitive tasks that involve the wrists, such as hand tools, drilling, or masonry work.
   - They provide stabilization and reduce the strain on wrist joints, helping to prevent repetitive strain injuries.

Fig 8: Wrist Support

Each type of exoskeleton support is designed to enhance construction workers' safety and efficiency by providing targeted assistance where it is most needed.

EXOSKELETON PREFERENCES FOR CONSTRUCTION TRADES

- In construction, selecting an appropriate exoskeleton type is crucial for increasing the worker's safety, productivity, and comfort.
- Different construction roles involve unique physical demands, from repetitive overhead work to heavy lifting and awkward postures for prolonged periods.
- This section explores the preferences for passive and active exoskeletons along with the type of exoskeleton support based on the specific tasks and roles in the industry.
- By aligning the type of exoskeleton with the nature of the work, we can better support workers, reduce fatigue, prevent injuries, and enhance overall job performance.
- The following Tables 1, 2, and 3 and their corresponding descriptions provide detailed insights into the optimal exoskeleton types for a variety of construction tasks, illustrating how each can be tailored to meet the unique needs of different roles.

1) Task-Specific Exoskeleton Preferences

To understand the type of exoskeleton required for specific construction activities, we need to consider the physical demands associated with each task. Table 1 outlines the type of exoskeleton requirement in accordance with the type of activity.

Table 1: Activity-Specific Exoskeleton Preferences

Activity	Exoskeleton Type
Repetitive overhead work	Passive
Heavy lifting	Active
Awkward postures	Passive
Frequent bending and twisting	Passive

1) Detailed Insights on the types of works requiring the exoskeleton support:

The following insights can help us understand the type of exoskeleton requirement.

i) Repetitive Overhead Work:

- For tasks that involve repetitive overhead work, such as installing ceiling panels or painting, a passive exoskeleton is suitable.
- These exoskeletons are lightweight and designed to reduce shoulder and arm fatigue by providing mechanical support without the need for power.
- They help to maintain good posture and distribute the load more evenly across the upper body, thereby reducing the risk of fatigue and muscular injuries.

ii) Heavy Lifting

- Construction activities that require heavy lifting, such as moving building materials or operating heavy machinery, benefit from active exoskeletons.
- These powered exoskeletons provide significant assistance to the lower back and legs, making it easier to lift heavy objects with reduced risk of injury.

- By enhancing the user's support and strength, active exoskeletons help prevent overexertion and lower back strain, enhancing both safety and productivity.

iii) Awkward Postures

- Tasks that involve maintaining awkward postures for extended periods, like working in confined spaces and prolonged bending works, are best suited for passive exoskeletons.
- These exoskeletons support natural body movements and reduce stress on joints and muscles without requiring an external power source and being light weight.
- They help to relieve discomfort and prevent injuries associated with prolonged awkward postures.

iv) Frequent Bending and Twisting

- For roles that require frequent bending and twisting, such as bricklaying or carpentry, passive exoskeletons are ideal.
- These lightweight exoskeletons provide support that assists with dynamic movements, helping to prevent lower back injuries.
- The passive exoskeletons aid in reducing fatigue by offering support and reducing the effort needed to bend and twist.

Construction Task-Specific Exoskeleton Preferences

In accordance with Table 1 and the types of tasks, Table 2 was drafted to suggest the type of exoskeleton that best suits the work required in construction. This table specifies the suitable exoskeleton type for various construction roles, ensuring that workers receive the appropriate level of support for their specific tasks.

Table 2: Construction Task-Specific Exoskeleton Preferences

Construction Trades	Suitable Exoskeleton Type
Drywaller	Passive
Electricians	Passive
Plumbers	Passive
Carpenters	Passive
Rebar worker	Active
Masons	Passive
Roofers	Passive
Painters	Passive
HVAC technicians	Passive
Heavy equipment operators	Passive
Plasterer	Passive
Construction Labor	Active

These preferences indicate that passive exoskeletons are generally favored for tasks that require moderate physical support. In contrast, active exoskeletons are suitable for tasks that demand significant physical exertion, such as rebar work and general construction labor. The optimal support areas are primarily focused on the back, reflecting the common need for back support in most construction activities.

Optimal Exoskeleton Support by Task

To further refine the understanding of exoskeleton requirements, the following table outlines the optimal support areas for each construction task. Table 3 highlights the specific body parts that benefit the most from exoskeleton support, helping to ensure that workers receive targeted assistance where it is needed most.

Table 3: Optimal Exoskeleton-Support by Construction Trades

	Preferrable Exoskeleton support					
Construction Trades	**Back**	**Full-Body**	**Leg**	**Neck**	**Shoulder**	**Wrist**
Drywallers	**Optimal**	**Suggested**	**Least suitable**	**Least suitable**	**Suggested**	**Suggested**
Electricians	**Optimal**	**Least suitable**	**Least suitable**	**Suggested**	**Optimal**	**Optimal**
Plumbers	**Optimal**	**Least suitable**	**Least suitable**	**Suggested**	**Suggested**	**Suggested**
Carpenters	**Optimal**	**Suggested**	**Optimal**	**Least suitable**	**Suggested**	**Suggested**
Rebar Workers	**Optimal**	**Suggested**	**Medium**	**Least suitable**	**Suggested**	**Suggested**
Masons	**Optimal**	**Suggested**	**Medium**	**Least suitable**	**Suggested**	**Suggested**
Roofers	**Optimal**	**Suggested**	**Medium**	**Least suitable**	**Suggested**	**Suggested**
Painters	**Optimal**	**Least suitable**	**Least suitable**	**Suggested**	**Suggested**	**Suggested**
HVAC Technicians	**Optimal**	**Suggested**	**Suggested**	**Suggested**	**Suggested**	**Suggested**
Heavy Equipment Operators	**Suggested**	**Least suitable**	**Least suitable**	**Least suitable**	**Least suitable**	**Least suitable**
Plasterers	**Optimal**	**Least suitable**	**Suggested**	**Least suitable**	**Optimal**	**Optimal**
Construction Labor	**Optimal**	**Optimal**	**Suggested**	**Suggested**	**Suggested**	**Suggested**

ETHICAL AND SOCIAL RISKS ASSOCIATED WITH EXOSKELETONS IN THE CONSTRUCTION INDUSTRY

The use of exoskeletons can pose several ethical and social risks that need to be considered carefully before usage and implementation. The first step is to understand the different types of ethical and social risks associated with exoskeletons. Fig 9 demonstrates the categories of ethical and social risks of exoskeletons in the construction industry.

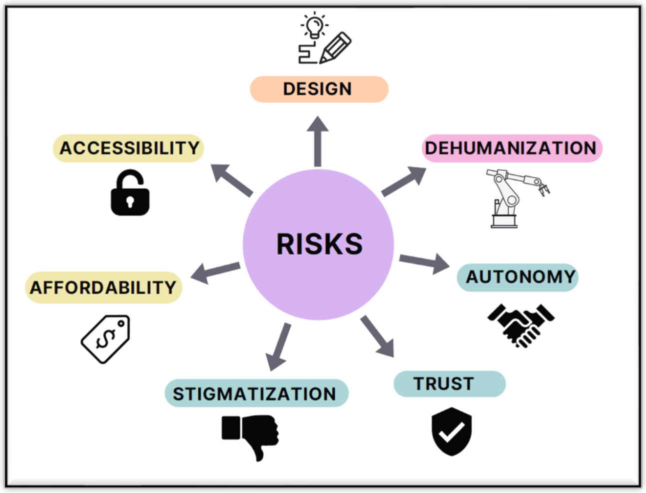

Fig 9: Ethical and Social risks associated with Exoskeletons

The following Table categorizes the different types of risks associated with exoskeleton use and provides detailed descriptions of each. By presenting these categories, Table 4 helps to identify key areas where exoskeletons might affect worker health, comfort, and overall work experience.

Table 4: Ethical and Social Risks of Exoskeletons in the Construction Industry

Categories	***Risks***	***Description***
Design Related Risks	Gender Unsuitability	Exoskeletons may not fit all genders.
	Weight Issues	Heavy exoskeletons can lead to discomfort & fatigue
	Weather Incompatibility	Exoskeletons may not be suitable for all weather.
	Movement Restriction	Exoskeletons can restrict natural movement.
Dehumanization Related Risks	Appearance	Robot-like appearance.
	Overdependence	May lead to reduced strength
	Psychological Impact	Could affect mental health by making workers feel less human.

Table 4: Ethical and Social Risks of Exoskeletons in the Construction Industry (continued)

Categories	***Risks***	***Description***
Autonomy Related Risks	Mandatory Use	Can reduce worker autonomy and cause discomfort.
	Reduced Control	Affects their independence and job performance.
Trust Related Risks	Data Privacy	Poses significant privacy concerns.
	Lack of Transparency	Create distrust among workers.
	Safety Concerns	Affects the acceptance and usage among users.
Stigmatization Related Risks	Perception of Weakness	Perceived as physically weak.
	Social Impact	Impact workers' mental health and social interactions
Affordability Related Risks	High Cost	Financial burden on construction companies.
	Cost Justification	Significant safety and productivity improvements.
Accessibility Related Risks	Economic Barriers	Barrier to widespread adoption.
	Gender Preferences	Limit accessibility for some users.
	Health Prioritization	Workers with pre-existing health conditions should be prioritized.

Having outlined these risks, the next step is to delve into the specific ethical and social risks surrounding the use of exoskeletons. These risks associated with Table 4 can be further classified into ethical and social risks. This focus is critical for ensuring that this technology is used in a way that respects worker rights and examines any ethical issues.

Table 5 provides a detailed examination of the ethical risks associated with exoskeletons in the construction industry. These ethical considerations are vital for understanding how exoskeletons might impact workers on a more personal level. Addressing these issues ensures that the technology is used in a manner that respects individual dignity and autonomy.

Table 5: Ethical risks of exoskeletons in the construction industry

Ethical risks	**Description**
Gender unsuitability	Exoskeletons may not be suitable for all genders, raising ethical concerns.
Weight issues	The weight of exoskeletons can pose ethical risks by causing fatigue or injury.
Health monitoring sensors	Embedding health monitoring sensors in exoskeletons can pose ethical risks regarding privacy and data security.

Table 5: Ethical risks of exoskeletons in the construction industry (continued)

Ethical risks	**Description**
Weather incompatibility	Exoskeletons may not be suitable for all weather conditions, raising ethical concerns.
Dehumanization	Wearing exoskeletons can make workers look like robots, impacting their dignity.
Overdependence	Workers may become overly dependent on exoskeletons, potentially weakening their physical capabilities.
Unauthorized data use	There can be unauthorized use of biometric data collected through exoskeletons.
Movement restriction	Wearing an exoskeleton can reduce workers' ability to move different body parts.
Mandatory use	Requiring workers to use exoskeletons can pose ethical concerns.
Safety assurance	Ensuring exoskeleton use is safe for all workers is a critical ethical concern.
Lack of trust	Workers may lack trust in exoskeletons, affecting their acceptance and effectiveness.
Stigmatization	Workers using exoskeletons may be perceived as physically weak.

With these ethical risks clarified, we can now turn our attention to the social implications of exoskeleton use. The focus shifts to understanding how these risks affect broader societal factors, including financial implications and barriers to adoption.

Table 6 shifts the focus to the social risks associated with exoskeletons. This Table highlights issues such as the financial burden on companies, cost justification, and barriers to widespread adoption. By examining these social factors, we gain insight into how the use of exoskeletons might influence organizational dynamics and accessibility within the industry. This understanding is crucial for evaluating the overall feasibility and impact of exoskeletons.

Table 6: Social Risks of Exoskeletons in the Construction Industry

Social risks	**Description**
Cost justification	The high cost of exoskeletons must be justified by their potential benefits.
Financial burden	Exoskeletons may impose a financial burden on construction companies.
Adoption barriers	The high cost of exoskeletons is a significant barrier to widespread adoption.
Gender preference	Gender preferences can influence workers' accessibility to exoskeletons.
Health prioritization	Workers with pre-existing health conditions should be prioritized for exoskeleton use.

In summary, the careful examination of risks, both ethical and social, is essential for the successful and responsible implementation of exoskeletons in the construction industry. Each Table presented provides a focused analysis of different risk aspects, helping stakeholders make informed decisions that balance the benefits of exoskeletons with the need to address potential challenges. By addressing these risks comprehensively, we can ensure that exoskeletons are deployed in a way that maximizes benefits while minimizing negative impacts on workers and organizations.

IMPACTS OF ETHICAL AND SOCIAL RISKS OF EXOSKELETONS ON THE WORKER'S HEALTH AND SAFETY

The potential ethical and social risks associated with exoskeleton use can significantly impact workers' health and safety. Understanding these risks is crucial for mitigating negative outcomes and ensuring that the deployment of exoskeletons benefits all workers without compromising their well-being. Table 7 categorizes the risks and outlines the severity of the potential impact on workers' health and safety.

Table 7: Impacts of Exoskeleton's Ethical and Social Risks on Workers' Health and Safety

Categories	***Ethical and Social Risks***	**Impact on workers' health and safety**
Design Related	Impact of non-gender-neutral exoskeleton designs.	**High**
	Consequences of exoskeleton weight on workers.	**High**
	Implications of exoskeleton malfunctions.	**High**
	Effects of health sensor data breaches on user's mental health	**High**
	Influence of unequal access to the exoskeleton.	**High**
	Overdependency on exoskeleton support.	**High**
	Exoskeletons' interference with workers' natural movement.	**High**
	Risks from insufficient exoskeleton training.	**Very High**
	Risks from exoskeleton overreliance.	**Very High**
Dehumanization Related	Risks from exoskeleton users appearing less human.	**Medium**
	Risks from exoskeleton-induced dehumanization.	**Medium**
	Risks from prolonged exoskeleton use.	**High**
	Psychological risks in unauthorized biometric data access.	**High**
	Misusing exoskeleton users' health and movement data	**High**
	Mental risks from lack of data transparency and control.	**High**
Autonomy, Trust, and Stigmatization Related	Risks from mandatory exoskeleton use	**High**
	Mental risks due to users being perceived as physically weak.	**Medium**
	Risks from workers' distrust in exoskeletons.	**High**
	Risks from societal stigmatization of exoskeleton users.	**Medium**

Table 7: Impacts of Exoskeleton's Ethical and Social Risks on Workers' Health and Safety

Categories	*Ethical and Social Risks*	**Impact on workers' health and safety**
Affordability and Accessibility Related	Impact of exoskeleton adoption costs on health and safety.	**High**
	Influence of gender-specific exoskeleton design on health and safety	**High**
	Prioritizing exoskeleton for workers with preexisting health conditions.	**High**
	Health and safety risks from inaccessibility to exoskeleton use due to gender preferences	**High**

Design-related risks have the highest impact on workers' health and safety, and it is closely followed by affordability and accessibility-related risks. It is also important to pay close attention to dehumanization-related risks as they can impact workers' psychological and mental health. This underscores the critical need for careful consideration and mitigation of these risks to ensure the safe and equitable integration of exoskeletons in the construction industry.

Detailed Explanation of the Impacts of Ethical and Social Risks on Construction Workers' Health and Safety.

1. Design-Related Risks: High risks

I. **Non-Gender Neutral Design**:
   - Exoskeletons designed without considering gender-specific anatomical differences can lead to discomfort and health issues.

II. **Weight and Fit Issues**:
   - Heavy or ill-fitting exoskeletons can cause fatigue, discomfort, or even injuries, negating the benefits they are intended to provide.

III. **Movement Restriction**:
   - Poorly designed exoskeletons may restrict natural movements, increasing the risk of falls or other accidents.

2. Dehumanization Risks

I. **Appearance: Medium risks**
   - The robotic appearance of exoskeletons can lead to feelings of dehumanization among users, affecting their self-perception and mental health.

II. **Overdependence: High risks**
   - There is a risk that prolonged use of exoskeletons could lead to physical atrophy and reduced resilience as workers become reliant on the technology to perform tasks.

3. Autonomy and Control Risks

I. **Mandatory Use: High risks**

- If the use of exoskeletons is mandated, workers may feel coerced and may have some impact on their mental health.

II. **Reduced Control and Data Privacy Concerns: High risks**

- If workers feel that their movements and health data are being monitored without adequate transparency and consent, it can lead to distrust and anxiety.
- Unauthorized biometric data access from exoskeletons may lead to psychological risks.

4. Stigmatization and Social Risks: Medium risks

I. **Perception of Weakness**:

- Workers using exoskeletons may be perceived as weaker or less capable, which may impact their mental health.

II. **Impact on Social Interactions**:

- The use of exoskeletons can alter workplace dynamics, affecting social interactions and communication.
- Workers may feel isolated or different from their peers, impacting their social well-being.

5. Affordability and Accessibility Risks: High Risks

I. **High Costs and Economic Barriers**:

- The high cost of exoskeletons can limit access to only larger firms, creating economic disparities in who benefits from the technology. This can result in continued workplace injuries.

II. **Inaccessibility Due to Health Prioritization**:

- Prioritizing exoskeletons for workers with pre-existing health conditions might result in masked/ untreated health issues.

III. **Inaccessibility due to gender preferences**

- Inaccessibility to exoskeleton use due to gender preferences can pose health and safety risks and discomfort for certain workers.

CRITICALITY OF ETHICAL AND SOCIAL RISKS OF EXOSKELETONS.

The introduction of exoskeletons in the construction industry presents several ethical and social risks. Understanding the criticality of these risks is essential to mitigate potential negative impacts on workers' health and safety. Table 8 provides a comprehensive overview of these risks, highlighting their severity. This Table serves as a crucial reference for identifying and addressing the most pressing concerns related to the deployment of exoskeletons in the construction industry.

Table 8: Criticality of Ethical and Social Risks Associated with Exoskeleton

Ethical and Social Risks	Criticality
Inadequate maintenance of the exoskeleton	Very Critical
Risks from prioritizing exoskeleton use	Very Critical
Unaffordability of exoskeletons	Very Critical
Inaccessibility of exoskeletons	Very Critical
Design of exoskeletons	**Critical**
Lack of trust in exoskeletons	**Critical**
Vulnerability to accidents from exoskeleton use	**Critical**
Exoskeleton users' data insecurity	**Critical**
Risk of autonomy from exoskeleton use	**Critical**
Risk of physical restriction from exoskeleton use	**Critical**
Risks from mandating exoskeleton use	**Critical**
Need to regulate exoskeleton use	**Critical**
Risk of overworking exoskeleton users	**Critical**
Risks from misusing exoskeletons	**Critical**
Stigmatization from exoskeleton use	**Less Critical**
Dehumanization of exoskeleton users	**Less Critical**
Risk of job insecurity from exoskeleton use	**Less Critical**
Violating exoskeleton users' rights	**Less Critical**
Loss of self-identity from exoskeleton use	**Less Critical**
Impact on physical appearance	**Less Critical**
Risk of job displacement from exoskeleton use	**Less Critical**
Risk of discrimination from exoskeleton use	**Less Critical**
Loss of social communications due to exoskeleton use	**Less Critical**
Risk of losing human identity due to exoskeleton use	**Less Critical**

1. Extremely Critical Risks

I. **Inadequate Maintenance:**

- Failure to properly maintain exoskeletons can lead to malfunctions or safety hazards, posing serious risks to users.
- The criticality of this issue is heightened by the potential for significant harm, making regular and thorough maintenance essential.

II. **Prioritizing Exoskeleton Use:**

- Prioritizing exoskeletons for workers with pre-existing health conditions might result in masked/ untreated health issues.

III. **Unaffordability**:

- The high cost of exoskeletons can be a significant barrier to their widespread adoption.
- This critical issue affects the rightful distribution of benefits, as only certain companies or workers may be able to access this technology.

IV. **Inaccessibility**:

- Inaccessibility, whether due to physical limitations (such as size and fit) or logistical issues (such as availability), is extremely critical.
- It can lead to unequal opportunities for workers and potentially exacerbate existing inequalities in the workplace.

2. Critical Risks

I. **Design of Exoskeletons:**

- A well-designed exoskeleton is crucial for safety and comfort. Poor design can lead to ergonomic issues, discomfort, or even injuries, making it a critical risk.
- Ensuring that exoskeletons are designed with the user's physical needs in mind is essential to prevent harm.

II. **Lack of Trust:**

- Trust is fundamental for the adoption of new technologies.
- A lack of trust in exoskeletons can arise from concerns about their safety, reliability, or the intentions behind their deployment.
- Distrust in the technology can lead to resistance, reduced confidence, and lower productivity, making it a critical issue.

III. **Vulnerability to Accidents**:

- Mechanical failures or unexpected movements could lead to accidents.
- The potential for increased vulnerability to workplace accidents makes this a critical concern that needs to be addressed through proper training and safety protocols.

IV. **Need for Regulation**:

- The absence of clear regulations governing the use of exoskeletons can lead to inconsistent practices and potential exploitation of workers.
- Establishing regulations ensures that there are standards for safety, training, and ethical use, which is critical for protecting workers' rights and well-being.

V. **Loss of Privacy**:

- Exoskeletons often involve data collection to monitor performance and health metrics.
- This can raise significant privacy concerns if data is not handled transparently and securely.
- Protecting workers' privacy is critical to prevent misuse of data and to maintain trust.

VI. **Risk of Autonomy and Physical Restriction**:

- The use of exoskeletons may limit workers' autonomy, making them feel controlled or restricted by the technology. Additionally, physical restrictions imposed by the device can hinder natural movement, leading to discomfort or injury.
- These issues are critical as they directly affect the user's experience and well-being.

VII. **Mandating Use**:

- Forcing workers to use exoskeletons can create ethical and legal issues.
- The critical nature of this risk lies in the potential for violating personal choice and bodily autonomy.

VIII. **Misuse of Exoskeletons**:

- There is a risk that exoskeletons could be misused by workers, either intentionally (e.g., bypassing safety features) or unintentionally (e.g., incorrect usage).
- Misuse can lead to accidents or injuries, making it a critical concern that needs to be addressed through comprehensive training and supervision.

IX. Overworking exoskeleton users:

- The enhanced physical capabilities provided by exoskeletons may lead to workers being overworked.
- This is a critical issue as it can negate the intended benefits of exoskeletons and lead to adverse health effects.

3. Less Critical Risks

I. **Stigmatization**:

- While there is some concern that using exoskeletons may lead to stigmatization or negative perceptions, it is generally considered less critical. However, it can still impact worker morale and acceptance of the technology.

II. **Dehumanization**:

- The risk of dehumanizing workers by viewing them more as components of a machine rather than individuals is a concern, though it is less critical compared to others.
- It emphasizes the need for a human-centric approach to implementing technology.

III. **Job Insecurity and Displacement**:

- Although the potential for job insecurity and displacement due to exoskeletons may exist, it is considered a less critical issue.
- However, addressing these concerns is important to ensure a smooth transition and maintain worker confidence.

IV. **Impact on Physical Appearance**:

- Changes in physical appearance due to exoskeleton use are seen as a minor concern but can still affect worker self-esteem and perception.

V. **Violation of Worker Rights**:

- While less critical, there is a need to ensure that the implementation of exoskeletons does not infringe on workers' rights, including their right to refuse to use the technology.

VI. **Loss of Self-Identity**:

- The use of exoskeletons could lead to a loss of self-identity, as workers may feel more like machines than humans.
- This issue, while less critical, underscores the importance of considering the psychological impact of technology.

VII. **Discrimination**:

- The risk of discrimination, whether towards those who use or do not use exoskeletons, is a less critical but noteworthy concern.
- It can affect workplace dynamics and inclusivity.

VIII. **Loss of Social Communication**:

- Exoskeletons may impact social interactions among workers, potentially leading to reduced communication.
- This is considered a less critical issue but is important for maintaining a cohesive work environment.

IX. **Loss of Human Identity**:

- The loss of self-identity there is a concern about losing a sense of human identity due to reliance on exoskeletons.
- This is a less critical issue but warrants attention to ensure that technology serves to enhance rather than diminish the human experience.

IMPACTS OF ETHICAL AND SOCIAL RISKS ON THE IMPLEMENTATION OF EXOSKELETONS IN THE CONSTRUCTION INDUSTRY

The implementation of exoskeletons in the construction industry is a significant step towards improving worker efficiency and safety. However, the ethical and social risks associated with these technologies can profoundly impact their adoption and integration. However, it is crucial to evaluate the ethical and social risks associated with their use to ensure that these technologies are implemented responsibly and effectively. Table 9 outlines the severity of these ethical and social risks on its implementation in the construction industry.

Table 9: Ranked Impacts of Ethical and Social Risks on Exoskeletons' Implementation

Risks	**Impact of the risks on implementation**
Risk of losing human identity due to exoskeleton use	**Very High**
Workers' vulnerability to accidents from exoskeleton use	**Very High**
Prioritizing workers with preexisting health conditions	**Very High**
Lack of regulation policies	**Very High**
Exoskeleton-induced physical restriction	**Very High**
Potential misuse of exoskeletons	**High**
Design-related risks	**High**
Inaccessibility due to gender preference	**High**
Cost implications	**High**
Potential stigmatization of exoskeleton users	**High**
Autonomy risks, including mandatory use	**High**
Risk of inadequate maintenance	**Moderate**
Potential overworking of exoskeleton users	**Moderate**
Risks of exoskeleton users appearing robotic	**Moderate**
Perception of exoskeleton users as physically weak	**Moderate**
Weight of exoskeletons	**Low**
Workers' distrust in exoskeletons	**Low**
Workers' over-dependency on exoskeletons	**Low**

Detailed Explanation of the Impacts of Ethical and Social Risks on the Implementation of Exoskeletons:

1. Very High Impact Risks:

I. The most significant ethical and social risks are those related to losing human identity, potential accidents, health prioritization, lack of regulation, and physical restrictions imposed by exoskeletons.
II. These issues are critical as they directly affect worker safety, dignity, and the overall acceptability of the technology.
III. Addressing these risks is essential to prevent negative outcomes and ensure that exoskeletons are integrated in a way that respects workers' rights and safety.

1. **Loss of Human Identity:**
    - Exoskeletons may affect how workers perceive themselves and how they are perceived by others, raising concerns about dehumanization and the impact on workers' self-esteem.
2. **Accident Vulnerability:**
    - There is a potential risk of accidents due to potential failures or misuse of exoskeletons, emphasizing the need for rigorous safety protocols.
3. **Health Prioritization:**
    - Prioritizing workers with preexisting health conditions may result in masked and untreated health conditions.
4. **Regulation and Policy:**
    - The lack of clear regulations can lead to inconsistent use and potential misuse, underscoring the need for comprehensive guidelines.
5. **Physical Restriction:**
    - Exoskeletons may restrict natural movement, affecting workers' comfort and effectiveness.

2. High Impact Risks:

I. These include concerns related to misuse, design flaws, gender accessibility, cost, stigmatization, and autonomy.
II. Although slightly less critical than the very high risks, these issues still play a significant role in determining the successful adoption of exoskeletons.

1. **Misuse:**
    - The potential for misuse or unintended consequences of exoskeletons can impact their implementation in the construction industry.
2. **Design-Related Risks:**
    - Poor design can affect usability and comfort, impacting workers' willingness to use the technology.
3. **Gender Inaccessibility:**
    - Gender-specific designs can limit access and effectiveness, highlighting the need for inclusive design.
4. **Cost:**

- High costs can be a barrier to adoption, making it essential to justify the investment with clear benefits.

5. **Stigmatization:**
    - The risk of being stigmatized for using exoskeletons can affect workers' social interactions and acceptance.
6. **Autonomy Risks:**
    - Mandatory use and reduced autonomy can lead to dissatisfaction and impact the adoption in the construction industry.

3. Moderate Impact Risks:

I. Issues such as inadequate maintenance, overworking, robotic appearance, and perceptions of weakness are considered moderate.

II. These risks still need to be managed but are seen as less immediate compared to very high and high risks.

1. **Maintenance:**
    - Inadequate maintenance can affect the longevity and effectiveness of exoskeletons.
2. **Overworking:**
    - Prolonged use may lead to overworking, necessitating appropriate work schedules and breaks.
3. **Robotic Appearance:**
    - The appearance of exoskeletons might impact how workers will embrace the implementation of exoskeletons in the construction industry.
4. **Perception of Weakness:**
    - There is a risk that exoskeletons could be seen as a sign of physical weakness, which can impact workers' intention to use them.

4. Low Impact Risks:

I. Risks related to weight, distrust, and over-dependency are ranked lower.

II. While still relevant, these issues are considered less critical compared to the other categories.

1. **Weight:**
    - Excessive weight of exoskeletons can affect usability but is generally manageable with proper design.
2. **Distrust:**
    - Workers' distrust in exoskeletons can impact acceptance but can be mitigated through education and transparency.
3. **Over-Dependency:**
    - Concerns about becoming overly dependent on exoskeletons are important but can be addressed with proper training and usage guidelines.

In conclusion, the ethical and social risks associated with exoskeletons in the construction industry present significant challenges to their implementation. Addressing these risks thoughtfully is necessary to ensure that the benefits of exoskeleton technology are achieved without compromising worker's health, privacy, and safety.

EFFECTIVE STRATEGIES FOR MITIGATING THE ETHICAL AND SOCIAL RISKS OF EXOSKELETONS IN THE CONSTRUCTION INDUSTRY.

This section provides a comprehensive analysis of the ethical and social risks associated with the use of exoskeletons in the construction industry. The strategies outlined here are designed to mitigate these risks, ensuring that exoskeleton technology is implemented in a manner that is effective, inclusive, safe, and ethical. Table 10 presents a detailed list of identified ethical and social risks, along with corresponding strategies to address each risk.

Table 10: Effective strategies for mitigating ethical and social risks of exoskeletons

S/N	STRATEGIES	Effectiveness
A	**Gender Biased**	
1	Develop exoskeletons which suit various body types (one-size-fits-all exoskeletons)	**Effective**
2	Utilize lighter materials in designing exoskeletons while maintaining the strength of the exoskeleton.	**Effective**
3	Design exoskeletons with adjustable features for women.	**Effective**
5	Features for wide ranges of heights and weights	**Suggested**
6	Design for adjustability for all body types	**Suggested**
7	Design for different body types.	**Suggested**
8	Inclusive Design for all - Ergonomically customizable with continuous improvement and development	**Suggested**
B	**Weight of exoskeleton**	
1	Add adjustable features for a balanced weight distribution.	**Effective**
2	Use light-weight materials in designing exoskeletons while maintaining the exoskeleton's strength.	**Effective**
3	Use lighter power systems like advanced batteries for active exoskeletons	**Effective**
4	Ensure engineering/design maximizes ideal load points (like hips) most efficiently.	**Suggested**
C	**Movement restrictions risks**	
1	Design exoskeletons with ergonomic features to improve natural movement	**Effective**
2	Provide frequent training on the use of exoskeletons.	**Moderate**
3	Use feedback from users' movements to refine exoskeleton’s functionality.	**Effective**
4	Build in adjustments to get the correct fit	**Suggested**
D	**Feeling Like Robot**	

Table 10: Effective strategies for mitigating ethical and social risks of exoskeletons (continued)

S/N	STRATEGIES	Effectiveness
1	Incorporate user feedback in the design process.	**Effective**
2	Provide options of less robotic (soft) exoskeletons for users.	**Effective**
3	Provide frequent training on exoskeleton capabilities and limitations.	**Effective**
4	make them cool looking--iron man	**Suggested**
5	Make designers use also, then they can see first-hand how their designs are affecting eventual users of exoskeletons.	**Suggested**
E	**Overdependency on exoskeletons**	
1	Monitor and schedule the use of the exoskeleton	**Effective**
2	Provide frequent training on exoskeletons' capabilities and limitations	**Effective**
3	Provide a Platform for getting frequent feedback on the use of exoskeleton	**Effective**
4	provide an exercise option for users so muscles do not get lost from non-use when using exoskeleton.	**Suggested**
F	**Mandatory exoskeleton use**	
1	Providing frequent training on exoskeleton capabilities and limitations in mitigating risks	**Moderate**
2	Ensuring transparency in how technology is used and its impact on users	**Effective**
3	Obtaining users' consent for mitigating risks	**Effective**
4	Include in training: benefits to users of exoskeletons	**Suggested**
5	Don't make it mandatory, it's a tool to make work safer, easier, faster, more efficient.	**Suggested**
G	**Health Monitoring Sensors**	
1	Obtain consent from users.	**Effective**
2	Test exoskeletons extensively for accurate sensor data to avoid misinformation.	**Effective**
3	Educate workers on the benefits of health monitoring sensors for exoskeletons.	**Effective**
4	Ensure data is encrypted/not accessible to bad actors	**Suggested**
5	Be selective on what is being monitored and restrict it to needed items only.	**Suggested**
6	Provide comprehensive training	**Suggested**
H	**False sense of security risks**	
1	Provide a brief guide on the capabilities of exoskeletons before every use	**Effective**

Table 10: Effective strategies for mitigating ethical and social risks of exoskeletons (continued)

S/N	STRATEGIES	Effectiveness
2	Offer frequent training on the proper use of exoskeletons.	**Effective**
3	Set up feedback systems to identify and correct any user misconceptions	**Effective**
I	**Unauthorized access risks**	
1	Implement multi-factor authentication to ensure system access is limited to authorized users.	**Effective**
2	Regularly update software to guard against vulnerabilities.	**Effective**
3	Establish and enforce access control policies that restrict access to only necessary users.	**Effective**
J	**Misusing Exoskeleton users' data**	
1	Offering comprehensive training on proper usage in mitigating the Misuse of Exoskeleton users' data.	**Effective**
2	Establishing and communicating clear policies on acceptable uses in mitigating the misuse of Exoskeleton users' data	**Effective**
3	Strict access controls to authorized personnel only in mitigating the misuse of Exoskeleton users' data	**Effective**
K	**Perceived as physically weak**	
1	Providing frequent training on exoskeleton capabilities and limitations	**Effective**
2	Detailed user guides	**Effective**
3	Frequent feedback	**Effective**
4	Begin a cultural shift in construction.	**Suggested**
5	Incentivize the use of exoskeletons	**Suggested**
6	Incorporate exercise into discussion and provide for user weight training so they do not get weak.	**Suggested**
L	**Distrust in exoskeleton**	
1	Regularly sharing information about exoskeletons' impacts	**Effective**
2	Providing a Platform for getting frequent feedback on the use of exoskeleton	**Moderate**
3	Demonstrating exoskeletons' reliability through consistent testing	**Effective**
4	Show the benefits to use and be clear about potential negatives or limitations.	**Suggested**
M	**inaccessibility of exoskeletons**	

Table 10: Effective strategies for mitigating ethical and social risks of exoskeletons (continued)

S/N	STRATEGIES	Effectiveness
1	Developing one-size-fits-all exoskeletons	Effective
2	Including users with diverse abilities in design and testing	Effective
3	Offering customizable features	Effective
4	Ensuring cost is affordable	Suggested
N	**Prioritizing workers with pre-existing health conditions**	
1	Obtaining users' consent	Effective
2	Monitoring and scheduling the use of the exoskeleton	Effective
3	Providing frequent training on exoskeleton capabilities and limitations	Effective
4	Show how the system can help people be better regardless of their current physical condition.	Suggested
5	Get consent from a doctor if they have pre-existing conditions	Suggested
O	**Unaffordability of exoskeletons**	
1	Adopting cheaper and effective exoskeletons	Effective
2	Partnering with healthcare and government agencies	Effective
3	Partnering with exoskeleton manufacturers	Effective
4	Partner with rental companies	Suggested
5	Get the industry involved to solve direct problems in the workplace to make the workplace safer.	Suggested
6	Work with insurance companies for contractors.	Suggested

A comprehensive breakdown of various mitigation strategies designed to tackle these challenges:

Each strategy is meticulously detailed, highlighting key aspects and considerations to effectively address the specific risks identified.

A. Gender Bias

1. **Develop Exoskeletons for Various Body Types (One-Size-Fits-All)**
    - Ensure exoskeletons accommodate a wide range of body types.
    - Employ a one-size-fits-all type exoskeleton to provide various physical characteristics. This could involve adjustable components, such as straps and padding, or modular design elements that can be customized for fit.
2. **Utilize Lighter Materials While Maintaining Strength**

- Use lightweight yet strong materials to reduce the burden on the user without compromising the exoskeleton's durability, making it easier for individuals of different physical builds to use.

3. **Design Adjustable Features Specifically for Women**
    - Include adjustable settings to better fit female users.

B. Weight of Exoskeleton

4. **Add Adjustable Features for Balanced Weight Distribution**
    - Include adjustable features that allow users to customize weight distribution according to their comfort and needs.
5. **Use Lightweight Materials**
    - Use lightweight materials to minimize the physical load on users, maintaining strength and durability for prolonged use of exoskeletons.
6. **Use Lighter Power Systems Like Advanced Batteries**
    - Implement advanced, lighter power systems to enhance the usability and efficiency of active exoskeletons.
    - Lighter and more efficient power systems can be utilized with advancements in battery technology, reducing the exoskeleton's overall weight.

C. Feeling Like a Robot

7. **Incorporate User Feedback in Design**
    - Involve users in the design process to ensure the exoskeleton feels natural and less robotic.
8. **Provide Options for Less Robotic (Soft) Exoskeletons**
    - Provide less rigid, more flexible exoskeletons to enhance user comfort and natural movement.
9. **Provide Frequent Training on Exoskeleton Capabilities and Limitations**
    - Provide regular training sessions on the capabilities and limitations of exoskeletons to help users feel comfortable and safe.
    - Educating the user is critical in understanding how to effectively use the exoskeleton, what it can and cannot do, and how to avoid any discomfort associated with its use.

D. Health Monitoring Sensors

10. **Obtain Consent from Users**
    - Always obtain informed consent from users before implementing health monitoring systems.
11. **Test Exoskeletons for Accurate Sensor Data**
    - Accurate data collection is essential to prevent misinformation and ensure user safety. Hence, conduct thorough testing to ensure the accuracy of sensors and data collection to avoid misinformation.
12. **Educate Workers on the Benefits of Health Monitoring Sensors**
    - Regularly educate users about the advantages of health monitoring sensors in exoskeletons to ensure acceptance and trust.
    - Education helps users understand the value of health monitoring, such as preventing overexertion or identifying potential health issues early, which can lead to better user acceptance.

E. Overdependence on Exoskeletons

13. **Monitor and Schedule Exoskeleton Use**
    - Monitor and schedule the use of exoskeletons to prevent over-reliance and promote natural physical activity.
    - To prevent overdependence, which can lead to physical deconditioning, the importance of structured monitoring and scheduling needs to be addressed. This ensures users do not rely on the exoskeleton excessively and maintain their physical fitness.
14. **Provide Frequent Training on Capabilities and Limitations**
    - Provide comprehensive training on the capabilities and limitations of exoskeletons to manage user expectations.
15. **Provide a Platform for Frequent Feedback**
    - Establish platforms for continuous feedback from users to refine and improve the technology.

F. Movement Restrictions Risks

16. **Design Exoskeletons with Ergonomic Features**
    - Design exoskeletons with ergonomic features to support natural movement patterns and reduce physical strain.
17. **Provide Frequent Training**
    - Offer regular training on the proper use of exoskeletons to prevent misuse and maximize benefits.
18. **Use Feedback from Users' Movements to Refine Functionality**
    - Use feedback from users' movements to continually refine the exoskeleton's functionality and usage.

G. False Sense of Security Risks

19. **Provide a Brief Guide on Exoskeleton Capabilities Before Each Use**
    - Provide clear information on the capabilities and limitations of exoskeletons to all users before use, reducing the risk of misuse or overconfidence.
20. **Offer Frequent Training on Proper Use**
    - Emphasize the importance of using exoskeletons correctly through continuous training programs.
21. **Set Up Feedback Systems to Identify and Correct Misconceptions**
    - Implement systems to identify and correct any misconceptions users may have about the exoskeleton's capabilities.

H. Unauthorized Access Risks

22. **Implement Multi-Factor Authentication**
    - Implement multi-factor authentication to restrict access to authorized users only, to prevent unauthorized access to the exoskeleton's systems and data protecting user privacy and safety.
23. **Regularly Update Software to Guard Against Vulnerabilities**
    - Regularly update software up to date to protect against vulnerabilities, unauthorized access, and system failures.

24. **Establish and Enforce Access Control Policies**
    - Develop strict policies that limit access to essential personnel only, ensuring security and privacy.

I. Misusing Exoskeleton Users' Data

25. **Offer Comprehensive Training on Proper Data Usage**
    - Offer detailed training on data protection and proper usage to prevent the misuse of exoskeleton users' data.
26. **Establish and Communicate Clear Policies on Acceptable Data Uses**
    - Communicate clear policies on acceptable data use and the consequences of violations.
27. **Implement Strict Access Controls to Authorized Personnel Only**
    - Implement strict controls to limit data access to authorized personnel, protect user information and privacy.

J. Mandatory Exoskeleton Use

28. **Provide Frequent Training on Capabilities and Limitations**
    - Provide frequent training on how to mitigate risks associated with exoskeleton use.
29. **Ensure Transparency in Technology Use and Impact**
    - Ensure full transparency regarding how the technology is used and its impact on users.
30. **Obtain Users' Consent for Mitigating Risks**
    - Always seek informed consent from users before mandating the use of exoskeletons.

K. Perceived as Physically Weak

31. **Provide Frequent Training on Exoskeleton Capabilities and Limitations**
    - Train users on the capabilities and limitations of exoskeletons to counteract any perceptions of physical weakness and emphasize the device's role in augmenting their abilities.
32. **Detailed User Guides**
    - Provide comprehensive user guides that clearly explain how to use exoskeletons effectively and safely.
33. **Frequent Feedback**
    - Encourage and collect continuous feedback to improve user experience and address any issues promptly.

L. Distrust in Exoskeleton

34. **Regularly Share Information About Exoskeletons' Impacts**
    - Regularly update users on the impacts and benefits of exoskeletons.
    - Transparency about the benefits and limitations of exoskeletons can help build trust among users, ensuring they feel informed and secure.
35. **Provide a Platform for Frequent Feedback on Exoskeleton Use**
    - Establish platforms for users to provide feedback and share their experiences with exoskeletons.
36. **Demonstrate Exoskeletons' Reliability Through Consistent Testing**

- Demonstrate the reliability of exoskeletons through consistent and transparent testing processes.

M. Inaccessibility of Exoskeletons

37. **Develop One-Size-Fits-All Exoskeletons**
    - Develop exoskeletons that fit a wide range of users, including those with diverse abilities.
38. **Include Users with Diverse Abilities in Design and Testing**
    - Include users with various physical abilities in the design and testing phases, ensures that the exoskeletons meet diverse needs and are inclusive.
39. **Offer Customizable Features**
    - Offer customizable features to accommodate specific user needs and preferences.

N. Prioritizing Workers with Pre-Existing Health Conditions

40. **Obtain Users' Consent**
    - Obtain explicit consent from users before deploying exoskeleton technology, particularly for those with pre-existing health conditions.
    - Clearly communicate the potential benefits and risks associated with using the exoskeleton.
    - Ensure that users fully understand and agree to the terms of use.
41. **Monitor and Schedule Exoskeleton Use**
    - Implement a regular monitoring and scheduling system to track the usage of exoskeletons by workers with pre-existing health conditions. This includes setting appropriate usage limits to prevent overuse and scheduling regular check-ins to assess the user's health and comfort.
    - Adjust the use of the exoskeleton as necessary based on individual health assessments.
42. **Provide Frequent Training on Exoskeleton Capabilities and Limitations**
    - Provide ongoing training sessions for workers, emphasizing the specific capabilities and limitations of the exoskeleton. This training should be customized to address the unique needs and concerns of workers with pre-existing health conditions.
    - Focus on proper usage techniques, safety protocols, and what to do if discomfort or issues arise.
    - Regularly update this training as new information or technology becomes available.

O. Unaffordability of Exoskeletons

43. **Adopt Cheaper and Effective Exoskeletons**
    - Focus on developing cheaper yet effective exoskeleton solutions.
44. **Partner with Healthcare and Government Agencies**
    - Partner with healthcare and government agencies to make exoskeletons more accessible and affordable.
45. **Partner with Exoskeleton Manufacturers**
    - Partner with exoskeleton manufacturers to reduce costs while maintaining quality and safety standards.
46. **Partner with Exoskeleton Rental companies**
    - Partnering with companies that can rent out exoskeletons will immensely increase their availability and accessibility.

In summary, addressing the identified risks associated with the use of exoskeletons in the workplace requires a comprehensive and proactive approach. By implementing these strategies, construction companies can better manage the risks associated with exoskeleton use, ensuring the technology benefits all users safely and effectively. Moreover, special considerations are required and necessary for managing data privacy, ensuring accessibility, and supporting workers with pre-existing health conditions.

BARRIERS TO IMPLEMENTING MITIGATION STRATEGIES

It is essential to understand not just the strategies for mitigating related risks but also the barriers that may limit their efficient implementation.

- This section provides a detailed analysis of the potential obstacles encountered when deploying various mitigation strategies.
- These barriers are present in different risk types, including design risks, autonomy and privacy concerns, stigmatization and trust issues, and affordability and accessibility challenges.
- By examining these barriers, stakeholders can better prepare for and address these challenges, ensuring a smoother integration of exoskeletons into the construction sector.
- Table 11 provides a clearer understanding of the severity and nature of each barrier associated with the implementation of exoskeletons.

Table 11: Barriers to implementing the strategies for mitigating ethical and social risks of exoskeletons

Ethical and Social Risks	Strategies	Barriers to mitigating identified strategies
Design Risks	Custom Features	Significant costs, moderate resistance from users, notable regulatory challenges
	Less Robotic Exoskeleton Choices	Moderate costs, notable design knowledge limitations
	Lighter Power Systems	Very high costs, minimal restrictions from manufacturers
	Obtaining Consent	Minimal costs, considerable regulatory challenges
	User Training	Moderate costs, extensive resistance from users
	Using Lighter Materials	High costs, minimal manufacturer restrictions
Autonomy, Privacy, Stigmatization & Trust Risks	Data Privacy	Moderate design knowledge limitations, extensive data protection regulations
	Procuring Feedback	Moderate resistance from users, considerable lack of support systems
	Software Update	Moderate manufacturer restrictions, moderate data protection regulations
	Strict Access	Moderate costs, moderate design knowledge limitations
	Transparency on Exoskeleton's Impacts	Moderate design knowledge limitations, moderate data protection regulations
Affordability and Accessibility Risks	Monitoring Exoskeleton Use	Moderate time constraints, considerable lack of specialized expertise
	One-size-fits-all Exoskeleton	High costs, moderate lack of specialized expertise

Table 11: Barriers to implementing the strategies for mitigating ethical and social risks of exoskeletons (con't)

Ethical and Social Risks	Strategies	Barriers to mitigating identified strategies
	Partnering with Exoskeleton Manufacturers	High costs, significant delays in partnerships
	Partnering with Government Agencies	High costs, notable lack of motivation from external agencies

Detailed breakdown of the barriers to mitigating identified strategies across various risk categories, for a comprehensive understanding.

1. Design Risks

Design risks involve challenges related to the physical and functional design of exoskeletons, impacting their usability and effectiveness.

I. **Custom Features**:

a. High expenses are a significant barrier, as creating custom features tailored to specific needs increases costs.

b. Restrictions from users and pre-existing health and safety regulations also pose challenges, as there may be resistance from workers and regulatory hurdles to overcome.

II. **Less Robotic Exoskeleton Choices**:

a. High expenses and knowledge restrictions on exoskeleton design are major barriers.

b. Developing more natural exoskeletons often requires advanced technology, which is costly and complex to design.

III. **Lighter Power Systems**:

a. The development of lighter power systems can hindered by high expenses and restrictions from exoskeleton manufacturers.

b. Cutting-edge technology is required, leading to increased costs and limitations in manufacturing capabilities.

IV. **Obtaining Consent**:

a. High expenses and pre-existing health and safety regulations present significant barriers.

b. Ensuring user safety and obtaining consent can be complicated by regulatory requirements and associated costs.

V. **User Training**:

a. Time constraints and restrictions from users are major barriers.

b. Comprehensive training programs are time-consuming and may face resistance from workers unfamiliar with new technologies.

VI. **Using Lighter Materials**:

a. High expenses and restrictions from exoskeleton manufacturers are primary barriers.

b. Utilizing advanced, lighter materials can significantly increase production costs and may be limited by manufacturers' capabilities.

2. Autonomy, Privacy, Stigmatization & Trust Risks

These risks pertain to concerns over user autonomy, data privacy, stigmatization of exoskeleton users, and building trust in the technology.

I. **Data Privacy**:

a) Knowledge restrictions on exoskeleton designs and complex data protection regulations are key barriers.
b) Protecting user data while ensuring the exoskeleton functions effectively is challenging due to stringent data laws.

II. **Procuring Feedback**:

a) Restrictions from users and a lack of online support systems can make gathering user feedback difficult due to privacy concerns and inadequate support infrastructure.

III. **Software Update**:

a) Restrictions from exoskeleton manufacturers and complex data protection regulations can hinder regular software updates, which are crucial for security and functionality.

IV. **Strict Access**:

a) High expenses and knowledge restrictions on exoskeleton designs present barriers.

b) Implementing strict access controls can be expensive and may require specialized knowledge.

V. **Transparency on Exoskeleton Impacts**:

a) Knowledge restrictions on exoskeleton designs and complex data protection regulations are major barriers.

b) Ensuring transparency about the effects of exoskeletons requires overcoming information management and regulatory hurdles.

3. Affordability and Accessibility Risks

These risks focus on the economic and practical aspects of exoskeleton availability and usability in the construction industry.

I. **Monitoring Exoskeleton Use**:

a) Time constraints and lack of specialized expertise are significant barriers.

b) Constant supervision is required, which can be time-consuming and necessitate specialized skills.

II. **One-size-fits-all Exoskeleton**:

a) High costs and lack of specialized expertise are major barriers.

b) Developing a universal exoskeleton design is challenging due to varying worker needs and the associated costs.

III. **Partnering with Exoskeleton Manufacturers**:

a) High costs and slow-paced partnerships are significant barriers.

b) Collaboration with manufacturers can be expensive and slow, impacting the timely implementation of exoskeleton solutions.

IV. **Partnering with Government Agencies**:

a) High costs and lack of motivation from external agencies present major barriers.

b) Government partnerships can be crucial for funding and regulatory support, but they often face administrative delays and a lack of initiative.

CONCLUSION

As the construction industry continues to adopt technological advancements, exoskeletons present a promising opportunity to enhance worker performance and safety. However, their use brings with it a host of ethical and social considerations that must be addressed to ensure their adoption has a positive impact on the workforce. This guide has outlined the types of exoskeletons and their specific applications in construction and highlighted the potential ethical and social risks they pose to workers' health and safety. To mitigate these risks, it is crucial to implement effective strategies that prioritize worker health and safety while addressing ethical concerns. This includes adopting rigorous safety standards, ensuring comprehensive training, and adopting open communication between workers and management. Additionally, overcoming barriers such as cost, resistance to change, and the need for continuous monitoring will be essential to the successful integration of exoskeletons in construction. By addressing these challenges, the construction industry can benefit from exoskeletons. This will allow the advancement of a future in which technical innovation and ethical responsibility coexist, creating a safer and more equal working environment for everyone.

Appendix C:

Research Project Approval By Georgia Tech Institutional Review Board (IRB)

CONSENT FORM

Key Information for virtual boundaries: investigating ethical and social risks of exoskeletons in the construction industry:

Consent is being sought for research purposes, and your participation is voluntary. It is expected that the survey will last for approximately 10 minutes.There risks from participating in this survey are minimal.

There are no benefits to you from your taking part in this research. However, possible benefits to others include protecting workers from the risks of exoskeletons and facilitating the implementation of exoskeletons in the construction industry. This can help reduce injuries that occur at the workplace. There are no alternative procedures in this study.

What Am I Being Asked To Do?

You are being asked to be a volunteer in a research study. This page will give you key information to help you decide if you would like to participate. Your participation of voluntary. As you read, please feel free to ask any questions youmay have about the research.

What Is This Study About and What Procedures Will You be Asked to Follow?The purpose of this study is to investigate the ethical and social concerns and risks that exoskeletons may have on workers in the construction industry.

You will complete three rounds of the survey. The results from each round depend on the other. The survey will be done online through Qualtrics and willlast about 10 minutes.

Are There Any Risks or Discomforts you Might Experience by Being in this study?

The risks to you are minimal and no more than what is to be experienced ineveryday life when answering questions or engaging in conversations.

What Are the Reasons You Might Want to Volunteer For This Study?

You are not likely to benefit in any way from joining this study. However, yourparticipation in this study may assist us to understand how exoskeletons can help the construction industry. This can in turn, help to reduce Work-related injuries among construction workers.

Do You Have to Take Part in the This Study?

It is fully your decision if you wish to be in this study or not. If you choose not to participate, or choose to participate and later determine you no longer wishto, you will not lose any rights, services, or benefits as a result of your withdrawal. The study is completely voluntary.

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology

Project Title: virtual boundaries: investigating ethical and social risks ofexoskeletons in the construction industry

Investigators: *Omobolanle Ogunseiju, Ph.D. and Yong Kwon Cho, Ph.D.*

Protocol and Consent Title: Virtual Boundaries: Investigating Ethical and Social Risks of Exoskeletons in the Construction Industry *(Main 05/30/2023 v1)*

You are being asked to be a volunteer in a research study. You are encouragedto take your time in making your decision. Discuss this study with your friendsand family.

Purpose:

Wearable robots such as exoskeletons are now being explored as interventions that can increase workers' human strength and reduce stress in the muscles, tiredness, and discomfort. However, while exoskeletons have passed benefits assessments in standardized laboratory conditions, wearing exoskeletons can mean that our privacy, morals, and social barriers are intruded. This calls for a continual evaluation of the benefits against potential risks so that constructionworkers who will be end users of exoskeletons are protected.

In this research, we want to understand exoskeletons' ethical and social risks in the construction industry by investigating:

1. the ethical and social risks that influence the adoption and sustainable use of these exoskeletons;
2. the impact of the ethical and social risks on workers' health and safety;and
3. how we can be design exoskeleton, such that these risks are minimized,workers are protected, and adoption is facilitated.

To understand the ethical and social risks of exoskeletons for construction work,this study is designed to obtain your feedback and response.

We expect to enroll 50-60 people in this study.

Exclusion/Inclusion Criteria:

Because we are using the Delphi technique for this survey, only experts in the construction industry can be included as participants. So, at the beginning of the survey, some screening questions will help us determine your eligibility. a.Participants must be 18 years old or older. Participants must be located in the U.S. while participating in the study.

Procedures:

The purpose of this study is to explore how the ethical and social risks of exoskeletons in the construction industry. You will complete three rounds of surveys via Qualtrics. Each survey will last approximately 10 minutes and be administered at different times. After the first round of surveys, results will be analyzed, and based on the level of agreement with the ethical and social risks of exoskeletons, some risks will be eliminated from the pool. This will inform the second round of the survey, which is expected to also last for approximately10 minutes. The results from the second round will be analyzed, and based on the level of agreement, the third round of surveys will be updated before beingdistributed to you. The third round is also expected to last for approximately 10 minutes.

Risks or Discomforts:

The risks to you are minimal and no more than what is to be experienced ineveryday life when answering questions or engaging in conversations.

Benefits:

You are not likely to benefit in any way from joining this study. We hope thatwhat we learn will someday help us understand the ethical and social risks ofExoskeletons in the construction industry. This will help reduce the Work-related musculoskeletal disorders among the workers.

Compensation to You:

There is no compensation for participation.

Storing and Sharing your Information:

Your participation in this study is gratefully acknowledged. It is possible that your information/data will be enormously valuable for other research purposes.By signing below, you consent for your de-identified information/data to be stored by the researcher and to be shared with other researchers in future studies. If you agree to allow such future sharing and use, your identity will be completely separated from your information/data. Future researchers will not have a way to identify you. Any future research must be approved by an ethics committee before being undertaken.

Use of Photographs, Audio, or Video Recordings:

Only the investigators will have access to your email for sending survey links and surveyreminders. We will not be procuring any photograph, audio or video recordings of you during the survey.

Confidentiality:

The following procedures will be followed to keep your personal information confidential in this study: We will comply with any applicable laws and regulations regarding confidentiality. To protect your privacy, your records will

be kept under a code number rather than by email. Your records will be kept inlocked files. Unless you give specific consent, only study staff will be allowed tolook at them. Your email and any other fact that might point to you will not appear when the results of this study are presented or published.

Costs to You:

There are no costs to you, other than your time, for being in this study.

Questions about the Study:

If you have any questions about the study, you may contact Dr. Ogunseiju. Investigator at telephone (404-894-7102) or PrincipalInvestigator@omobolanle.gatech.edu.

Questions about Your Rights as a Research Participant:

- Your participation in this study is voluntary. You do not have to be in thisstudy if you don't want to be.
- You have the right to change your mind and leave the study at any timewithout giving any reason and without penalty.
- Any new information that may make you change your mind about beingin this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

If you have any questions about your rights as a research participant, you maycontact the Georgia Institute of Technology Office of Research Integrity Assurance at IRB@gatech.edu.

If you click I consent below, it means that you have read (or have had read toyou) the information given in this consent form, and you would like to be a volunteer in this study.

I consent

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Consent to Store and Share your Information:

[Insert signature line with clear options for subjects to agree or decline.]

"I agree that my de-identified information/data may be stored and shared for future,unspecified research.

I agree

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I do not allow my de-identified information/data to be stored and shared for future,unspecified research. These may only be used for this specific study.

I do not agree

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