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ETHICAL AND SOCIAL RISKS OF EXOSKELETON IN THE CONSTRUCTION INDUSTRY: A SYSTEMATIC LITERATURE REVIEW

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SUMMARY*: As exoskeletons gain traction in the construction industry, evaluating the ethical and social dimensions of exoskeletons and devising strategies to mitigate these risks becomes imperative. This review focuses on assessing the ethical and social risks associated with the integration of exoskeleton technology in construction, with a goal to enhance worker safety and well-being. Exploring both the potential benefits and challenges of exoskeleton usage, the paper underscores the importance of a balanced approach that reconciles technological advantages with ethical considerations. A systematic literature review was conducted to gather insights into the ethical and social aspects of incorporating exoskeletons in the construction industry. The research involved a comprehensive analysis of existing literature. While the study's background provides a comprehensive overview of the current state of exoskeleton usage in the global construction industry, this review reveals significant ethical and social concerns surrounding exoskeletons in construction. These include device design, stigmatization, regulatory standards, worker consent and autonomy, trust, potential job displacement, and data privacy. Social considerations include accessibility and affordability, human rights, cultural diversity, and social communication. Effectively addressing these risks requires the establishment of clear ethical guidelines, training, vigilant monitoring, compliance, public engagement, government intervention, and collaboration with researchers and industry stakeholders. While exoskeletons hold the potential to reduce musculoskeletal disorders and ergonomic risks, addressing ethical and social risks is paramount. Neglecting these aspects may impede the acceptance and adoption of exoskeletons, leading to risks such as misuse, decreased social communication, and job displacement. The study proposes a framework that offers insights for industry stakeholders and guides the ethical adoption of exoskeleton technology. A collective effort is necessary to ensure the responsible integration of exoskeletons, fostering a safer and more sustainable construction industry and optimizing their advantages while mitigating disparities and discrimination in the construction industry.*

KEYWORDS*: ethical risk, social risk, exoskeleton, systematic review, wearable robot, construction.*

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1. INTRODUCTION

The construction industry consistently ranks among industries with high fatality rates. Despite the Occupational Safety and Health Act of 1970 leading to a decline in worker deaths, in 2020, the private sector recorded 2.7 injuries for every 100 full-time workers and 3.4 fatalities per 100,000 workers (Khalid, 2022; OSHA, 2022; Shrestha et al.). Annually, there are 340 million occupational incidents worldwide, costing over $1.25 trillion. The persistently high rate of construction fatalities highlights the urgent need for improved safety measures (Morrissey et al., 2023) and innovations in the construction industry to reduce these fatalities. In addition to fatalities, the construction industry also struggles with a high incidence of work-related musculoskeletal disorders (WMSDs), as noted by Roy (Albers et al., 2005). Despite various safety measures (Albers et al., 2005), around 46% of construction workers experience a WMSD in their careers (Dong et al., 2019).

To tackle these issues, a range of methods, from ergonomic adjustments to devices assisting with heavy loads, have been explored (Choi et al., 2014; *NIOH*). Notably, wearable robots, especially exoskeletons, have emerged as potential game-changers (Wang et al., 2015). These devices, which provide body support through torque, are categorized into active exoskeletons, powered by external sources, and passive ones using mechanisms like springs for support (Antwi-Afari et al., 2021; de Looze et al., 2016; Gonsalves et al., 2023) They vary in design, catering to different parts of the body and ranging from soft, pliable forms to more rigid structures (de Looze et al., 2016; Gonsalves et al., 2023). The development of exoskeletons, originally aimed to assist differently abled workers in strenuous conditions, has seen significant advancements (Golabchi et al., 2023; van Sluijs et al., 2023). Their use has expanded from rehabilitation to fields like construction, enhancing worker safety and efficiency (Yang et al., 2019). Recent studies underscore the effectiveness of exoskeletons in construction, especially in providing passive lumbar support and reducing muscle strain during physically demanding tasks (Golabchi et al., 2023; van Sluijs et al., 2023). For example, Gonsalves et al. (2023) examined the interaction of concrete workers with these exoskeletons, noting improvements in work efficiency and ergonomic benefits. Kim et al. (2019) and Bennett et al. (2023) illustrated how these devices ease muscle and joint strain, while also reducing risks like falls at high altitudes, a common cause of construction accidents (Bennett, 2023; Kim et al., 2019). Exemplifying this progress, studies by Baldassarre et al. (2022); (Zhu et al., 2021) have highlighted exoskeletons' role in improving workers' stability, particularly in precarious environments like high-altitude construction sites (Baldassarre et al., 2022; Zhu et al., 2021). This technology not only aids in physical support but also contributes significantly to minimizing the occurrence of musculoskeletal injuries, thereby fostering a safer and more efficient workforce. As the scope of exoskeleton applications broadens, their potential to transform occupational health and safety standards across various industries becomes increasingly evident (Bennett, 2023; Kim et al., 2019).

The adoption of exoskeletons in the workplace, while heralding ergonomic benefits, brings with it a host of risks spanning from health and safety risks to ethical and social considerations. While studies such as Nnaji et al. (2023); Okpala and Nnaji (2023); Kim et al. (2019), and Cho et al. (2018) have highlighted several health and safety risks of exoskeletons, the ethical and social risks such as overdependency, loss of autonomy, and potential job displacement (de Looze et al., 2016; Hensel & Keil, 2019) are yet to be explored. Additionally, the need for new training and expertise introduces changes in worker interactions, which can alter workplace dynamics. Furthermore, the societal and ethical implications of using exoskeletons in construction have been identified as significant concerns, especially in the gap noted by Alemi et al. (2020); (Kim et al., 2019). These concerns are not just theoretical but are rooted in real-world dynamics (Baltrusch et al., 2021; Govaerts et al.); S. Gilotta (2018). Their studies underscore the complex interplay between individual choices and broader social contexts, emphasizing the potential for peer pressure and the difficulty of reconciling personal apprehensions with emerging workplace norms.

Moreover, the role of social influence in the adoption of new technologies like exoskeletons cannot be understated (Lee & Chung, 2022; Viswanath Venkatesh). Workers' decisions are not made in a vacuum but are heavily influenced by societal norms and peer perceptions. This is further complicated by ethical considerations related to safety, as discussed by Anwer et al. (2021); (Kim et al., 2019). Their research urges a cautious enthusiasm towards these technologies, emphasizing the importance of not overlooking potential risks in the rush to embrace innovation. Therefore, the integration of exoskeletons into the workplace is a multifaceted issue. It involves not only the technological and ergonomic aspects but also complex ethical and social considerations that must be carefully balanced to ensure a responsible and beneficial adoption of these technologies.

Thus, this paper conducts an in-depth systematic review of the ethical and social consequences of employing exoskeletons in construction. This research is essential to navigate the complex landscape of adopting such advanced technology. While there has been considerable focus on the technological and functional aspects of exoskeletons, the ethical and social dimensions within a construction setting remain underexplored. Given the transformative potential of exoskeletons in reshaping construction practices, investigating the ethical and social risks associated with their deployment becomes crucial. A deeper comprehension of these challenges will ensure that exoskeletons' adoption not only aligns with ethical norms but also addresses potential societal concerns. This study contributes to existing knowledge by offering one of the first systematic reviews that maps the ethical and social risks associated with exoskeletons in the construction industry, an area currently underrepresented in scholarly discourse. This paper provides a comprehensive foundation for informing ethical guidelines, policy development, and future research, tailored to the unique demands of construction environments. The insights provided to construction stakeholders, policymakers, and scholars offered a refined perspective, enabling well-informed choices and promoting more interdisciplinary studies on the integration of technology and ethics within the construction realm.

2. BACKGROUND OF THE STUDY

2.1 Overview of exoskeleton risks, findings, and industry applications

The integration of exoskeletons in construction, while holding promise for augmenting worker capabilities, introduces risks demanding careful consideration. Key concerns include health challenges, where extended use can lead to reduced muscle strength and strain due to extended exoskeleton usage among workers (Agarwal & Deshpande, 2019; Kim et al., 2019), and safety hazards due to device malfunctions (Olar et al., 2021; Sang Choi et al., 2022). Adaptation challenges, ethical considerations, and maintenance requirements further underscore the multifaceted risks associated with exoskeleton use in construction, (Maurice et al., 2018b). These findings collectively emphasize the necessity for proactive risk management strategies and comprehensive regulatory frameworks to harness the potential benefits of exoskeleton technology while addressing inherent challenges (Maurice et al., 2018b; Zhu et al., 2021).

Risk categories were defined based on frameworks from occupational ergonomics and technology ethics research, which classify risks into *technical/physical, psychological, ethical, social, legal,* and *organizational* dimensions (Berx et al., 2022). Technical/physical risks encompass biomechanical strain, musculoskeletal fatigue, and device malfunction; psychological risks include discomfort, stress, and dependency; while ethical and social risks involve autonomy, fairness, identity, and justice concerns; legal risks relate to liability and accountability issues; and organizational risks involve workforce adaptation and workload redistribution (Berx et al., 2022). Industries were categorized using standardized industry classification systems such as the US Census Bureau and the North American Industry Classification System (Beckhusen, 2020; NAICS, 2022), complemented by exoskeleton and robotics literature that distinguishes between healthcare, manufacturing, construction, and policy-related contexts (e.g., (Massardi, Briem, et al., 2023; Morgan et al., 2022; Ryalat et al., 2025)).

While extensive research has been conducted on the health and safety risks of exoskeletons (Table 1), studies addressing their ethical and social implications remain relatively limited. Previous studies have examined the ethical and social risks of exoskeletons in the health industry (Felzmann et al., 2020; Kapeller, Felzmann, et al., 2020; Nielsen et al., 2022a), while studies like Greenbaum (2016b) has analyzed these risks from the legal perspective. Moreover, Greenbaum (2016a) exploration of the ethical, legal, and social aspects of exoskeletons, complemented by Maurice et al. (2018b) broader focus on societal implications provides a foundational understanding of technology integration ethics. Adnan et al. (2012) perspective offers insights into human–technology interaction and workplace ethics relevant to construction. However, the exploration of these non-technical risks within the construction industry remains largely uncharted. Synthesizing these perspectives enables a holistic framework that situates construction within broader discourses on responsible technology integration and workforce well-being.

2.2 Research gaps and objectives

The overview in Table 1 reveals that while healthcare and manufacturing industries have identified exoskeletons' ethical and safety risks, construction remains critically underrepresented in discussions of non-technical risks. This absence of ethical and social analysis in construction-specific studies underscores an urgent need for further research and policy development that combines technical and safety challenges with social and ethics concerns. This study addresses the gap by offering one of the first systematic reviews that maps the ethical and social risks of exoskeletons specifically within the construction industry. Unlike previous studies that have primarily focused on the ethical and social risks of exoskeletons in healthcare and manufacturing industries, this work fills a significant gap by synthesizing construction-specific risks and proposing a conceptual framework tailored to guide responsible exoskeleton implementation in construction settings. This comprehensive synthesis seeks to cultivate robust ethical and social frameworks that are specifically tailored to address the distinct needs of the construction industry, facilitating the responsible integration of exoskeleton while effectively tackling industry-specific concerns. This study offers a more holistic understanding and facilitates informed decision-making regarding the adoption of exoskeletons in construction settings. Hence, this research aims to broaden the scope by exploring a range of ethical and social risks associated with exoskeletons. Furthermore, the study aims to present strategic proposals aimed at mitigating these multifaceted risks comprehensively and effectively. Achieving this goal will assist stakeholders, manufacturers, employers, and workers of exoskeletons by providing direction on the associated ethical and social risks with exoskeletons and possible strategies to mitigate the risk. To accomplish the research goal, this study aims to answer the following questions:

- RQ1: What ethical and social risks are associated with exoskeleton use in construction?
- RQ2: What are the strategies for mitigating exoskeletons' ethical and social risks?

Table 1: Overview of Exoskeleton Risks, Findings, and Industry Applications.

Industry	Risks category	Findings – Highlighted risks	References	Research Gaps
Manufacturing/ Industrial Settings	Physical ergonomics	Joint strain due to prolonged usage	(Maurice et al., 2018a; Zhu et al., 2021),	Prior studies focus on ergonomic and safety performance; no analysis of ethical or social implications.
Construction	Physical ergonomics, Safety Hazard	Reduced muscle strength over prolonged use, Potential accidents due to malfunction	(Akinloluwa Babalola, 2023; Bennett, 2023; Choi et al., 2022; Kim et al., 2019; Okpala & Nnaji, 2023; Wang et al., 2015)	Focus on physical discomfort only; no ethical or psychosocial analysis in construction contexts.
Healthcare	Technical, Ethical, Legal, and Social	Worker stress and discomfort; dependency, trust, and vulnerability; issues of autonomy, fairness, identity, and social justice; and broader ethical principles of beneficence and non-maleficence, vulnerability, and identity impact	(He Y, 2017; Massardi, Pinto-Fernandez, Babič, Dežman, Trošt, Grosu, Lefeber, Rodriguez, Bessler, Schaake, et al., 2023; Zelik et al., 2022)	Focused on clinical ethics and patient autonomy; lacks insights into worker-oriented ethical and social challenges.
Rehabilitation	Safety hazard	Discomfort or skin issues with exoskeleton use	(Adnan et al., 2012; Maurice et al., 2018b)	
Law / Standards / Policy	Ethical, Legal, and Social	Ethical: Dual use. Social: dependency, withdrawal, Ableness, and access. Legal: Lack of standardization, unclear accountability, Privacy, workers' rights, compensation, criminal tort, liability law	(Greenbaum, 2016a; Kapeller et al., 2021)	Conceptual discussions without applied frameworks for construction or workplace ethics.

2.3 Theoretical frameworks

This study employs two key theoretical frameworks to guide systematic literature review and the development of the resulting conceptual frameworks: the Four Principles of Biomedical Ethics and the Responsible Innovation Framework. The Four Principles of Biomedical Ethics and the Responsible Innovation (RI) were selected due to their relevance in assessing both the ethical considerations and broader social implications associated with technologies use. These frameworks provide a foundation for evaluating both individual, societal implications and the responsibilities of innovators and organizations deploying such technologies.

2.3.1 Four principles of biomedical ethics

The Four Principles of Biomedical Ethics are autonomy, beneficence, non-maleficence, and justice, originally proposed by (Beauchamp & Childress, 1994). It is a widely recognized framework for evaluating ethical issues in healthcare and is increasingly applied to technology ethics, particularly those involving for human-centered design and deployment (Beauchamp & Childress, 1994; Elendu et al., 2023). In the context of technology use, autonomy concerns the worker's right to make informed decisions about using assistive devices (Beauchamp, 2018; Lawrence, 2007), while beneficence relates to the intention of enhancing workers' health, safety and well being (Beauchamp, 2018; Lawrence, 2007), in terms of reducing fatigue and preventing musculoskeletal injuries. Conversely, non-maleficence emphasizes the obligation to avoid potential harm, such as unforeseen physical strain, dependency, or mental stress induced by technology adoption (Hutler et al., 2024). Justice addresses the equity in access and benefits to exoskeletons among various workers and organizational hierarchies (Beauchamp, 2018; Lawrence, 2007). This principle emphasizes the importance of carefully considering the potential risks associated with the deployment of these devices. For instance, failures in the accuracy or reliability of wearables can lead to misdiagnoses or inappropriate medical recommendations, thereby causing harm to patients (Hutler et al., 2024). Ethical guidelines suggest that developers must prioritize user safety by ensuring that devices are rigorously tested and validated before gaining widespread use (Bulboacă et al., 2017; Elendu et al., 2023; Elger, 2019). Adopting this framework in the present study enables a systematic categorization of risks and mitigation strategies in a way that aligns with normative ethical values. Similar applications of this framework have been explored in human-robot interaction ethics and wearable technology adoption in healthcare and industrial settings (Bulboacă et al., 2017; Elendu et al., 2023; Elger, 2019; van Kemenade, 2020).

2.3.2 Responsible innovation theoretical framework

The Responsible Innovation (RI) framework provides a complementary perspective on the socio-technical lens by emphasizing anticipation, reflexivity, inclusion, and responsiveness as key components of technology development processes (Stilgoe et al., 2020). RI principles, addresses social acceptability, equity in access, and unintended long-term consequences of exoskeleton use, thereby promoting ethically sustainable technological adoption (Salvini et al., 2019). According to Stilgoe et al. (2020) and Stahl and Coeckelbergh (2016), this framework extensively explain that anticipation involves exploring plausible futures and identifying potential risks and societal impacts of emerging technologies through foresight, scenario planning, and vision assessment (Stilgoe et al., 2020). Reflexivity emphasizes the need for researchers and institutions to critically examine their own assumptions, values, and roles in shaping innovation, often facilitated by multidisciplinary collaboration and ethical assessments (Salvini et al., 2019; Stilgoe et al., 2020). Inclusion promotes the engagement of diverse stakeholders, including lay publics, in shaping research and innovation trajectories, using participatory methods such as focus groups, citizen juries, and consensus conferences (Salvini et al., 2019). Finally, responsiveness reflects the ability of manufacturers, employers, and institutions to adapt policies, research agendas, and practices based on evolving knowledge, societal needs, and stakeholder feedback, through mechanisms like open access, regulatory adjustments, and strategic roadmaps (Salvini et al., 2019; Stilgoe et al., 2020). In terms of exoskeleton, these dimensions ensure that exoskeleton technologies are ethically aligned, socially acceptable, and responsive to the dynamic needs of the construction workforce. Similar applications of this framework have been explored in human-robot interaction ethics and adoption in healthcare settings (McBride & Stahl, 2014; Salvini et al., 2019; Stahl & Coeckelbergh, 2016).

3. METHOD

The research adopted a systematic literature review to thoroughly explore the ethical and social risks associated with exoskeletons in the construction industry. According to Pan (Pan et al., 2022), a systematic review is a meticulous process aimed at comprehensively exploring related research works. The review approach (illustrated in Figure 1) involved paper search and collection, screening, and selection, in which relevant articles were identified and analyzed. These steps are elaborated upon in the subsequent paragraphs. The profile of publications was scrutinized in terms of publication year, sources, and affiliations, offering valuable insights into the distribution and trends within the literature. This systematic approach, guided by well-defined inclusion and exclusion criteria, ensured the relevance of the selected articles to our research objectives. The synthesis and analysis of extracted data provided a nuanced understanding of the landscape surrounding ethical and social risks related to exoskeletons in construction.

3.1 Literature search and collection

This study employed a systematic literature review approach to identify and synthesize existing research on the ethical and social risks of exoskeletons. Google Scholar was used as the main web search and database platform to collect related academic research papers that were published up till August 2023. The search was executed directly in the database search interface using Boolean logic (AND, OR), and the document type included any peer-reviewed articles published between 2010 and 2023. The search logic focused on Title, Abstract, and Keywords, and the inclusion and exclusion criteria are detailed in Table 3. The search keywords ensured that the search results included at least one of the specified keywords in the title of the journal articles. Initially, the author used the keywords "Ethical" risks and "social" risks of "wearable robot" in the “construction industry” in Google Scholar. The keyword string was executed directly in the main search bar using the string in Table 2. However, the search only yielded 14 articles, and none of these 14 papers met the inclusion criteria, indicating a limited pool of relevant literature.

Following several trials of searches and modifications, the search sequences that combined either the ethical or social risk of the exoskeleton in the construction industry were limited. Consequently, the authors used the keywords "Ethical" risks and "social" risks of "exoskeleton" to expand the search. The articles obtained through the search were from 2010 to August 2023, amounting to 6,370 records. However, after applying the inclusion/exclusion criteria (Table 3) and conducting manual screening, a total of 46 studies across all fields met the criteria for detailed review. To ensure greater thoroughness, we expanded our search strategy by including broader and related keywords such as “challenges”, “AEC sector”, “AECO industry”, "wearable assistive devices", "wearable robotics", and "wearable devices". However, these additional search keywords return 21,300 studies. Manual screening by relevance does not return any new additional papers aside from the initial 46 used. Given the relatively smaller number of articles related to ethical and social risk in construction, we expanded the scope to include relevant studies from other industries, such as healthcare, industry, engineering, and policy, to build a more comprehensive foundation of ethical and social risks and mitigation strategies. The systematic literature review across other industries could still provide valuable insights and recommendations on the chosen topic of interest, with 46 peer-reviewed articles.

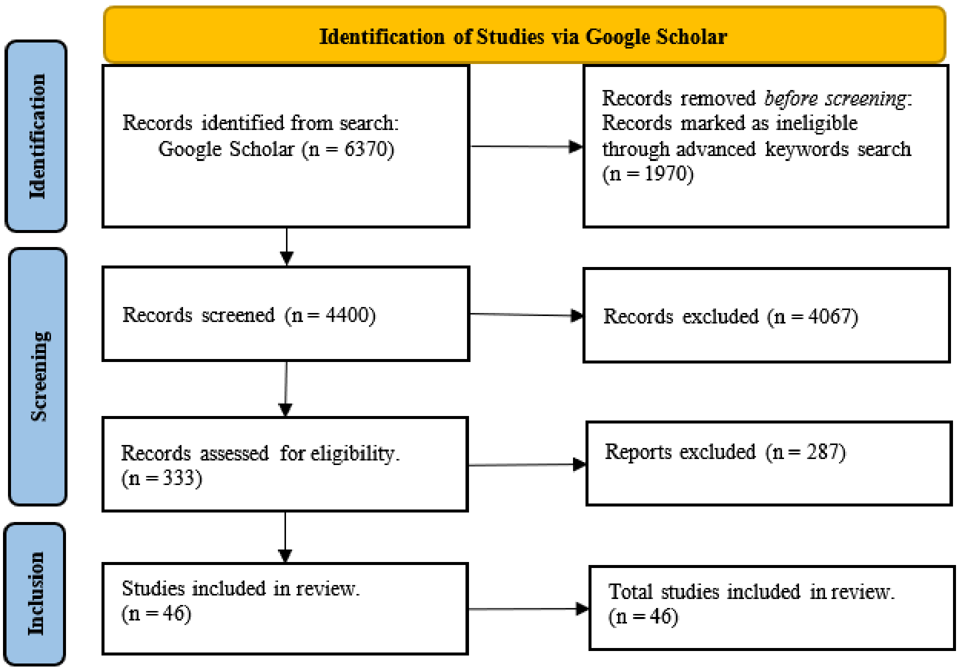

Figure 1: Flow diagram of literature search.

Table 2: Literature search results on Google Scholar.

S/N	SEARCH STRING WITH ADVANCED PARAMETERS (AND, OR)	NUMBER OF ARTICLES
1	"Ethical" OR "social") AND ("risk" OR "challenge" OR "concern" OR "implication" OR "limitation" OR "discomfort") AND ("exoskeleton" OR "wearable robot" OR "wearable assistive devices" OR "wearable robotics" OR "wearable devices") AND ("construction" OR "AEC sector" OR "AECO industry" OR "built environment"	21300
2.	"Ethical" risks and "social" risks of "exoskeleton"	6370
3.	"Ethical" “risk” and "social" “risk” of "exoskeleton"	4400
4.	"Ethical" "risk" of "exoskeleton" in the "construction" "industry"	1,540
5.	"Ethical" risks and "social" risks of "wearable robot"	333
6.	"Ethical" risks and "social" risks of "wearable robot" in “construction”	130
7.	"Ethical" risks and "social" risks of "exoskeleton" in “construction industry”	122
8.	"Ethical" risks and "social" risks of "wearable robots" in “construction industry”	14

3.2 Literature screening and selection

The screening process involved reviewing the articles’ titles, keywords, and abstracts while considering duplicates and relevance to the research topic. Articles unrelated to the research topic, without accessible full texts, and those whose contents were loosely related to the research subject were excluded from the review. The inclusion and exclusion of criteria defined in the review are shown in Table 3. After this initial screening process, a full-text reading was conducted on the remaining articles. From the screening, the author could not identify any related articles on the research topic in the construction field. With that, the author expanded the selection of articles to other fields, and as a result, 46 articles were deemed eligible for detailed review. Figure 1 displays an overview of the literature search framework.

Table 3: Inclusion and exclusion criteria for the systematic literature review.

CRITERIA	COMMENT
	INCLUSION
Non-construction industry related (NCIR)	The article is explicitly and specifically dedicated to research issues on the Ethical and social risks of exoskeletons and their mitigation strategies.
Closely related (CR)	NCIR-1: The article is not related to the construction industry but related to the exoskeleton
	NCIR-2: The article is particularly related to the construction field
	CR- The article is related to wearable robots, wearable devices, or wearable technology.
	EXCLUSION
Loosely related (LR)	NER- The article is related to ethical and social risks but not related to the exoskeleton.
Non exoskeleton related (NER)	LR-1: Exoskeleton in the construction industry is only used as an example.
	LR-2: Exoskeleton is only used as a part of the article’s future research area.
	LR-3: Research on exoskeleton without mentioning the key terms in the title, abstract, and keywords.
	LR-4: Research about exoskeletons generally used in the construction industry.

3.3 Data extraction

Each paper underwent a critical analysis, where data was extracted to address the research objective. For this study, two types of data were extracted for each article: general information for profile analysis and data for content analysis to address specific research questions. General information, including article title, keywords, abstract, publication year, and journal title, was collected to provide an overview of research on ethical and social risks associated with exoskeletons in the construction industry. To refine data extraction for specific research inquiries, articles were further categorized as follows:

- Review or survey articles, focusing on the comprehensive review or survey of ethical and social risks of exoskeletons.
- Discussion articles, emphasizing discussions on opportunities, challenges, potentials, and scenarios of ethical and social risks of exoskeletons without detailed technical solutions.
- Technical solution articles, concentrating on the development or application of detailed ethical and social risk solutions related to exoskeletons.

To ensure accuracy and minimize errors, biases, and inconsistencies, a double extraction process was implemented. This involved a thorough review by two research assistants, and their findings were compared to reconcile any discrepancies. Subsequently, all extracted data were organized and managed using Excel.

3.4 Data synthesis

This stage involves collating, summarizing, and cumulating the extracted data from the related research studies. In this research, the qualitative method was used to analyze the extracted data. The extracted data were first subjected to preliminary processes and checks to ensure data correctness, format consistency, and usability for data synthesis.

3.5 Literature analysis

This literature analysis aims to provide a deeper understanding of the landscape of research on ethical and social risks associated with exoskeletons in the construction industry, offering insights into publication trends. Using descriptive statistics, these articles were further categorized based on: (1) the publication year (Figure 2); (2) the distribution of the articles by authors' continent (Figure 3); (3) the distribution of the articles by authors' country (Figure 4); (4) the methodology adopted in articles (i.e., review or survey, discussion, technical solution (Table 3)); and (5) the distribution of article by industry application and research focus (Table 4). The descriptive literature analysis for Table 4 is to understand how prior studies have investigated ethical and social risks, which is a necessary component of the systematic review because it provides methodological transparency. Systematic reviews not only summarize findings but also examine how knowledge in the field has been generated, identify the strength and type of evidence available, reveal gaps in the current body of knowledge, and demonstrate rigor and reproducibility in the review process.. Figure 5 and Table 4 shows that the majority of the reviewed studies (17 out of 46) adopted a technical solution approach, while review papers also made up a significant portion (11), empirical methods such as interviews, surveys, and case studies were less common, suggesting a need for more user-centered and contextual research in this field. All collected data were sorted and analyzed using Microsoft Excel. The analysis of the bibliographic information of the synthesis articles was conducted in terms of year, country, and industry application. Accordingly, 46 articles were analyzed from the year 2010 to 2023 as shown in Figure 2. The chart shows a rise in the research trend of ethical and social risks of exoskeletons from 2015 till date.

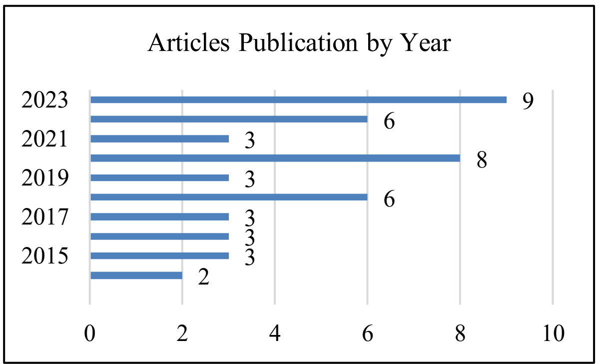

Figure 2: Articles by year of publication.

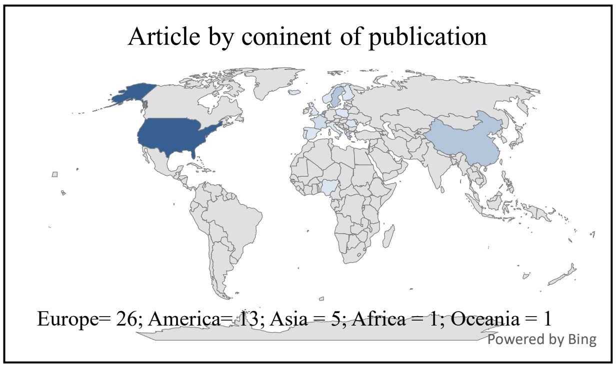

Figure 3: Articles by Continent of publication.

Figure 3 and Figure 4 show articles by continent and country of publication, respectively. The geographical analysis was done based on the countries of the authors. It was discovered that the United States has the highest research trend on ethical and social risks of exoskeletons, followed by the Netherlands, Sweden, and China. Based on the authors' distribution by continent, the research topic is more represented in America and Europe. Only the first authors were used for this analysis.

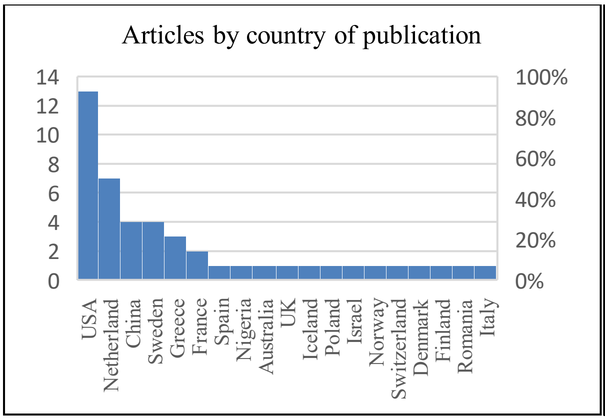

Figure 4: Articles by Country of publication.

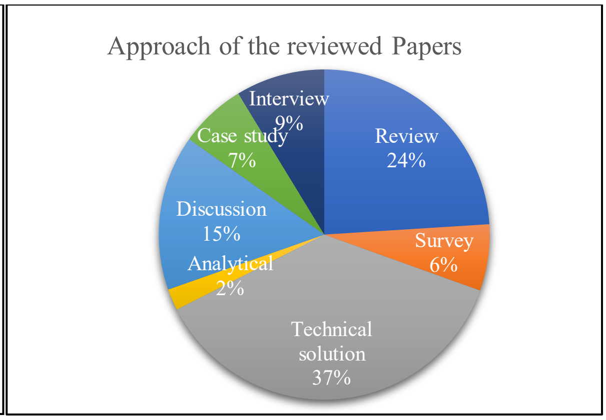

Figure 5: Article by research method.

3.5.1 Article distribution by industry

Articles were categorized into industry applications based on the primary focus and context described in the research objectives, methodology, or the use case presented. The classification of industry was defined according to standardized industry classification systems, such as the US Census Bureau and the North American Industry Classification System (Beckhusen, 2020; NAICS, 2022), complemented by categorizations in recent exoskeleton and robotics literature (e.g., (Massardi, Briem, et al., 2023; Morgan et al., 2022)).

Table 4: Article distribution by method.

Method/Approach	No. of Papers	References
Review	11	(Adeloye et al., 2023; Bulboacă et al., 2017; Felzmann et al., 2020; Fosch-Villaronga et al., 2023; Fosch-Villaronga et al., 2020; Guan et al.; Hill et al., 2017; Kapeller, Felzmann, et al., 2020; Khakurel et al., 2018; Lee, 2022; Nussbaum et al., 2019)
Survey	3	(Ármannsdóttir et al., 2020; Borenstein et al., 2018; Massardi, Pinto-Fernandez, Babič, Dežman, Trošt, Grosu, Lefeber, Rodriguez, Bessler, & Schaake, 2023)
Technical Solution	17	(Almpani et al., 2023; Bissolotti et al., 2018; Cawthorne, 2022; Dai & Zhou, 2023; Elger, 2019; Fosch-Villaronga & Drukarch, 2023; Gonsalves, 2023; Howard et al., 2020; International; Kapeller et al., 2021; Lowe et al., 2019; O'Sullivan et al., 2015; Pote, 2022; Robertson et al., 2019; Søraa & Fosch-Villaronga, 2020; Van der Vorm, 2015; Zafeirakopoulos et al., 2022)
Analytical	1	(Almpani et al., 2020)
Discussion	7	(De Looze et al., 2017; Greenbaum, 2016a; Li, 2021; Pote et al., 2023; Różańska-Walczuk, 2022; Sadowski, 2014; Zuboff, 2023)
Case study	3	(Fosch-Villaronga & Özcan, 2020; Kapeller, Nagenborg, et al., 2020; Matarić & Scassellati, 2016)
Interview	4	(Lin et al., 2023; Maurice et al., 2018a, 2018b; Popa et al., 2021)
Total	**46**	

For instance, where the application context was clearly stated, such as exoskeleton for rehabilitation, or an article from a computer science lab with industrial focus, or exoskeleton design for commercial, or exoskeleton for construction settings, then the article was assigned to that corresponding industry (e.g., Healthcare, Manufacturing Commercial, or Construction, respectively). For example, studies emphasizing ergonomics or repetitive task reduction in industrial settings were classified under *Manufacturing/Industrial*, whereas papers focused on health-related outcomes, rehabilitation, or assistive technology were assigned to *Healthcare*. Articles addressing broad technical design, robotic control, or system architecture without direct application were categorized under *Engineering*. Research centered on legal, regulatory, or policy frameworks was classified under *Law/Standards/Policy*. In cases where the industry application was not explicitly identified, categorization was based on the affiliation and disciplinary background of the first author as a secondary criterion. For instance, papers originating from legal or policy institutes were assigned to the *Law/Standards/Policy* category, while those from computer science or engineering faculties were categorized under *Engineering* unless otherwise specified. While some categories (e.g., “Manufacturing/Industrial”) were merged due to their overlapping practical contexts. The industry areas and their definitions are presented in Table 5.

Table 5: Article distribution by industry.

Industry	**Industry definition**	**Ethical and social risks**		**Mitigation Strategies**	
		References	No. of Papers	References	No. of Papers
Healthcare	Articles related to medical, therapeutic, and rehabilitative services aimed at health and well-being, including assistive and rehabilitative exoskeleton applications. (Morgan et al., 2022)	(Bissolotti et al., 2018; Borenstein et al., 2018; Bulboacă et al., 2017; De Looze et al., 2017; Elger, 2019; Fosch-Villaronga et al., 2020; Fosch-Villaronga & Özcan, 2020; Hill et al., 2017; Kapeller, Nagenborg, et al., 2020; Matarić & Scassellati, 2016; Popa et al., 2021; Sadowski, 2014; Søraa & Fosch-Villaronga, 2020)	13	(Ármannsdóttir et al., 2020; Bulboacă et al., 2017; De Looze et al., 2017; Fosch-Villaronga et al., 2020; Fosch-Villaronga & Özcan, 2020; Kapeller, Nagenborg, et al., 2020; Sadowski, 2014; Søraa & Fosch-Villaronga, 2020)	8
Manufacturing/ Industrial	Articles involving the mechanical, physical, or design of exoskeletons to be use in factories or warehouses, focusing on ergonomic support and repetitive task assistance.(GICS, 2020; ISIC, 2008)	(Dai & Zhou, 2023; Howard et al., 2020; Lee, 2022; Lin et al., 2023; Maurice et al., 2018b; Pote, 2022; Pote et al., 2023; Różańska-Walczuk, 2022)	8	(Guan et al.; Li, 2021; Robertson et al., 2019)	6
Engineering	Articles focus on the general design, development, and evaluation of its systems and processes, like robotic system architecture (ISIC, 2008)	(Almpani et al., 2020; Cawthorne, 2022; Guan et al.; Li, 2021; Massardi, Pinto-Fernandez, Babič, Dežman, Trošt, Grosu, Lefeber, Rodriguez, Bessler, & Schaake, 2023; Robertson et al., 2019)	6	(Almpani et al., 2023; Fosch-Villaronga et al., 2023; Fosch-Villaronga & Drukarch, 2023; International; Kapeller et al., 2021; Lowe et al., 2019; O'Sullivan et al., 2015; Van der Vorm, 2015; Zafeirakopoulos et al., 2022)	3
Law/ Standard/ Policy	Articles that focus on the development of regulatory frameworks, standards, ethical guidelines, and public policies governing technology design, deployment, and social impact. (Chatila et al., 2018)	(Felzmann et al., 2020; Fosch-Villaronga et al., 2023; Greenbaum, 2016a; Kapeller, Felzmann, et al., 2020; Zuboff, 2023)	5		9
Construction	Articles related to the construction of buildings and infrastructure, where exoskeletons assist in heavy lifting, overhead work, and dynamic, high-risk tasks. (Beckhusen, 2020)	(Gonsalves, 2023)	1	(Gonsalves, 2023)	1

Notes: Of the 46 articles reviewed, fourteen papers addressed both risks and proffered solutions, thirty-three papers focused on ethical and social aspects, and twenty-seven papers discussed mitigation strategies. Totals by industry may not equal 46 due to some articles being cross-categorized across industry applications.

The findings based on industry application of ethical and social risks of exoskeletons found in the literature (Table 5) show a higher research trend in the healthcare, manufacturing, and commercial industries, with limited construction. It is important to note that not all articles addressed both ethical/social risks and mitigation strategies. Some focused exclusively on identifying risks, while others proposed mitigation measures either independently or alongside a limited discussion of risks. As such, the total number of articles under each category (risks and mitigation strategies) does not necessarily match the total number of articles reviewed. Fourteen articles addressed both aspects, while thirty-three focused on ethical and social risks, and twenty-seven discussed mitigation strategies. This categorization approach highlights a gap in the literature, reinforcing the need for integrated studies that holistically address both risk identification and mitigation strategies. Due to the limited research in the construction industry, the author broadened their review to include articles from other industries to develop a thorough understanding of the ethical and social risks of exoskeletons and the strategies proposed to address them.

4. RESULTS AND DISCUSSION

This section presents an overview of the ethical and social risks of exoskeletons in the construction industry. Due to the limited research in the construction industry (as analyzed in Table 4), a broadened review of other industries was conducted in order to develop a thorough understanding of the ethical and social risks of exoskeletons and the strategies proposed to address them. Hence, to gain vast insights into these risks, a systematic review of literature from various industries, including construction, healthcare, industrial, and military settings, was conducted. Finally, a conceptual framework was proposed that serves as a foundational guide in addressing the ethical and social considerations surrounding the utilization of exoskeletons in the construction industry.

4.1 Overview of ethical and social risk of exoskeletons in the construction industry

The ethical and social risks of exoskeletons comprise a range of moral issues related to human beings and society. Ethical risks, as defined by Saner (2010) are those "actions, procedures, standards, policies and decisions that could represent a real or perceived violation of an ethical value or standard". Ethics play a significant role in engineering design, guiding important considerations about what is being built and why, as well as the implications for humans and the broader engineering community (Robertson et al., 2019). Social risks, on the other hand, focus on the dissemination, affordability, and accessibility of technologies (Robertson et al., 2019). Thus, integrating ethical and social factors into the design process not only facilitates market entry but also fosters trust and user acceptance of exoskeletons (Almpani et al., 2020; Ármannsdóttir et al., 2020; Hill et al., 2017). Likewise, examining the ethical and social risks associated with exoskeletons serves as foundational groundwork for engineers and designers to comply with the current and yet to be developed ethical guidelines (Kapeller et al., 2021). With the current implementation level of exoskeletons in the construction industry, this acceptance is crucial for widespread adoption, and successful implementation (Kapeller, Nagenborg, et al., 2020; Różańska-Walczuk, 2022). Tables 5 and 6 present findings from different scholars regarding ethical and social risks associated with exoskeletons and the strategies to mitigate them.

4.2 Ethical risks of exoskeleton in the construction industry

The ethical considerations presented in Table 5 were developed based on a thematic synthesis of ethical and social risks frequently discussed in the selected literature on exoskeleton use. Key studies (e.g., (Fosch-Villaronga et al., 2023; Fosch-Villaronga et al., 2020; Kapeller et al., 2021; Maurice et al., 2018a, 2018b) were analyzed to identify recurring concerns, which were then grouped under nine categories. Each category reflects a specific ethical category, such as user autonomy, data privacy, or system design. These categories were informed by literature on technology ethics and previous research in wearables and assistive technologies (Elendu et al., 2023; Holden & Duffy, 2023; Kapeller et al., 2021; Kendal, 2022; Maurice et al., 2018a; Nielsen et al., 2022b; Panel, 2021; Spuskanyuk; Tu & Gao, 2021; Uen, 2024). The categorization aligns with ethical principles such as beneficence, non-maleficence, autonomy, justice, and privacy, widely referenced in technology ethics literature (Bulboacă et al., 2017; Elger, 2019; Greenbaum, 2016a). Table 6, Table 7, and Table 8 reveal detailed reviews of extant studies on the ethical concerns of the exoskeleton, and they can be broadly classified into nine categories, including design, data protection, privacy, worker consent and autonomy, dehumanization, trust, stigmatization, vulnerability, and maintenance. These risks are often interrelated; for example, inadequate design can exacerbate maintenance issues, and data privacy concerns can influence worker trust and consent. These ethical concerns are discussed in the subsequent paragraph.

A brief explanation of each category is as follows: Design concerns how the physical and functional aspects of the exoskeleton affect users' comfort, capability, and identity; Privacy involves risks related to data collection, surveillance, and consent; Standards, Regulations, and Guidelines relates to the presence or absence of legal and ethical frameworks; Autonomy addresses the user's right to voluntary use and decision-making control; Trust captures social acceptance, transparency, and perceived fairness; Stigmatization involves potential for discrimination or misinterpretation of users; Vulnerability concerns the safety and protection of users in physically demanding or risky contexts; Dehumanization relates to loss of human agency or identity due to over-reliance on or misuse of the technology; Maintenance focuses on hygienic and technical upkeep affecting user health.

4.2.1 Risks associated with the design of exoskeletons

Inclusive and ergonomic design remains a critical ethical concern in exoskeletons. Research shows that the design of exoskeletons should consider ethical factors and the diverse needs of users in terms of body shapes, sizes, and genders (Fosch-Villaronga & Özcan, 2020; Pote, 2022). Unfortunately, exoskeleton engineers often prioritize other aspects of development over ensuring that these devices can accommodate a broad user base (Søraa & Fosch-Villaronga, 2020). It is essential to understand that the success of integrating exoskeleton technology into daily life depends not only on the device's weight but also on how well it fits the user's body (Pote, 2022; Søraa & Fosch-Villaronga, 2020). Studies note that failure to accommodate such differences can cause discomfort, limit movement, and result in muscle strain or overexertion, especially for workers engaged in physically demanding construction tasks (Gonsalves, 2023; Howard et al., 2020; Maurice et al., 2018a, 2018b; Pote et al., 2023). Also, the appearance and shape of the exoskeleton can impact user acceptance and usability. These risks can also impact workers' health and safety. For example, Maurice et al. (2018b) explained that the inappropriate design of exoskeletons could put additional strain on the user's body, leading to discomfort and potential limitations in movement.

4.2.2 Maintenance risk

The poor maintenance of exoskeletons can pose significant ethical considerations, particularly concerning the safety and well-being of users. For example, the use of exoskeletons requires cleaning and maintenance after use. Studies report that long-term use of an exoskeleton without disinfecting can cause skin irritation (Gonsalves, 2023; Howard et al., 2020). Howard et al. (2020) further stated that wearable devices could cause skin irritation or chemical burns if an exoskeleton battery leaks corrosive materials. Wearing some types of exoskeletons can result in increased chest pressure, pain, and muscle strain (Maurice et al., 2018a). These findings are particularly relevant in construction, where hygiene protocols may be difficult to maintain on active job sites. From an ethical perspective, organizations bear the responsibility to prioritize regular inspection, servicing, and repair of exoskeletons to safeguard the well-being of workers and mitigate associated risks.

4.2.3 Lack of standards, regulations, and guidelines

The literature highlights a lack of clear regulatory frameworks governing exoskeleton use (Fosch-Villaronga et al., 2023). This means that there is a need for clear regulations and accountability mechanisms for the use of exoskeletons. In construction, where safety is already a critical concern, such frameworks could play a vital role in promoting trust and widespread adoption. These involves ensuring that companies adhere to safety and ethical standards and are held accountable for any misuse or negligence is crucial (Maurice et al., 2018a). This will make a big step forward for people to trust new technologies. Without ethical standards, it will be difficult to gain universal trust and acceptance among the public (Pote et al., 2023; Różańska-Walczuk, 2022).

4.2.4 Data protection and privacy risk

Many exoskeletons are equipped with sensors and data collection mechanisms to monitor worker movements and health (Li, 2021; Lin et al., 2023), and wearing sensors on the body can raise confidentiality concerns due to discomfort and potential privacy issues. The data generated by these devices, such as user movement and biometric information, location information, and other private information relating to the user, can raise privacy concerns if not properly managed and protected (Fosch-Villaronga & Özcan, 2020; Zafeirakopoulos et al., 2022). Collecting and storing this data can cause data insecurity and unauthorized access, potentially compromising user data and safety (Maurice et al., 2018a). Workers should have a say in how their data is collected, used, and protected

(Cawthorne, 2022; Khakurel et al., 2018; Matarić & Scassellati, 2016). Maurice et al. (2018b) highlighted the risk of exoskeleton hacking, which could result in loss of control and potential tracking of employees' productivity through data manipulation.

Table 6: Ethical risks of exoskeleton: Design and Maintenance Concerns.

Category	Risk	Mitigation Strategy	Risk References	Strategies References
Design	Exoskeleton shape and body	Design for biomechanical fit for diverse users.	(Fosch-Villaronga et al., 2020; Kapeller et al., 2021; Pote, 2022; Søraa & Fosch-Villaronga, 2020)	(Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021; Nnaji et al., 2023; Pote, 2022)
	Human identity impact	Use aesthetic and customizable features	(Fosch-Villaronga & Özcan, 2020; Greenbaum, 2016b; Kapeller et al., 2021; Maurice et al., 2018a; Pote, 2022)	(Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021; Maurice et al., 2018a; Pote, 2022)
	Discomfort & Stress	Incorporate ergonomic features to reduce strain. Use lightweight, breathable materials	(Choi et al., 2022; Gonsalves, 2023; Howard et al., 2020; Maurice et al., 2018a; Pote et al., 2023)	(Gonsalves, 2023; Maurice et al., 2018a; Nnaji et al., 2023; Pote, 2022; Pote et al., 2023; Søraa & Fosch-Villaronga, 2020)
	Gender bias	Ensure gender-inclusive fit and sizing	(Fosch-Villaronga et al., 2020; Fosch-Villaronga & Drukarch, 2023; Pote, 2022)	(Dai & Zhou, 2023; Fosch-Villaronga et al., 2023; Fosch-Villaronga & Özcan, 2020)
	Functional capability	Equip devices with multi-functional adjustable control buttons.	(Fosch-Villaronga et al., 2023; Fosch-Villaronga & Drukarch, 2023; Maurice et al., 2018a)	(Maurice et al., 2018a; Pote et al., 2023)
	Overexertion	Enable self-adjustment, with real-time feedback sensors	(Fosch-Villaronga & Özcan, 2020; Gonsalves, 2023; Maurice et al., 2018a)	(Maurice et al., 2018a)
	Movement restriction	Develop lightweight, flexible exoskeletons	(Fosch-Villaronga et al., 2023; Maurice et al., 2018a; Pote, 2022; Pote et al., 2023)	(Fosch-Villaronga et al., 2023; Maurice et al., 2018a; Pote et al., 2023)
	Muscle strain/atrophy	Add variable support modes and limit prolonged reliance	(Fosch-Villaronga & Özcan, 2020; Maurice et al., 2018a)	(Maurice et al., 2018a; Pote et al., 2023)
Maintenance	Skin irritation	Train workers on safe use and hygiene	(Gonsalves, 2023; Howard et al., 2020; Popa et al., 2021; Pote et al., 2023; Sang Choi et al., 2022)	(Howard et al., 2020; Lowe et al., 2019; Nnaji et al., 2023; Pote et al., 2023)
	Contagious disease	Implement cleaning/disinfection protocols	(Gonsalves, 2023)Gonsalves, 2023; Maurice et al., 2018a	(International; Lowe et al., 2019; Nnaji et al., 2023; Pote et al., 2023)

4.2.5 Worker consent and autonomy

A recurring concern in the literature is the potential that workers may feel obliged to use exoskeletons, even if they have concerns about the technology's safety or comfort (Bissolotti et al., 2018; Bulboacă et al., 2017). Employers should ensure that workers have a choice in using exoskeletons and that their consent is freely given (Elger, 2019). Workers should not be coerced into using technology that they are uncomfortable with (Khakurel et al., 2018; Matarić & Scassellati, 2016; Nussbaum et al., 2019; Pote et al., 2023). Mandating the use of exoskeletons without considering individual preferences, physical conditions, or ethical concerns may lead to resistance, dissatisfaction, and potential negative consequences for users (Pote, 2022). Kapeller et al. (2021) also argued that mandating the use of wearable exoskeletons by workers might be driven more by financial motives, potentially serving as a means of control and subjugation, rather than a genuine effort to enhance the health and well-being of employees (Nussbaum et al., 2019). According to Maurice et al. (2018b), If workers lack direct control over the robot, they will be hesitant to delegate their technical tasks to it. Construction firms must foster participatory adoption processes where workers' input shapes technology integration, safeguarding autonomy concerns.

Table 7: Ethical Risks of Exoskeletons: Privacy, Autonomy, and the Absence of Standards and Regulatory Frameworks.

Category	Risk	Mitigation Strategy	Risk References	Strategies References
Lack of Standards, Regulation and Guidelines	Responsibility	Develop ethical use guidelines. Enforce justice and governance. Law governing manufacturers, employers, and employees of exoskeletons. Safe and transparent device	(Fosch-Villaronga et al., 2023; Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021; Maurice et al., 2018a)	(Almpani et al., 2020; International; Kapeller et al., 2021; Li, 2021; Maurice et al., 2018a)
	Misconduct	Enforce strict adherence to laws Explicit fines or penalties for violators	(Almpani et al., 2023; Elger, 2019; Pote et al., 2023)	(Elger, 2019; Li, 2021; Maurice et al., 2018a; Nnaji et al., 2023)
	Incompliance	Monitoring and legal compliance, Justice and good governance for users Accountability Non-maleficence & Beneficence	(Greenbaum, 2016b; Kapeller et al., 2021; Li, 2021; Nussbaum et al., 2019; Zafeirakopoulos et al., 2022)	(International; Kapeller et al., 2021; Pote et al., 2023; Różańska-Walczuk, 2022)
Privacy	False sense of security	Educate users on the limitations of data systems	(Fosch-Villaronga et al., 2023; Fosch-Villaronga et al., 2020; Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021)	(Maurice et al., 2018a)
	Unauthorized access	Enforce informed consent and strict authentication protocols	(Maurice et al., 2018a; Zafeirakopoulos et al., 2022)	(International; Lowe et al., 2019; Pote et al., 2023)
	Data insecurity	Implement robust data protection and access controls	(Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021; Li, 2021; Lin et al., 2023; Maurice et al., 2018a; Zafeirakopoulos et al., 2022)	(International; Kapeller et al., 2021; Lowe et al., 2019)
	Tracking workers' data	Informed consent with transparent data use disclosure	(Cawthorne, 2022; Khakurel et al., 2018; Lee, 2022; Matarić & Scassellati, 2016)	(Maurice et al., 2018a; Pote et al., 2023)
Autonomy	Employer autonomy	Empower workers with informed, voluntary use choices	(Elger, 2019; Kapeller et al., 2021; Nussbaum et al., 2019; Pote, 2022)	(Li, 2021; Pote et al., 2023)
	Misuse	Limit employer control and safeguard user rights	(Kapeller et al., 2021; Khakurel et al., 2018)	(Greenbaum, 2016b; Lee & Chung, 2022; Lee, 2022; Maurice et al., 2018a)
	Limited user control	User authority to control or deactivate within safe limits	(Guan et al., 2022; Maurice et al., 2018a; Pote, 2022)	(Lin et al., 2023; Maurice et al., 2018a)
	Mandatory use	Prohibit obligatory use without consent	(Kapeller et al., 2021; Pote, 2022)	(Maurice et al., 2018a; Pote et al., 2023)

4.2.6 Level of trust

Studies show that the implicit trust placed in the seamless collaboration between humans and exoskeletons could potentially lead to complacency and diminished awareness of safety protocols (Kapeller et al., 2021). Misplaced trust in technology without adequate training can lead to errors or accidents (Borenstein et al., 2018; Fosch-Villaronga et al., 2020). It is important to address this issue and ensure that there are safeguards in place to prevent any misuse or abuse of exoskeleton technology (Fosch-Villaronga et al., 2023). Additionally, transparency in communicating both benefits and limitations is critical to building realistic expectations and ensuring responsible use, particularly on construction sites where precision and safety are paramount.

4.2.7 Risk of dehumanization

The literature suggests that workers using exoskeletons risk being perceived more as tools than as individuals (Cawthorne, 2022; Greenbaum, 2016b). Like any technology, exoskeletons could be misused. For example, they could be used to enhance human abilities in ways that give certain individuals an unfair advantage, such as in sports or military applications (Greenbaum, 2016b). This could cause a risk of dehumanizing workers. In the case of the construction industry, the use of exoskeletons in areas requiring heavy repetitive lifting, managers and others overseeing the workers may overlook the human components and needs of their workers, seeing them only for their enhanced mechanical abilities that the exoskeletons provide. Ethical deployment must include training and awareness to maintain dignity and promote human-centered integration (Cawthorne, 2022; Pote et al., 2023).

Table 8: Ethical Risks of Exoskeletons: Trust, Stigmatization, Vulnerability, and Dehumanization Concerns.

Category	Risk	Mitigation Strategy	Risk References	Strategies References
Trust	Acceptance	Education & awareness programs	(Borenstein et al., 2018; Fosch-Villaronga et al., 2020; Kapeller et al., 2021)	(Kapeller et al., 2021; Nussbaum et al., 2019)
	Equity	Equitable access to tech & training Multi-stakeholder engagement	(Kapeller et al., 2021; Maurice et al., 2018a)	(Kapeller et al., 2021; Maurice et al., 2018a)
	Distrust	Transparent benefit–risk communication	(Borenstein et al., 2018; Fosch-Villaronga et al., 2023; Kapeller et al., 2021; Maurice et al., 2018a; Pote et al., 2023)	(Dai & Zhou, 2023; Maurice et al., 2018a)
	False interest in usage	Clear benefit–risk messaging & user control Strengthen user control & accountability	(Elger, 2019)	(Elger, 2019; Maurice et al., 2018a)
Dehumanization	Human identity impact	Ethical guidelines for human dignity	(Greenbaum, 2016b; Kapeller et al., 2021; Maurice et al., 2018a; Pote et al., 2023)	(Cawthorne, 2022; Maurice et al., 2018a; Pote et al., 2023)
	Social interaction	Ethical implementation standards	(Cawthorne, 2022; Zhu et al., 2021)	(Maurice et al., 2018a)
Stigmatization	Discrimination	Public & workplace awareness campaigns	(Kapeller et al., 2021; Maurice et al., 2018a; Uen, 2024)	(Kapeller et al., 2021; Maurice et al., 2018a; Nussbaum et al., 2019)
	Misinterpretation	Worker–supervisor education on Exo use	(Kapeller et al., 2021; Maurice et al., 2018a)	(Kapeller et al., 2021; Maurice et al., 2018a; Nussbaum et al., 2019)
Vulnerability	Harm	Routine inspections & safety training	(De Looze et al., 2017; Fosch-Villaronga et al., 2023; Fosch-Villaronga & Özcan, 2020; Kapeller et al., 2021; Maurice et al., 2018a; Popa et al., 2021)	(International; Lowe et al., 2019; Maurice et al., 2018a)

4.2.8 Risk of stigmatization

While exoskeletons hold immense potential to enhance the safety of construction workers, they often face several misconceptions and biases (Kapeller, Nagenborg, et al., 2020; Lin et al., 2023; Uen, 2024). Some studies highlight how exoskeleton users may be unfairly labeled as weak or dependent (Maurice et al., 2018a; Panel, 2021). Studies shows that people perceive exoskeleton users as "less capable" or "dependent" on machines, inadvertently stigmatizing them (Maurice et al., 2018a). This negative perception can hinder the widespread adoption of exoskeletons and deter individuals from seeking the assistance they need. It's crucial to mitigate the stigma challenge and foster a more inclusive perspective on exoskeletons by promoting public awareness, education, and training (Maurice et al., 2018a).

4.2.9 Vulnerability risk

There are concerns about the protection and safety of exoskeletons, both for the users and those around them (Fosch-Villaronga et al., 2023). Studies show that users may become vulnerable to overreliance on the exoskeleton, leading to potential muscle atrophy or loss of natural physical strength (Fosch-Villaronga & Özcan, 2020). Moreover, if a technical malfunction occurs and causes harm, questions of liability and responsibility arise (De Looze et al., 2017; Fosch-Villaronga & Özcan, 2020; Maurice et al., 2018a). In construction, where the environment is unpredictable, such overreliance can have severe consequences. especially when workers rely on this technology for their safety, potentially leading to complacency or a false sense of security. Ensuring that exoskeletons are rigorously tested and reliable is essential to address this concern (Popa et al., 2021; Różańska-Walczuk, 2022).

4.3 Social risks of exoskeletons in the construction industry

Social considerations in the construction industry include the assessment of an employer's engagement with its workers, customers, suppliers, and the local community (network). These social factors (as shown in Table 9) include human rights, diversity and inclusion, public awareness, and community impact (network). Inattention to these factors can lead to accessibility risk, acceptance risk, affordability risk, job security, trust deficiency, cultural prejudice, and bias (Greenbaum, 2016b; Lee, 2022). By addressing these social concerns and fostering equitable access, affordable pricing, and cultural sensitivity, the construction industry can leverage exoskeleton technology while minimizing potential disparities and discrimination.

4.3.1 Accessibility and affordability risks

A consistent concern across the literature is the economic inaccessibility of exoskeletons for small firms and low-income workers. While exoskeletons offer significant potential to reduce injury and improve performance, they are currently expensive, and not all workers or companies may have equal access to this technology (Fosch-Villaronga et al., 2020; Pote, 2022). This can create disparities in the industry, potentially favoring larger companies or more financially well-off workers (Greenbaum, 2016b). While exoskeletons can provide mobility and independence for some users, they may also exacerbate social disparities if not made accessible and affordable to all who could benefit from them. (Li, 2021). This could lead to discrimination and inequality. Some articles noted that the price range of exoskeletons varies between US$5,000 and US$70,0000 (Charts; Limakatso, 2023). This poses a challenge for smaller subcontractors and firms in the construction industry (Pote et al., 2023; Søraa & Fosch-Villaronga, 2020). This suggests that without proactive policy or design interventions, such as determining the cost incurred and return on investment is crucial in deciding whether to invest in wearable technologies. Some authors remain optimistic that increasing demand and broader market uptake will drive down costs over time (Adeloye et al., 2023); that is, as these technologies become more prevalent, prices are expected to decrease, making them more affordable for smaller firms (Adeloye et al., 2023).

4.3.2 Job displacement

Several studies caution that while exoskeletons aim to augment human labor, their unintended consequence may be job displacement, particularly among manual laborers (Khakurel et al., 2018; Lin et al., 2023). This suggests that there is a risk that they could lead to job displacement in the construction industry. While exoskeletons can improve productivity, safety, and efficiency, they might contribute to worker obsolescence if companies opt to reduce labor in favor of technology (Matarić & Scassellati, 2016). This raises social concerns about the impact on workers' livelihoods and job security. Companies adopting exoskeletons should consider workforce development and retraining programs to mitigate these concerns (Khakurel et al., 2018; Lin et al., 2023; Matarić & Scassellati, 2016).

4.3.3 Risks of Overdependence

A growing body of research raises concern over the risk that people could become overly reliant on exoskeletons, leading to a decrease in their physical capabilities (Pote, 2022). Most especially if they're used for rehabilitation or mobility assistance. This overreliance could potentially lead to a decline in their natural physical abilities. This could potentially lead to physical or psychological issues, causing a long-term consequences for users' health and fitness, user engagement, attachment, perception, and personification of the exoskeleton (Matarić & Scassellati, 2016). Kapeller et al. (2021) warn that increased efficiency through wearables may prompt employers to raise performance expectations, inadvertently intensifying workloads. This could lead to physical overexertion or chronic fatigue, negating the very benefits exoskeletons were meant to provide. For example, suppose workers become more efficient owing to exoskeleton use. In that case, employers may raise task performance targets instead of taking a holistic approach that considers the broader effects of intensified work practices on the well-being of their workforce (Kapeller et al., 2021).

Table 9: Social risks of exoskeleton in construction.

Social Consideration	Associated Risk	Mitigation Strategy	Risks References	Strategy References
Accessibility	Accessibility	Promote equitable access for all workers.	(Fosch-Villaronga et al., 2020; Lee, 2022; Pote, 2022)	(Fosch-Villaronga et al., 2020; Kapeller et al., 2021; Lee, 2022)
	Inequality	Develop fair access policies.	(Greenbaum, 2016b; Kapeller et al., 2021)	(Greenbaum, 2016b; Kapeller et al., 2021)
	Bias	Design for user diversity. Ensure inclusive training protocols.	(Fosch-Villaronga et al., 2020; Søraa & Fosch-Villaronga, 2020)	(Greenbaum, 2016b; Li, 2021)
Affordability	High cost	Use affordable, locally sourced designs.	(Fosch-Villaronga et al., 2020; Greenbaum, 2016b; Pote, 2022)	(Gonsalves, 2023; Greenbaum, 2016b)
	Affordability	Support multiple producers to reduce cost.	(Kapeller et al., 2021; Lee & Chung, 2022)	(Gonsalves, 2023; Lee, 2022)
Job Displacement	Job insecurity	Establish training and reskilling.	(Khakurel et al., 2018; Lin et al., 2023; Matarić & Scassellati, 2016)	(Khakurel et al., 2018; Lin et al., 2023; Lowe et al., 2019)
	Fear of losing jobs	Support workforce development. Promote awareness on assistive purpose.	(Khakurel et al., 2018; Matarić & Scassellati, 2016; Maurice et al., 2018a, 2018b; Pote et al., 2023)	(Matarić & Scassellati, 2016; Maurice et al., 2018a; Pote et al., 2023)
Dependence	Overly reliant	Educate users; prevent overreliance.	(Kapeller, Nagenborg, et al., 2020; Pote, 2022)	(Lowe et al., 2019; Maurice et al., 2018a)
	Lost trust in physical capabilities	Educate users.	(Kapeller et al., 2021; Pote, 2022)	(Lee, 2022; Maurice et al., 2018a)
	Over engagement	Train users; introduce rest cycles.	(Kapeller, Felzmann, et al., 2020; Kapeller et al., 2021)	(Kapeller et al., 2021)
	Personification as PPE	Explain device limits and functions.	(Kapeller, Felzmann, et al., 2020; Matarić & Scassellati, 2016)	(Maurice et al., 2018a)
	Misuse	Regular training, guidelines, and audits.	(Greenbaum, 2016b; Matarić & Scassellati, 2016; Maurice et al., 2018a)	(International; Lowe et al., 2019; Maurice et al., 2018a)
Cultural and Inclusion	Ethnicity	Promote inclusive design and use.	(Fosch-Villaronga et al., 2020; Søraa & Fosch-Villaronga, 2020)	(Nussbaum et al., 2019; Søraa & Fosch-Villaronga, 2020)
	Cultural belief	Host user awareness sessions.	(Fosch-Villaronga et al., 2020; Søraa & Fosch-Villaronga, 2020)	(Maurice et al., 2018a; Nussbaum et al., 2019)
	Varying levels of acceptance	Design bias-free models. Explain exoskeleton limitations.	(Nussbaum et al., 2019; Søraa & Fosch-Villaronga, 2020)	(Maurice et al., 2018a; Nussbaum et al., 2019)
	Discrimination	Develop standard workplace policies.	(Fosch-Villaronga et al., 2023; Fosch-Villaronga & Drukarch, 2023; Kapeller et al., 2021; Li, 2021)	(Maurice et al., 2018a; Nussbaum et al., 2019)
Review and Assessment	Inadequate feedback	Collect user feedback regularly.	(Maurice et al., 2018a; Pote et al., 2023)	(Maurice et al., 2018a, 2018b; Pote et al., 2023)
	Inadequate stakeholder collaboration / Lack of periodic reviews	Foster stakeholder collaboration and reviews.	(Maurice et al., 2018a; Pote, 2022)	(Maurice et al., 2018a, 2018b)

4.3.4 Cultural and inclusion considerations

Social acceptance of exoskeletons varies significantly across cultural contexts. Studies (Søraa & Fosch-Villaronga, 2020) suggest that designs which overlook socio-cultural and racial inclusivity may reinforce barriers to adoption, especially in multicultural workforces (Fosch-Villaronga et al., 2020). To enhance social acceptance and address these concerns, it's vital to consider cultural and inclusion perspectives (Fosch-Villaronga et al., 2020). Different sociocultural backgrounds may have varying levels of acceptance and usage patterns for exoskeletons (Fosch-Villaronga & Drukarch, 2023). For example, perceptions of privacy, masculinity, assistive devices, and even uniform design aesthetics may differ across cultural groups, affecting willingness to adopt and trust the technology. To mitigate this, Søraa and Fosch-Villaronga (2020) suggested that designers should adopt a robust social-technical perspective to better tailor exoskeletons to different cultural backgrounds. Such practices should include multilingual interfaces, customizable fits, user diversity in prototyping, field testing, and culturally resonant training protocols (Nussbaum et al., 2019; Søraa & Fosch-Villaronga, 2020).

4.3.5 Inadequate review and impact assessment Risk

The inherent risk of inadequate review and impact assessment stems from the evolving nature of exoskeleton technology, characterized by a lack of inclusive engagement with stakeholders and limited feedback from users. Insufficient examination and assessment may result in overlooking crucial factors related to the usability, safety, and overall effectiveness of exoskeletons in real-world applications. To mitigate this risk, it is imperative to establish a comprehensive and ongoing review process that actively involves stakeholders and encourages user feedback. This approach ensures a more thorough evaluation of the technology, addressing concerns, and incorporating valuable insights to enhance the overall impact assessment of exoskeletons in diverse operational settings.

4.4 Strategies to mitigate ethical and social risks of exoskeleton

The highlighted ethical and social risks of exoskeletons in Tables 6, 7 and 8 underscore the need for a standardized framework in the design, production, and deployment of exoskeletons. To address these ethical and social risks, policymakers, developers, and society at large must engage in discussions, establish regulations, and promote responsible and equitable use of exoskeleton technology. Also, it's important to consider these issues and work towards solutions that maximize the benefits of technology while minimizing the risks. The ethical and social risks of exoskeleton technology are quite diverse and complex. Figure 6 and Figure 7 present a flow chart illustrating each risk and its corresponding mitigation strategies. Below are some potential approaches from extant studies to mitigate these risks. However, the mitigation strategies synthesized in this review are research-guided recommendations rather than empirically validated solutions. Most existing studies propose these strategies conceptually, without testing them in real-world or experimental settings, which limits the strength of the evidence. As such, the strategies presented here serve as a foundational starting point to inform future research, standards development, and industry practice.

4.4.1 Ethical design guidelines

To address ethical concerns in exoskeleton design, manufacturers should ensure products are aesthetic, comfortable, and accessible for diverse users (Almpani et al., 2023; Dai & Zhou, 2023; Fosch-Villaronga & Özcan, 2020; Nnaji et al., 2023). Key factors include height and weight considerations, using lightweight materials to prevent imbalance and discomfort during prolonged use (Pote et al., 2023). Maurice et al. (2018a) added that wearing an exoskeleton on one’s body for several hours may be uncomfortable regarding its weight, movement restriction, and temperature. These factors are paramount for the effective use of exoskeletons (Pote et al., 2023; Søraa & Fosch-Villaronga, 2020). Gender and sex differences should be addressed to ensure comfort for all users, and functional controls should make the devices easy to operate (Dai & Zhou, 2023; Maurice et al., 2018b; Pote et al., 2023). User concerns related to movement restrictions, discomfort, compatibility with safety gear, risk of catching and snagging, hygiene practices, balance loss, and durability (Gonsalves, 2023; Howard et al., 2020; Maurice et al., 2018a, 2018b; Pote et al., 2023) should be taken into account during the design phase. For example, discomfort due to increased sweating during summer use should be considered, and measures to alleviate pressure points and movement restrictions caused by chest and leg pads should be explored (Gonsalves, 2023; Nnaji et al., 2023).

It is necessary to design an exoskeleton that can be used by both men and women (Maurice et al., 2018a). For example, in the design of the exoskeleton, the studies have noted that the following should be considered: attention should be paid to forces applied to the chest; exoskeletons should allow for self-adjustments; exoskeletons should be inclusive and accommodate wide ranges of size and physique (Van der Vorm, 2015); inclusion of a functional button for automating the removal and wearing of an exoskeleton; incorporation of health monitoring sensors to detect users not in good fit; ensuring exoskeletons are lightweight; ensuring exoskeleton materials are suitable for all weather conditions (Maurice et al., 2018a). In addition, the ASTM International (F48.01) guidelines on exoskeletons suggest the standardization of structural functions, such as mechanical and electrical components, embedded components, energy systems, cooling and fluid power systems, software, and user experiences (International).

4.4.2 Worker informs consent

Ensuring that workers have the choice to use exoskeletons and that their consent is obtained can mitigate risks stemming from worker privacy and autonomy.(Pote et al., 2023). Users should always give explicit informed consent before using the device. Also, users should provide explicit consent before their data is accessed or used, and be informed about how their data will be used and who will have access to it. Employers should ensure that the use of exoskeletons does not lead to exploitation or discrimination and that workers' rights are protected (Pote et al., 2023). This can be achieved by communicating data usage, storage, and protection (Maurice et al., 2018a). It is also paramount to involve workers in safety decision-making regarding the use of exoskeletons (Nussbaum et al., 2019). ASTM International (F48-05) stated the importance of "developing standards for the practice of security and privacy protocols to protect data associated with exoskeleton systems, including appropriate protocol testing methods (International; Lowe et al., 2019).

4.4.3 Training and education

The strategy focuses on equipping construction workers with comprehensive knowledge and skills essential for the proper use of exoskeletons (Lowe et al., 2019). This involves developing thorough training programs covering the assembly, maintenance, and safe operation of exoskeletons (Nnaji et al., 2023). Workers must gain a deep understanding of the technology's limitations, benefits, and potential risks. Skilled technologists should regularly inspect exoskeletons to identify and resolve any issues promptly. User training protocols, encompassing processes for hands-on training, documentation, record-keeping, recalls, warranty issues, and certifications, ensure workers are well-prepared (International; O'Sullivan et al., 2015). Continuous learning and feedback mechanisms facilitate ongoing improvement, integrating exoskeleton training into the broader workplace safety culture (Van der Vorm, 2015). This approach empowers construction workers with the necessary skills and knowledge, actively involving them in the ethical deployment of exoskeleton technology.

4.4.4 Clear guidelines and regulations

Developing a comprehensive strategy for managing the ethical risks associated with exoskeletons is crucial to ensure their safe and responsible use (Li, 2021). This involves establishing clear guidelines and regulations that communicate the benefits, limitations, and potential risks to all stakeholders, including workers, management, and investors. Transparency between employers and workers is essential, and guidelines should cover aspects such as proper training, usage limitations, and maintenance protocols (Maurice et al., 2018a). According to the American Society for Testing and Materials (ASTM), in its policy guidelines for exoskeletons (ASTM F3323-21; ASTM F3358-20; ASTM WK65295 and ASTM WK65295), the importance of enhancing communication among individuals involved in the research, design, deployment, and use of exoskeletons and exosuits is stated. It is imperative to implement labeling and instruction guidelines for manufacturers (International). These guidelines should adhere to standard SI units and include essential information such as where tags can be affixed, safety instructions (Van der Vorm, 2015) required warnings, warranty details, and user information. The objective is to provide a standardized framework that helps identify potential malfunctions and highlights higher-risk situations (International). In particular, ASTM mentioned that the instructions on the safe use of exoskeletons for load handling should be emphasized. This involves providing clear guidance on the proper techniques and procedures for handling loads while wearing the exoskeleton (Van der Vorm, 2015). Workers need to be educated on how to operate the exoskeleton safely to prevent accidents and injuries (International). By implementing these guidelines and regulations, the ethical risks associated with exoskeletons can be effectively managed. This strategic approach ensures that all stakeholders are well-informed, risks are minimized, and the use of exoskeletons aligns with ethical considerations in various applications.

4.4.5 Monitoring and compliance

Ensure compliance with safety procedures through periodic training and spot checks. Employers and users should observe and adhere to the manufacturer's information on the scope of use. It is also important to obtain and review safety data sheets from the exoskeleton manufacturer and ensure that exoskeletons do not infringe on human rights (Maurice et al., 2018a). Employers should ensure that the dignity, autonomy, and privacy of individuals utilizing the technology are protected.

4.4.6 Justice and Accountability

The system needs to promote accountability (Maurice et al., 2018b). Researchers and developers should make diligent efforts to reduce the potential for technology misuse (Maurice et al., 2018a). To mitigate the risk of exoskeleton misuse, all users and employers should assume responsibility (Bissolotti et al., 2018). Legal provisions should be in place to hold those who deviate from established standards and regulations accountable (Nussbaum et al., 2019). Collaborative robotics systems must make real-time decisions about their actions and interactions with humans. Stakeholders and end users should be the evaluators of the technologies, and their feedback should be taken into account in the definition of rules, guidelines, and means of use of these technologies (Maurice et al., 2018b).

4.4.7 Collaboration with researchers

To mitigate the risks associated with exoskeleton implementation, a key strategy involves forming partnerships with academic institutions and research organizations (Maurice et al., 2018b). By collaborating with these entities, the aim is to conduct independent interventions on the impact of exoskeletons on worker safety, health, and well-being. Leveraging the expertise of researchers, these studies can provide valuable insights into the effectiveness and potential risks associated with exoskeleton use in various work environments. The findings can then be used to inform and establish best practices, ensuring a data-driven and evidence-based approach to the integration of exoskeleton technology in the workplace.

4.4.8 Workers' feedback

One crucial strategy is to actively seek feedback from construction workers using exoskeletons. Listen to their concerns and adjust the technology or procedures based on their input (Maurice et al., 2018a). Continuously evaluate the effectiveness of exoskeletons and make improvements as necessary. By creating a robust feedback mechanism, construction companies can foster an environment of open communication and responsiveness. Encourage an open dialogue to address ethical and social concerns.

4.4.9 Public engagement and enlightenment

It is important to maintain an open and transparent dialogue about the benefits and implications of exoskeleton use in construction (Nussbaum et al., 2019). Misinterpretation by the public could hinder the development and deployment of exoskeleton technology. It could give false hopes and mystification. To mitigate this, there should be proper education and awareness activities regarding exoskeletons (Maurice et al., 2018a).

4.4.10 Safety guidelines

A strict adherence to safety requirements established by the manufacturer is crucial. This involves obtaining and meticulously reviewing safety data sheets provided by the exoskeleton manufacturer, a crucial step in ensuring comprehensive awareness of potential risks and safety guidelines (Maurice et al., 2018b). Adhering diligently to these safety protocols is paramount for fostering a safer and more responsible utilization of exoskeleton technology (Lowe et al., 2019), minimizing the likelihood of accidents or ethical lapses during deployment [21, 87]. Furthermore, the International Organization for Standardization (ISO 13482 – 2014) stated that beyond certifying device safety, it is imperative to guarantee that operational rules and working conditions are consistently clear to users (O'Sullivan et al., 2015; Van der Vorm, 2015). As part of this strategy, a comprehensive educational initiative should precede the deployment of the technologies, offering users in-depth insights into their safe and ethical use. Additionally, while device safety can be certified, it is essential to ensure that rules and working conditions are always clear to users (Maurice et al., 2018b).

4.4.11 Transparent guidelines

It is imperative to provide clear information about the advantages and potential risks associated with Exoskeleton (Maurice et al., 2018a). The exoskeleton functionality should be transparent to its users (Dai & Zhou, 2023). Users should retain their freedom of choice and decision-making abilities when using these systems. Safety certifications are important, but clear rules and working conditions must be communicated to users for their safety. Prior education on the use of technology is essential. Transparency in data collection is also necessary, with users having control over their data (Maurice et al., 2018b).

4.4.12 Maintenance practice

Regular equipment cleaning and proper disinfection of the exoskeleton after each use form the cornerstone of this approach (Nnaji et al., 2023), ensuring a high standard of hygiene that not only safeguards user well-being but also minimizes the potential spread of contaminants or pathogens. Addressing durability concerns that may arise from potential impacts of site tools. In particular, promoting hygienic practices becomes imperative when multiple users share devices, especially in warmer climates where infectious diseases may proliferate (Howard et al., 2020; Nnaji et al., 2023). Prioritizing individualized cleaning procedures akin to personal protective equipment (PPE) clothing can further alleviate these concerns. Moreover, considering the decontamination and/or disposal of exoskeleton systems following exposures to radioactive or hazardous chemicals is a part of the ASTM (F48.04) standards for the maintenance and disposal of exoskeleton systems (International; Lowe et al., 2019), reinforcing the ethical commitment to safety and responsible use in scenarios involving hazardous conditions.

4.4.13 Government Intervention and Investment Strategy

To foster the advancement of exoskeleton technology and enhance its accessibility, a strategic approach involves global initiatives to promote and invest in exoskeletons. Governments should actively encourage collaboration and investment on an international scale. By fostering partnerships and financial support globally, the aim is to drive down the production costs of exoskeletons. This strategy not only promotes technological growth but also ensures that the benefits of exoskeleton technology are more widely accessible, contributing to its broader adoption and integration into various industries.

4.4.14 Beneficence

The beneficence principle can be used as a framework guiding the ethical use of exoskeleton (Bulboacă et al., 2017). This involves actively promoting the well-being and positive outcomes of individuals interacting with the technology (Elger, 2019). This includes ensuring that the deployment of exoskeletons contributes to enhancing the user's physical abilities, work efficiency, and overall quality of life. Strategies encompass user-centric design, customization to individual needs, and continuous improvement based on user feedback (Elger, 2019). Ethical guidelines should prioritize the positive impact on users' health, safety, and overall experience. Ongoing research collaboration with professionals and a commitment to user empowerment contribute to beneficence, aiming to maximize the benefits while minimizing any potential harm or negative consequences associated with exoskeleton technology (Bulboacă et al., 2017).

4.4.15 Non-maleficence

The principle of Non-maleficence as a strategy to mitigate ethical risks associated with exoskeleton use involves prioritizing user safety through thorough testing, risk assessment, and adherence to safety standards (Elger, 2019). It emphasizes comprehensive training, education, and informed consent, ensuring individuals are aware of the technology's capabilities and potential risks. Regular monitoring, maintenance, and a focus on human-robot interaction design contribute to minimizing the risk of physical or psychological harm. Privacy protection measures, continuous user feedback loops, and the involvement of ethics committees further enhance ethical considerations. By adhering to regulatory compliance and addressing potential risks proactively, stakeholders aim to prevent harm, prioritize safety, and responsibly integrate exoskeleton technology into various settings (Elger, 2019).

4.5 Mapping ethical and social risks of exoskeletons to their mitigation strategies

The reviewed literature highlights that while exoskeleton technology offers significant ergonomic and productivity benefits, it also introduces multifaceted ethical challenges. Across the ethical risks reviewed in Sections 4.2.1 to

4.2.9, a recurring theme emerges between technological advancement and human-centered design. Figure 7 presents a flowchart categorizing ethical risks along with the corresponding proposed mitigation strategies. Many of these risks, such as discomfort due to poor design, lack of autonomy, privacy concerns, and stigmatization, stem from inadequate consideration of the user's experience (Dai & Zhou, 2023; Kapeller et al., 2021; Maurice et al., 2018b; Pote et al., 2023). A central concern across the literature is the lack of inclusive design, which can lead to discomfort, reduced mobility, and increased risk of injury, especially when devices do not account for the diverse body types and physical conditions of users (Almpani et al., 2023; Dai & Zhou, 2023; Fosch-Villaronga & Özcan, 2020; Nnaji et al., 2023). The findings reveal that a holistic, user-centered approach is essential for the responsible integration of exoskeletons in construction settings. To address these issues, researchers advocate for transparent communication, inclusive design, worker participation, and public education to build trust and foster responsible, human-centered deployment of exoskeleton technologies in high-risk industries like construction (Cawthorne, 2022; Greenbaum, 2016b; Kapeller et al., 2021; Maurice et al., 2018a). Similarly, most studies converge on the need for ethical frameworks that prioritize transparency, user choice, and regulatory safeguards, especially in high-risk industries like construction. Beyond ethical considerations, the integration of exoskeletons introduces significant social risks that extend beyond physical and technical concerns. Accessibility and affordability remain critical challenges, as high costs may limit availability to large firms and poses significant barrier for smaller construction firms and low-income workers (Fosch-Villaronga et al., 2020; Greenbaum, 2016b; Pote, 2022). The literature also highlights the risk of overdependence, where physical capabilities may deteriorate over time or workplace productivity demands may increase to capitalize on the benefits exoskeletons offer. Furthermore, the cultural and inclusion risks cannot be overlooked without consideration for diverse body types, languages, and cultural perceptions of wearable technologies by multicultural workforces (Fosch-Villaronga et al., 2020; Greenbaum, 2016b; Søraa & Fosch-Villaronga, 2020). Figure 6 presents a flowchart categorizing social risks along with the corresponding proposed mitigation strategies.

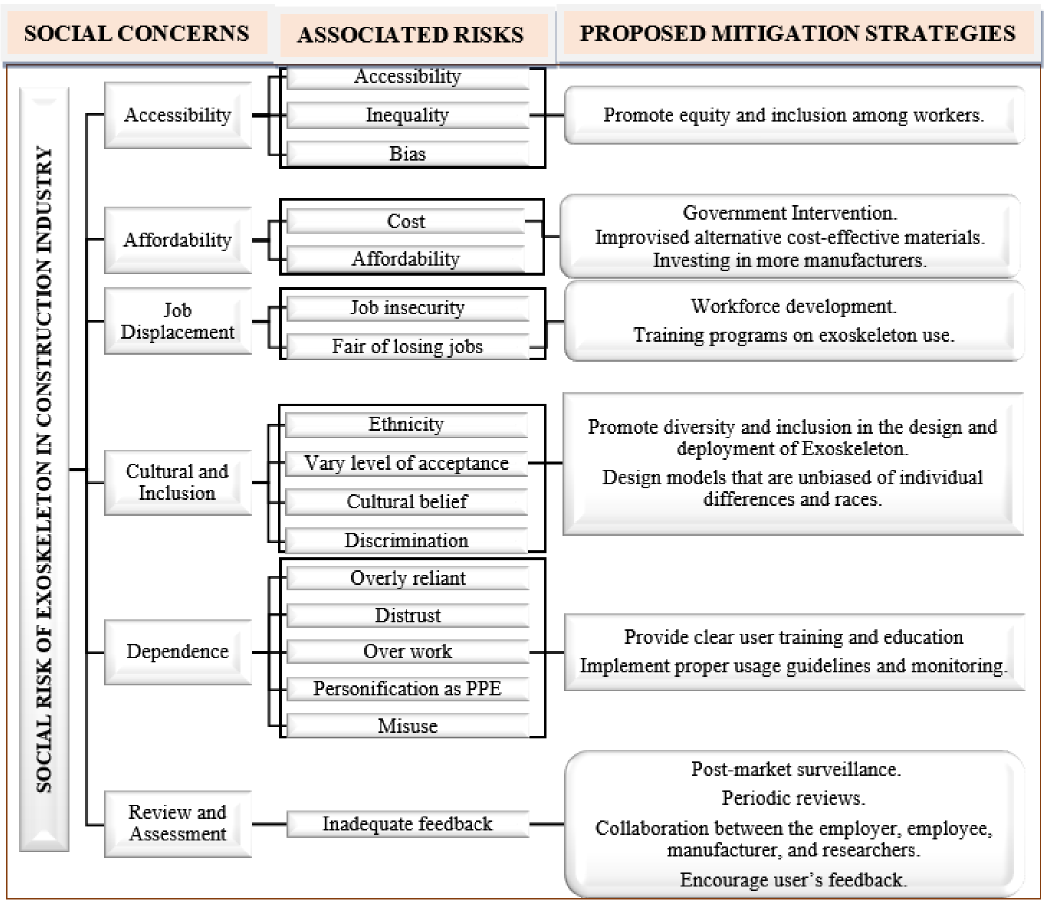

Figure 6: Flow chart mapping social risks and proposed mitigating strategies.

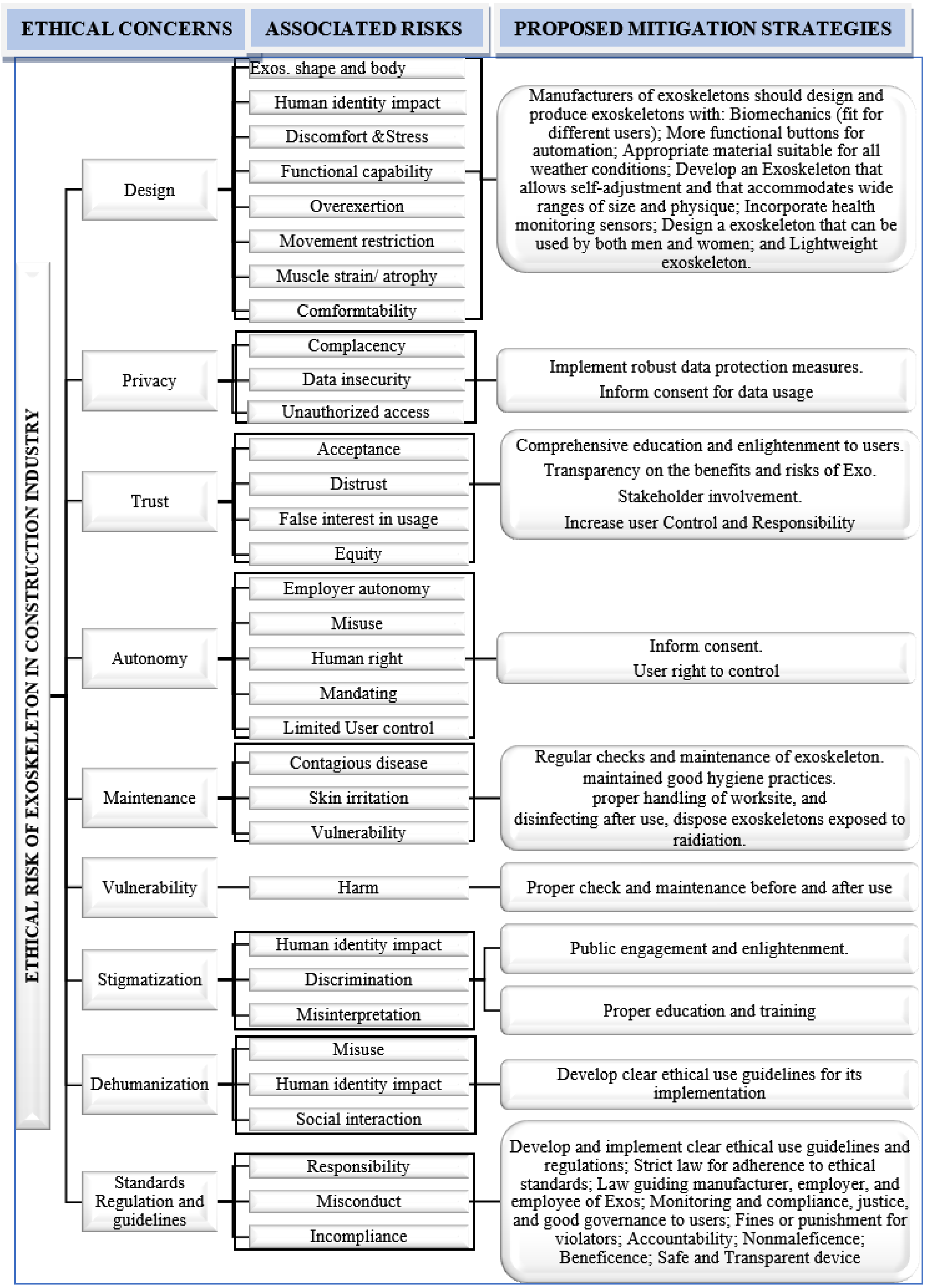

Figure 7: Flow Chart mapping ethical risks and proposed mitigating strategies.

4.6 Conceptual frameworks

The researchers proposed 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 8 and Figure 9 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. The development of this framework was meticulous, drawing insights from a thorough review of existing literature and academic sources dedicated to the ethical and social dimensions of exoskeleton implementation. The framework incorporates the Responsible Innovation Framework (Stilgoe et al., 2020)and the principle of biomedical ethics (Beauchamp & Childress, 1994). Each risk area is mapped to tailored mitigation strategies that uphold fairness, inclusivity, and social cohesion (Bulboacă et al., 2017; Elger, 2019).

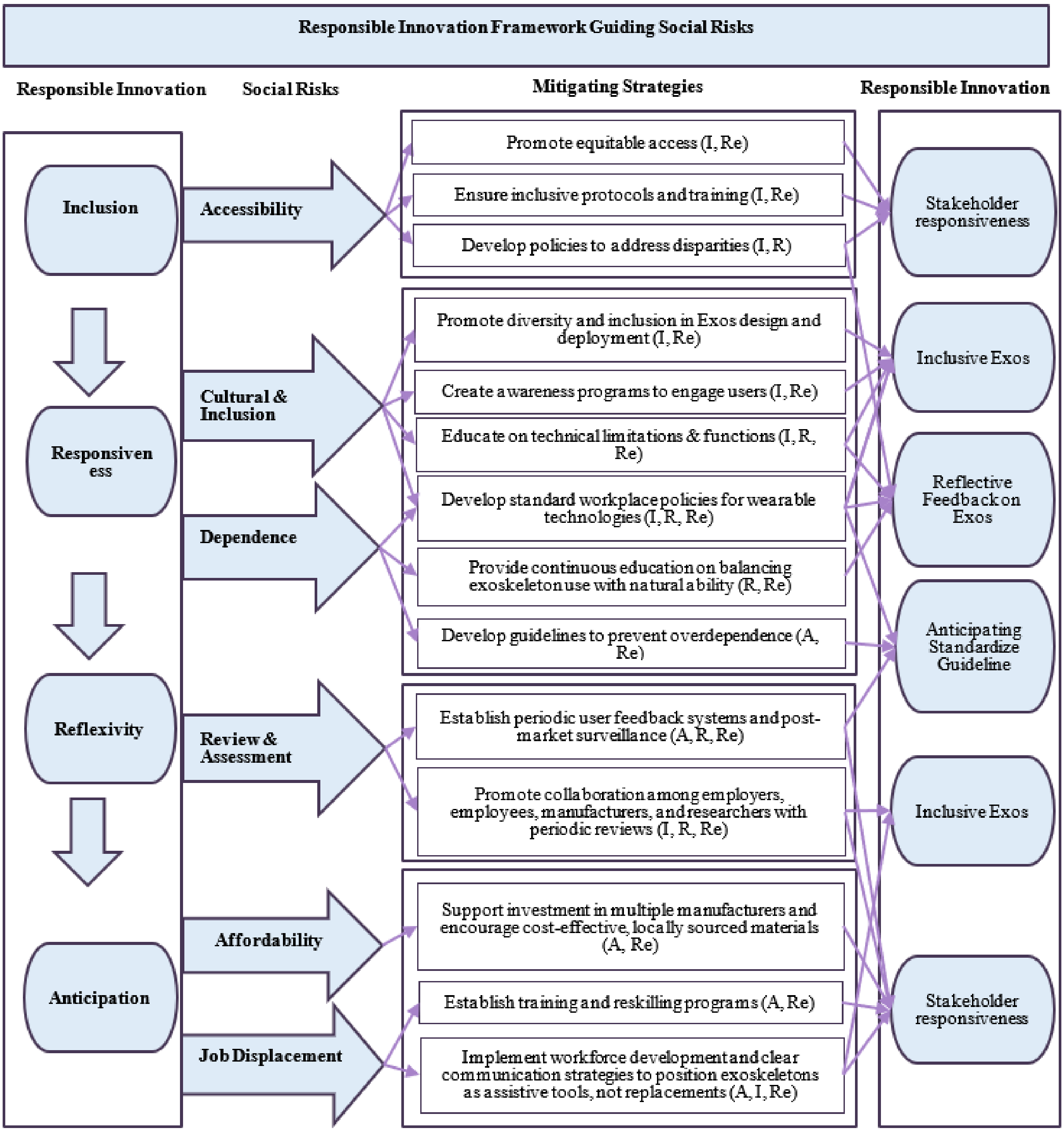

Figure 8: A Conceptual Framework for Addressing the Social Risks of Exoskeleton Use (guided by the Responsible Innovation framework). Note: Exos. denotes Exoskeleton, I, R, RE, and A represent Inclusion, Responsiveness, Reflexivity, and Anticipation, respectively.

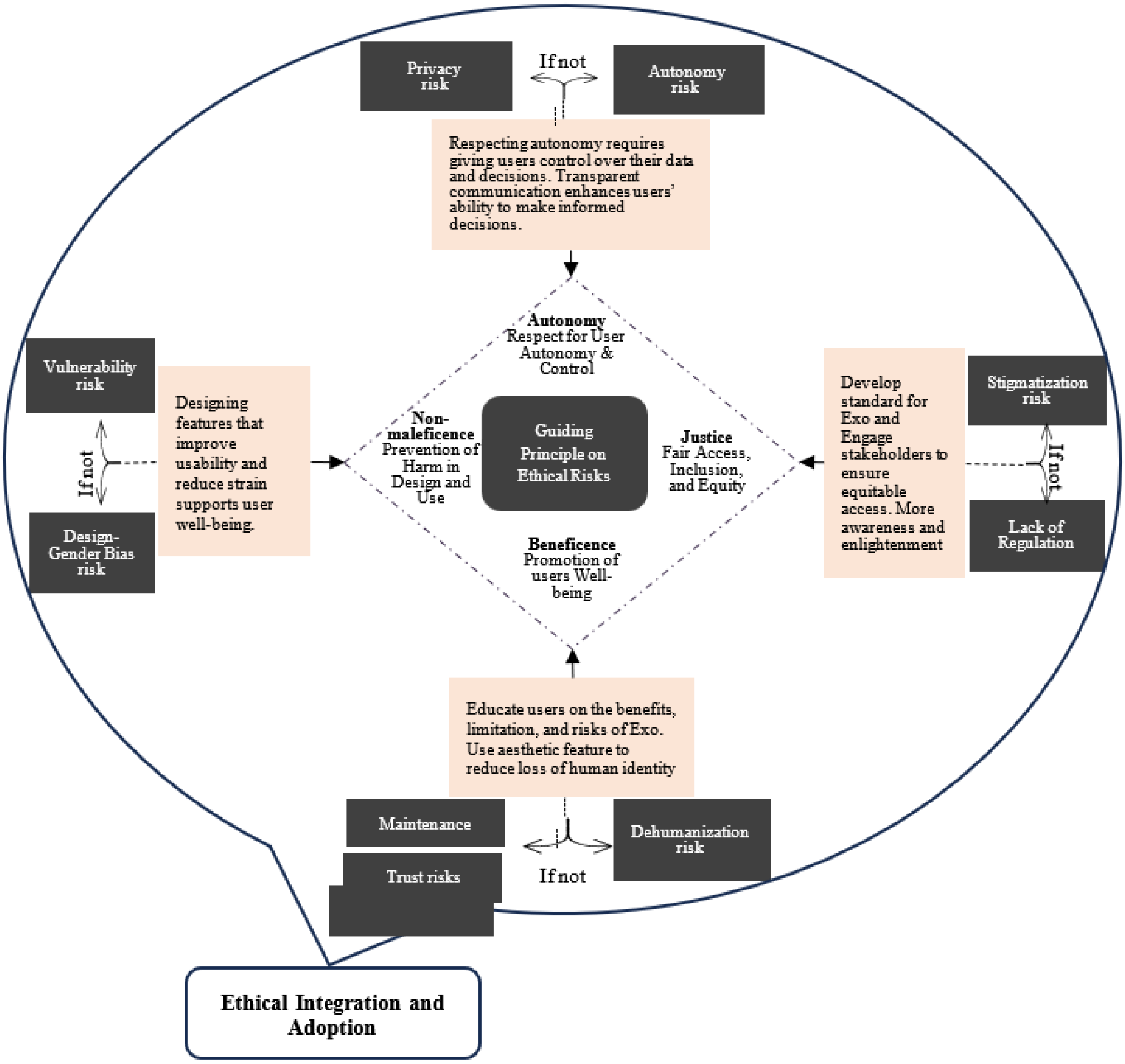

Figure 9: A Conceptual Framework for Addressing Ethical Risks of Exoskeleton Use (guided by the 4 ethical principles).

Ethical considerations are anchored in the four principles of biomedical ethics autonomy, non-maleficence, beneficence, and justice, which focuses on the individual user's interaction with exoskeletons provide a foundation for human-centered design and deployment (Beauchamp & Childress, 1994; Elendu et al., 2023). Autonomy is promoted through informed consent, privacy safeguards, and respect for user choice (Beauchamp, 2018; Lawrence, 2007). Non-maleficence is achieved by mitigating risks such as design flaws, discomfort, or harm through ergonomic optimization and routine maintenance (Beauchamp, 2018; Lawrence, 2007). Beneficence emphasizes maximizing user well-being through education and usability enhancements (Beauchamp, 2018; Lawrence, 2007), while justice calls for inclusivity, fairness, and equitable distribution of benefits (Beauchamp, 2018; Lawrence, 2007). The framework incorporates core ethical risks privacy, autonomy, trust, vulnerability, dehumanization, stigmatization, and design risks and aligned it to tailored strategies to mitigate each (Kapeller et al., 2021; Maurice et al., 2018a; Nussbaum et al., 2019). For instance, respecting autonomy entails giving users control over data and ensuring informed consent (Kapeller et al., 2021). Non-maleficence is addressed by emphasizing ergonomic design and maintenance to prevent harm (Fosch-Villaronga & Drukarch, 2023; Maurice et al., 2018a; Nielsen et al., 2022a). Beneficence is reflected in efforts to educate users about benefits and limitations to support well-being and identity (Fosch-Villaronga et al., 2023; Fosch-Villaronga et al., 2020). Justice is emphasized through inclusive standards, stakeholder engagement, and promoting equitable access (Fosch-Villaronga et al., 2023; Nussbaum et al., 2019). By aligning ethical considerations with engineering practices, the framework supports responsible by centering user well-being, promoting equitable access, and involving construction workers in design and decision-making processes, the industry can foster broader social acceptance and trust.

Simultaneously, social risks are addressed using the Responsible Innovation (RI) framework, which emphasizes anticipation, reflexivity, inclusion, and responsiveness as key components for ethically sustainable technological adoption (Stilgoe et al., 2020). RI advocates for proactive, inclusive, and reflexive approaches to technology development by integrating anticipation, inclusion, reflexivity, and responsiveness (Stilgoe et al., 2020). It addresses risks such as accessibility, affordability, job displacement, cultural exclusion, overdependence, and insufficient stakeholder feedback. Anticipation is reflected in proactive policy development and impact assessment mechanisms (Stilgoe et al., 2020). Reflexivity entails continuous monitoring, feedback loops, and design iteration (Stilgoe et al., 2020). Inclusion involves the participation of workers, employers, researchers, and policymakers in shaping how exoskeletons are integrated (Stilgoe et al., 2020), while responsiveness requires adjusting strategies based on evolving needs and user concerns (Stilgoe et al., 2020). For example, to address accessibility and inequality, the framework calls for equitable design standards and policies ensuring all workers, regardless of physical ability or background, have access to exoskeleton technology (Fosch-Villaronga et al., 2020; Kapeller et al., 2021; Maurice et al., 2018a). These frameworks consider not only the ethical implications but also the broader social context in which exoskeletons operate. Furthermore, the framework is intended to guide key stakeholders, including designers, manufacturers, employers, employees, and policymakers, in translating human values into tangible design requirements for exoskeletons. The emphasis is on designing an exoskeleton that not only aligns with ethical principles but also fosters the well-being of individuals involved. In essence, these conceptual frameworks offers a robust and structured approach for the ethical adoption of exoskeletons, ensuring their integration into the construction industry is mindful, responsible, and conducive to the betterment of human experiences.

4.7 Discussion and practical implications

RQ1: What ethical and social risks are associated with exoskeleton use in construction?

This systematic review highlights a growing scholarly and industry interest in the ethical and social implications of exoskeleton use. The findings also reveal a significant gap in construction-focused research, amidst other industries like healthcare, industrial, and engineering industries. This lack of construction-specific literature underscores an urgent need for further research and policy development tailored to the high-risk and labor-intensive nature of construction environments. The dominance of literature from the United States and Europe suggests geographical disparities in the discourse, indicating the need for broader, global engagement on this issue. The review identifies a wide range of ethical and social concerns, including design limitations, maintenance, autonomy, privacy, dependency, accessibility and data protection risks. Poorly designed exoskeletons that fail to accommodate the physical diversity of construction workers not only risk physical harm but may also erode trust in technology adoption. Similarly, data security concerns related to exoskeleton-generated biometric and performance data threaten privacy rights and could potentially be misused by employers or third parties. A notable issue is the potential for reduced worker autonomy and the risk of exoskeletons being mandated without adequate consultation, undermining workers' control over their own bodies and labor conditions. Social risks, such as inequity in access, affordability, cultural exclusion, and job displacement fears, further complicate the adoption of exoskeletons on construction sites. Moreover, the absence of industry-specific regulations and ethical guidelines for exoskeleton use in construction exacerbates these risks. Existing frameworks are fragmented, often derived from healthcare or industrial applications, which may not align with the dynamic, high-risk, and diverse nature of construction sites. This review's findings advocate for a holistic, interdisciplinary approach that combines technical innovation with ethical foresight and participatory governance.

RQ2: What are the strategies for mitigating exoskeletons' ethical and social risks?

To address these ethical and social risks, this study identifies several **strategic approaches** proposed in the literature. Key among them is the development of ethical design guidelines that ensure devices are inclusive, adjustable, gender-sensitive, and suitable for diverse work environments. Other practical strategies include design practices, data protection protocols, maintenance standards, and the development of ethical guidelines, offering a roadmap for responsible adoption. Exoskeleton designs should prioritize *user-centered and inclusive design principles*, ensuring physical compatibility, gender inclusivity, and body diversity in device development. Obtaining informed consent and respecting worker autonomy are foundational to ethical deployment. Data protection measures, including secure data storage, access control, and transparency regarding data use, are crucial to maintain trust between employers and workers. Organizational and employer strategies must include participatory deployment processes where workers are actively consulted before adoption decisions. Training programs and awareness workshops can further support informed and voluntary participation, helping workers understand both benefits and limitations. At a policy level, industry-wide standards and ethical codes should be established to guide responsible implementation. These standards must integrate human-centered ethics focusing on fairness, autonomy, accountability, and social sustainability into procurement, testing, and evaluation processes. Government intervention and investment strategies will also be pivotal in driving affordability and innovation (Gonsalves, 2023). Other essential strategies include routine monitoring and maintenance, public awareness campaigns, and collaborative research efforts to evaluate long-term social and health impacts.

Practical Implications

From a practical standpoint, this study provides a roadmap for responsible exoskeleton adoption in the construction industry. The study proposed a framework as a foundational model for identifying, categorizing, and addressing these risks within the construction industry. It can serve as a guide for researchers, safety managers, and developers to proactively manage ethical challenges while promoting safe, equitable, and sustainable adoption of exoskeletons. (i) These findings highlight the need for manufacturers to integrate ergonomic and ethical considerations at the early stages of design, including body diversity, gender inclusivity, physical compatibility, comfort, and long-term usability. (ii) For employers and policymakers, transparent communication, workforce engagement, and privacy protection should be central to technology deployment strategies. To foster trust and mitigate social risks, employers should invest in workforce training, promote transparency around the benefits and limitations of exoskeletons, and involve workers in the deployment process. (iii) For researchers, the proposed framework offers a replicable model for identifying, categorizing, and mitigating risks, thereby advancing the evidence base for ethical technology integration.

Limitations and Future Work

This review synthesized major categories of ethical and social risks associated with exoskeleton adoption; however, additional risks may emerge when examined through different disciplinary perspectives or within specific industry contexts. Likewise, most mitigation strategies reported in the literature are conceptual in nature. These limitations highlight the need for further empirical research. Future studies should examine ethical and social risks through systematic field investigations within construction environments, assess how risks evolve across different stages of exoskeleton deployment, and evaluate the effectiveness of proposed mitigation strategies. Experimental and longitudinal research designs would also strengthen understanding of how workers, managers, and organizations adapt to exoskeleton use over time. The findings of this review have informed a subsequent Delphi study conducted by the authors to further refine and validate the identified risks and strategies, emphasizing the importance of continued expert-driven and context-specific research.

5. CONCLUSION

The adoption and implementation of exoskeletons in the construction industry have the potential to significantly reduce musculoskeletal disorders, ergonomic risks, as well as overall fatality and mortality rates among construction workers. However, it is crucial to assess the ethical and social risks associated with emerging technologies like exoskeletons. This study conducted a systematic review of 46 peer-reviewed articles published between 2010 and 2023, offering the most comprehensive synthesis to date of ethical and social risk considerations for exoskeletons relevant to construction. The literature review revealed that most research on these risks is concentrated in the healthcare industry, with limited representation in the construction industry. Quantitative analysis of the reviewed literature revealed several notable trends. First, research activity in ethical and social risk across all industries has increased steadily, with over 63% of all publications appearing from 2019 onward, including 9 publications (20%) in 2023 alone. Second, geographical analysis showed strong regional concentration with 28% of all studies originating from the Americas (primarily the United States), 56% from Europe, 11% from Asia, and fewer than 5% collectively from Africa and Oceania. At the country level, the United States leads global research efforts in ethical and social risks, accounting for 28% of all publications, while other countries, particularly in the Global South, remain underrepresented. Third, regarding methodological approach, 37% of the studies focused on technical solutions, 24% were review papers, 15% discussion pieces, 7% case studies, 6% surveys, and only 2% analytical studies. Fourth, industry distribution showed that the majority of ethical/social risk studies on exoskeletons originate in Healthcare and Manufacturing industries, with construction representing less than 5% of the total evidence base. This scarcity reinforces the critical need for construction-specific ethical guidance.

This study identifies numerous ethical and social risks that, if not properly addressed, can hinder the acceptance and adoption rate of exoskeletons in the construction field. Ethical considerations encompass design, data privacy, worker consent, autonomy, dehumanization, trust, stigmatization, vulnerability, and maintenance. Inattention to these factors may result in risks such as misuse, human identity impact, decreased social communication, job displacement, discomfort, etc. Social considerations of exoskeletons in the construction industry assess the engagement with workers, employers, manufacturers, and the local community. These considerations include human rights, diversity and inclusion, public awareness, and community impact. Failure to address these factors can result in accessibility risk, acceptance risk, affordability risk, job security concerns, trust deficiency, cultural prejudice, and bias risks. Effectively addressing these concerns demands the establishment of clear ethical guidelines, educational initiatives, vigilant monitoring, compliance, public engagement, government intervention, and collaboration with researchers and industry stakeholders. Prioritizing worker safety, autonomy, and well-being and acknowledging broader societal implications are crucial for ensuring the ethical adoption of exoskeletons. In addition to its practical implications, this review offers valuable academic contributions by advancing the discourse on ethical and social risk assessment within human-wearable robot interaction research. It integrates two robust theoretical frameworks, biomedical ethics and responsible innovation into construction. These frameworks serve as a foundational model that can inform future academic investigations, policy analysis, regulatory standards, and educational curriculum development around responsible technology adoption in construction. Importantly, the findings from this study can serve as a guide to train the next generation of construction professionals and engineers on ethical technology adoption. It can also guide industry-led training programs aimed at upskilling the current workforce, ensuring that both new entrants and experienced workers are equipped to safely, effectively, and ethically engage with exoskeleton technologies. Additionally, the proposed frameworks can serve as a valuable insight for industry stakeholders, guiding the adoption of technologies that can revolutionize safety management practices in construction. Creating awareness and promoting the adoption of these technologies can contribute to a safer and more efficient future, mitigating risks and enhancing the well-being of the construction workforce. This study not only informs policy and practice but also contributes to the growing academic conversation on the ethical governance of human-technology interactions in the built environment. Future research should prioritize empirical studies within real-world construction contexts to validate the proposed frameworks, refine risk mitigation strategies, and inform policy development. Overall, the ethical and social dimensions surrounding exoskeletons in the construction industry are intricate and multifaceted. A collective effort from stakeholders is imperative to ensure the responsible and ethical adoption of exoskeletons, paving the way for a safer and more sustainable construction industry.

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