

**ORIGINAL ARTICLE**

# A Review of Exoskeleton Integration to Enhance Workplace Safety

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## ABSTRACT

Creating a safe workplace in physically demanding working environments faces significant challenges; from the risk of musculoskeletal disorders to the increasing physical demands of labour, compounded by an ageing workforce. This review synthesises existing materials on the integration of exoskeleton technology designed to improve occupational safety and ergonomics at workplaces. It evaluates the biomechanical benefits of various exoskeleton types, including load reduction and improved stability, while addressing gender-specific adaptations and task performance outcomes. Another theme explored is the feasibility of exoskeleton integration. Therefore, this paper also discusses barriers to adoption, including device usability, psychosocial factors affecting users, and economic considerations, alongside safety risks and regulatory gaps. Furthermore, it examines cutting-edge design, evaluation methodologies, and real-world implementation strategies as part of the viability assessment. With strong emphasis on technology adoption, integration within Industry 4.0 and the emerging Industry 5.0 highlights the potential for synergistic human-robot collaboration and smart workplace environments. The review concludes with recommendations for bridging the gaps that emphasise human-centric, ethical, and sustainable approaches for future research and practice in exoskeleton deployment to improve workplace safety and productivity.

**Keywords:** exoskeletons, workplace safety, ergonomics, musculoskeletal disorders, adoption barriers, Industry 4.0, human-robot collaboration

## INTRODUCTION

Physically demanding occupations such as manual handling, construction, and healthcare present significant occupational hazards, particularly related to musculoskeletal disorders (MSDs) and injuries. In these industries, workers are frequently engaged in repetitive and strenuous physical activities for material or human transfer. These activities include lifting, carrying, awkward postures, and sustained static positions, all of which contribute to a high incidence of work-related musculoskeletal disorders (WMSDs). For example, Antwi-Afari et al. (2023) review the widespread prevalence of WMSDs among construction workers,

emphasising that ergonomic risks remain a prevalent concern in such environments. The review, despite being limited to construction in the US, Canada and Hong Kong, underscores the necessity for ergonomic interventions to avert WMSDs. The increasing rates of MSDs pose a serious challenge across sectors and industries. As one of the largest industries, construction employs many workers, and most site work is largely completed by manual labour. Manual labour exerts considerable biomechanical loads to workers, which then result in fatigue, discomfort and long-term injury risks (Gutierrez et al., 2024). The physically demanding nature of the construction industry is exacerbated by an ageing workforce. The workers are more susceptible to injuries due to declining physical capacity and slower recovery times (Nnaji et al., 2023). This demographic shift, combined with rising physical demands, necessitates agile intervention strategies for implementation to ensure worker safety and productivity. In healthcare, workers are exposed to occupational hazards when handling patients. Cullen et al. (2025) reported that patient transfer poses high risk for back and upper extremity injuries. The manual patient handling procedures often involve inconsistent task variability and exposure to awkward postures. These elevate biomechanical strain and injury likelihood. The complexity of such environments adds to physical and cognitive overload, increasing the vulnerability of healthcare workers to injury. Apart from the ergonomic risks due to manual tasks performed, workplace distractions and cognitive demands also contribute indirectly to physical safety risks. Ke et al. (2021), using the Electroencephalography (EEG) device, have found that noise-induced distraction among construction workers amplifies safety hazards by impairing sustained attention, increasing error rates, and degrading safety performance. This multi-factorial nature of risk highlights the interactions between ergonomic and cognitive challenges in physically demanding occupations. The challenges are intensified by the dynamic and varied nature of tasks in sectors such as manufacturing and timber prefabrication, where customised products and constant changes of materials induce variable physical stresses (Bances et al., 2022). In some cases, there were ergonomic interventions, but those were inadequate to improve the situation. Inadequate quality of ergonomic design and technologies persistently elevate workers' risk of exposure, thus heightening the need for comprehensive safety and ergonomic solutions. Based on these occupational health and safety problems presented, there is a need for a review of the current integration success and the future direction of exoskeleton integration in industries to ensure a safe workplace and sustainable industry. Hence, this review offers a comprehensive synthesis of recent developments and the present landscape of occupational exoskeleton technology, emphasising their effectiveness, challenges to adoption, design approaches, and their incorporation into contemporary industrial frameworks such as Industry 4.0 and Industry 5.0.

## **THE ROLE OF EXOSKELETONS IN OCCUPATIONAL SAFETY AND ERGONOMICS**

There are three primary categories of exoskeletons employed in occupational settings: passive, powered, and hybrid systems. Passive exoskeletons operate without active energy inputs. Loads transmitted are redistributed by mechanical

elements installed, such as springs and dampers. On the other hand, powered exoskeletons incorporate actuators in their systems for external energy assistance. Hybrid systems combine features from both, aiming for optimum support and usability. These devices are designed to minimise physical strain during demanding tasks, particularly by mitigating musculoskeletal overexertion in the back and shoulder regions. Research consistently indicates that exoskeletons are effective in minimising muscle activity and alleviating physical workload. Khan et al. (2025) reported notable decreases in muscle activity associated with plantar pressure distribution during dynamic tasks such as load lifting and carrying. Female participants demonstrated reductions of up to 17.7% in peak heel pressure, while their male counterparts exhibited adaptive load increases in the forefoot regions, indicating the action of compensatory mechanisms. It was also observed that gender-specific biomechanical effects have emerged as critical considerations in exoskeleton design and application. Similarly, Ojha et al. (2024) reported that introducing powered back-support exoskeletons resulted in a reduction of muscle fatigue by an average of 60% in back and abdominal muscles. In addition, they also managed to reduce the metabolic cost by 17%. In this research, the ergonomic risks have been lowered by 50% without impairing stability. In another research, Mukherjee et al. (2025) shown that whereas exoskeleton users experienced a reduced upper extremity muscle activity, there is a corresponding rise in lower back activity, highlighting the rapid need for customised designs that accommodate individual biomechanics. Fosch-Villaronga et al. (2023) highlighted the ethical and societal dimensions associated with exoskeleton integration, encompassing safety issues and user acceptance, which indirectly influence the results of the ergonomic assessment. Research conducted by Park et al. (2024) investigated balance recovery in forward loss-of-balance situations, both with and without the use of passive back-support exoskeletons, concerning dynamic postural stability and performance. Users demonstrated less net positive leg effort and impaired reactive stepping, with compensatory ankle engagement predominantly in female participants, indicating that exoskeletons may modify natural balance mechanics and necessitate careful implementation in dynamic tasks. Mukherjee et al. (2025) also documented that when workers wear passive shoulder exoskeletons while performing complex visuomotor tasks, there were lower mental demands and improved task accuracy. These cognitive advantages augment the physical adaptations, thus improving total task performance. Further evaluations of static balancing and stability by Ma et al. (2025) have introduced biomechanical models that predict ankle moments linked to exoskeleton contact pressures, pertinent for initial design considerations aimed at reducing instability hazards. The significant physical demands tools and machinery have catalysed the advancements and implementation of exoskeletons in manufacturing settings. The benefits range from enhancing workers' strength and endurance, to mitigate disorders associated with tool handling, particularly in elevated tasks (Flor-Unda et al., 2023).

Based on previous reports on the integration of exoskeleton technologies, it has certainly benefited the workers by minimising the occupational health risks that had been identified before the integration. However, in some cases, it then caused

other health risks that need to be addressed immediately with a customised device design with consideration of user biomechanics.

## **STAKEHOLDERS AND ORGANISATIONAL READINESS**

Organisational readiness is an important aspect that contributes to the successful implementation of exoskeleton technology in workplaces, especially in physically demanding sectors such as construction, manufacturing, and healthcare. Fostering and promoting organisational readiness relies fundamentally on identifying and engaging key stakeholders, providing awareness of the importance of exoskeleton integration and how they will benefit from the technology. The primary stakeholders include construction workers and line operators utilising exoskeletons, supervisors managing daily activities, ergonomists guiding ergonomic suitability and safety, regulatory agencies enforcing compliance with safety regulations, and corporate management concentrating on strategic implementation and cost-benefit analysis (Gonsalves, et. al., 2024; Schwerha et. al., 2021).

Findings from surveys and focus groups reveal that construction workers and supervisors play a vital role in adoption decisions, influencing perceived usability and acceptance, whereas regulatory agencies and ergonomists are responsible for ensuring safety and compliance (Gonsalves et al., 2024). Management commitment serves as a crucial factor that can either facilitate or hinder the allocation of financial resources, the development of policies, and the provision of training necessary for the effective implementation of exoskeletons (Gutierrez et al., 2024).

The size of the organisation greatly influences adoption trends. Research indicates that larger corporations typically possess more resources for investing in structured implementation strategies and pilot programs. Small and medium-sized firms (SMEs), on the other hand, sometimes have budgetary limitations, inadequate technical assistance and doubts around the return on investment associated exoskeleton integration (Schwerha et al., 2021). Notwithstanding these disparities, the interest in leveraging exoskeleton technology to alleviate occupational musculoskeletal hazards is increasing across enterprise sizes, particularly when repetitive high-load tasks are difficult to eliminate.

Organisational readiness is substantially influenced by aspects like cost justification, device usability, worker comfort, and general compatibility with prevailing work practices (Gutierrez et al., 2024; Nnaji et.al., 2023). Participatory design and human-centric approaches are recognised as effective methods for improving the acceptance and suitability of exoskeleton solutions. Involving end-users during the early design and testing phases addresses concerns related to usability, safety, and social acceptance (Moencks et. al., 2022). Inclusive strategies enhance worker ownership, diminish resistance, and increase the practical adaptability of exoskeletons.

Furthermore, successful integration of exoskeletons demands organisational alignment with broader human-technology integration frameworks, emphasising

communication, training, and continuous feedback loops. Tools like the Augmented Workforce Canvas offer structured guidance to align stakeholders around value-driven technology adoption, ensuring that exoskeleton deployment enhances rather than disrupts workflow and worker well-being (Moencks et al., 2022). In addition, digital transformation initiatives aimed at ergonomic improvement must be accompanied by adjustments in organisational culture, leadership support, and skill development tailored to workers' evolving roles (Rusu et. al., 2021).

The review's findings indicate that the majority of organisations recognise the ergonomic hazards linked to manual labour and the necessity to enhance workplace ergonomics and safety. However, many still lack comprehensive strategies for systematic evaluation and mitigation of the risks before exoskeleton deployment. Addressing this gap necessitates investing in proactive risk assessments, participatory design approaches, and tailored training programs, positioning organisations to leverage the full potential of exoskeleton technology while safeguarding worker health and productivity (Bogue, 2018; Zhu et al., 2020). Consideration of sizing and adjustability in exoskeletons is also crucial to accommodate a diverse user population, ensuring proper fit and usability across various body geometries (Toxiri et al., 2019). Furthermore, when dealing with devices for work assistance, organisations must address issues relating to device maintenance, cleaning protocols, and long-term operational support, all of which affect exoskeleton durability and lifecycle costs (Lasota, 2020).

## **ERGONOMIC AND BIOMECHANICAL BENEFITS OF EXOSKELETONS**

Exoskeleton use in industrial and construction environments has demonstrated significant benefits in reducing muscular effort and biomechanical loads, particularly for the back, shoulders, and upper limbs. Khan et al. (2025) reported that powered passive wearable exoskeletons (pwExos) significantly affect plantar pressure distribution during dynamic activities such as lifting and carrying. Female participants demonstrated significant decreases in peak heel pressure (17.7%) and pressure-time integrals (52.8%), indicating improved load redistribution and stability. Male participants exhibited distinct compensatory loading patterns characterised by increased forefoot loading, suggesting gender-specific biomechanical adaptations (Khan et al., 2025). This highlights the necessity for gender-sensitive exoskeleton designs that consider unique biomechanical responses.

Ojha et al. (2024) empirically confirmed that powered back-support exoskeletons considerably decrease muscle activity in key musculature groups, including back and abdominal muscles, by approximately 60%. This reduction is accompanied by a 17% decrease in metabolic cost and a 50% drop in ergonomic risk scores without negatively affecting user stability during common construction tasks. Such outcomes suggest exoskeletons are effective in mitigating fatigue and musculoskeletal disorder risks.

Park et al. (2024) assessed the impact of back-support exoskeletons on lower-limb kinetics in the context of balance recovery following a forward loss of balance. Exoskeletons were found to modify hip flexion torque and the distribution of mechanical work across lower-limb joints, negatively affecting reactive stepping and balance recovery, with significant variations observed between sexes. Females demonstrated a notable compensatory enhancement in ankle joint contribution, providing essential insight into the alterations in dynamic stability associated with exoskeleton integration.

Further biomechanical assessments by Mukherjee et al. (2025) underlined that passive shoulder exoskeletons reduce upper extremity muscle activity, while some increases in lower back loading were noted. Importantly, exoskeleton users demonstrated decreased mental demands and improved task accuracy during complex visuomotor tasks, indicating a correlation between ergonomic and cognitive benefits that synergistically enhancing performance.

Task-specific performance improvements have also been reported in labour scenarios. Bouffard et al. (2025) highlighted that arm-support exoskeletons effectively reduce deltoid and trapezius muscle activity associated with upper extremity work. However, challenges include ensuring that such assistance does not inadvertently increase strain on other body regions or prolong task completion times, underscoring the need for holistic ergonomic evaluations before implementation.

Technological advancements further enhance biomechanical assessment and ergonomic optimisation. Rettenmeier et al. (2024) used model-driven approaches to assess exoskeleton applications in traction battery dismantling, providing practical recommendations for ergonomic benefits within specific manual assembly steps.

Finally, integrating cognitive training and digital technologies into exoskeleton-related workflows as proposed by Longo et al. (2023) supports enhanced ergonomic outcomes by improving situational awareness and worker competence, further reducing biomechanical strain and enhancing overall worker safety and productivity.

Together, these studies demonstrate that exoskeletons contribute substantially to ergonomic improvements and biomechanical relief in various occupational settings, yet the design and application must be tailored to the complexities of human variability, task demands, and technological integration.

Barriers and challenges remain significant impediments to the widespread adoption of exoskeletons in occupational settings. Physical barriers such as improper fit, excessive weight, and discomfort are frequently reported by users, hindering usability and compatibility with specific work tasks (Gutierrez et al., 2024; Nnaji et al., 2023). Fit issues can lead to restricted movement and increased discomfort, undermining the potential ergonomic benefits. Usability and comfort concerns also encompass donning and doffing difficulties, which affect how consistently workers may use these devices during shifts (Schwerha et al., 2021).

Functional risks surrounding exoskeleton use include catch and snag hazards that arise from external elements interacting with exoskeleton components, leading to increased safety risks on dynamic job sites such as construction (Nnaji et al., 2023). Mobility restrictions imposed by the rigid or semi-rigid structural designs can limit operators' freedom of movement, potentially disrupting task performance or causing compensatory biomechanical stresses (Bonakdar et al., 2025).

Psychosocial barriers have emerged as critical factors influencing user acceptance. Users may experience a sense of dehumanisation or altered self-perception when wearing exoskeletons, linked to how the technology modifies body image and personal identity (Siedl and Mara, 2024). Trust in the technology is another significant concern, with some workers showing scepticism about the devices' reliability and fear of impaired safety, which can negatively affect adoption rates (Gutierrez et al., 2024; Ojha et al., 2025).

Economic considerations, including cost justification and return on investment (ROI), are frequently cited as obstacles by corporate decision-makers. Despite demonstrated ergonomic and productivity benefits, the high upfront costs and uncertainties regarding long-term advantages limit organisational willingness to invest extensively (Gonsalves et al., 2024; Gutierrez et al., 2024). This economic hesitation is particularly evident within small and medium-sized enterprises, where resource limitations are more pronounced (Schwerha et al., 2021).

Further organisational and social acceptance challenges include concerns over worker acceptance, social stigma, and disruptions to established workplace norms (Pupkes et al., 2025). Limited knowledge, inexperience with exoskeleton technology, and insufficient training programs contribute to resistance and slow diffusion across industries (Gutierrez et al., 2024; Musarat et al., 2024). Multi-stakeholder involvement, including supervisors, safety personnel, and ergonomists, is critical to effectively address these barriers and foster acceptance (Gonsalves et al., 2024).

Previous research suggested a proven improvement in workplace safety with exoskeleton integration. However, the integration requires a thorough investigation of potential hazards, human factors, and task-specific needs to enhance user acceptance and effectiveness (Joshi et al., 2023; Kim et al., 2019; Koopman et al., 2020; Preethichandra et al., 2024).

Overall, addressing these multifaceted barriers requires a holistic approach involving user-centred design improvements, economic incentives, thorough safety evaluations, and organisational strategies emphasising participatory implementation and social integration.

## **SAFETY RISK MITIGATION AND REGULATORY GAPS**

The integration of exoskeletons in occupational settings introduces several safety and ergonomic risks that require comprehensive mitigation strategies and regulatory oversight. Nnaji et al. (2024) conducted a scoping review that identified 36 distinct hazards related to occupational health and safety associated with

wearable robots in construction. These hazards encompass ergonomic concerns such as musculoskeletal strain, joint motion restrictions, and novel risks stemming from human-robot interaction (HRI). These hazards underscore the need for layered safety controls encompassing design, organizational policies, and worker training. Similarly, Bonakdar et al. (2025) assert that poor ergonomic designs and misuse can elevate injury risks, underscoring the importance of incorporating safety considerations at the initial design stage and implementing risk-informed enhancements to human-machine interfaces.

Mitigation strategies outlined by Arkouli et al. (2021) involve balanced cooperative robot-human workstations and safety protocols, including real-time monitoring through sensor integration and adaptive automation that accounts for operator fatigue and task complexity. Nnaji et al. (2023) promote a combination of engineering controls, administrative approaches, and worker education to address risks such as catch and snag hazards, mobility limitations, and physiological overload. These measures align with proposals for comprehensive training programs and participatory design approaches to ensure safety and acceptance.

From a regulatory perspective, Fosch-Villaronga et al. (2023) critically analysed ISO 13482:2014, the primary standard addressing safety requirements for robotic personal care devices, including exoskeletons. The standard demonstrates significant limitations, notably in its insufficient treatment of safety, neglect of legal liabilities, and failure to adequately consider ethical and societal impacts. The absence of comprehensive risk assessment frameworks within the standard creates gaps that may expose users to harm despite compliance. Fosch-Villaronga et al. recommend augmenting ISO 13482 with detailed risk management protocols and embedding ethical considerations, such as privacy safeguards and accountability mechanisms, into regulatory frameworks.

Moreover, ethical and societal concerns involve the psychological impact of exoskeleton use. Siedl and Mara (2024) discussed potential user self-dehumanisation manifested as altered self-perceptions of warmth and attractiveness when wearing exoskeletons, raising questions about long-term social acceptance and ethical deployment. This ethical dimension complements safety considerations and implies a need for responsible design that preserves human dignity.

Bonakdar et al. (2025) also highlight the importance of validating emerging markerless motion capture technologies for ergonomic assessment to improve risk detection and reduce reliance on intrusive wearable sensors, enhancing safety monitoring in operational environments.

This review presents the need for proactive safety mitigation measures, highlighting the importance of robust regulatory frameworks, risk-informed design, and ethical considerations to ensure exoskeletons are safely and responsibly deployed in occupational settings (Heinold et al., 2023). The European Commission guidelines highlight the necessity of identifying hazards stemming from physical, psychological, organisational, communicative, cultural, and systematic factors. Additionally, the International Organization for

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Standardization advocates for the inclusion of all reasonably imaginable hazards into robot risk assessments (Lee et al., 2021).

## **EXOSKELETON DESIGNS, EVALUATION AND IMPLEMENTATION STRATEGIES**

The design and evaluation of exoskeletons have evolved significantly to address diverse occupational demands, incorporating innovations in active, passive, and hybrid systems that cater to differing ergonomic needs across industries. Powered exoskeletons often provide active assistance by reducing muscular load and fatigue, while passive variants rely on mechanical support structures, offering energy-efficient alternatives with lower power dependency (Bouffard et al., 2025; Liu et al., 2025). Hybrid designs seek to balance these approaches by optimising energy consumption and assistance levels. Thermal comfort, which is a critical design consideration, was extensively examined through the use of manikins and thermoregulation modelling. This approach simulates variations in sweat rate, skin temperature, and core body temperature during the application of exoskeletons in hot and humid environments (Joshi et al., 2023). The findings demonstrated that design modifications, including perforation, significantly improve evaporative cooling, which is essential for enhancing user comfort and safety.

The integration of digital twin models aids in real-time ergonomic optimisation, enabling continuous evaluation and adjustment to support individual operator needs (Gonsalves et al., 2024). Additionally, IoT devices facilitate continuous monitoring of biomechanical parameters and worker postures, feeding into adaptive systems designed to improve workflow and safety protocols (Benachour et al., 2025).

Despite laboratory validations, discrepancies exist between controlled testing environments and the field performance of exoskeletons. Users report varied experiences about comfort, safety, and psychosocial factors when transitioning from short-term lab trials to real-world use over extended periods (Bouffard et al., 2025; Ojha et al., 2025; Gonsalves et al., 2024). These disparities highlight challenges such as task variability, environmental conditions, and individual differences that affect usability and acceptance. Consequently, longitudinal studies and participatory design approaches incorporating end-user feedback during pilot deployments have become integral to refining exoskeleton integration strategies (Antwi-Afari et al., 2023; Marcon et al., 2025).

Successful implementation roadmaps emphasised comprehensive employer and worker training programs focused on device operation, health and safety considerations, and fostering positive attitudes towards exoskeleton use. Pilot programs served as crucial test beds for evaluating integration challenges and tailoring interventions to specific occupational contexts (Antwi-Afari et al., 2023). Real-world case studies, such as ergonomic assessments in manual disassembly tasks and maintenance operations, reveal the potential of exoskeletons to reduce physical strain while underscoring the need for task-specific adaptations and ergonomic validations (Moencks et al., 2022; Rettenmeier et al., 2024).

## INTEGRATION WITH INDUSTRY 4.0 AND FUTURE WORK

The use of exoskeletons in Industry 4.0 frameworks and the changing idea of the future of work are changing the manufacturing industry to be more focused on people. Exoskeletons are becoming more and more important parts of Smart Workplaces. They support the Operator 4.0 paradigm, which focuses on using sophisticated technology to increase safety, productivity, and well-being by enhancing human capacities (Rusu et al., 2021; Di Natali et al., 2023). Digital transformation makes it possible to record physiological data in real time, improve ergonomics, and provide adaptive assistance in these settings. This creates interactions between workers and technology that help both parties.

More fluid and adaptable human-exoskeleton partnerships are possible because of synergies with AI, XR/AR, HCI, and robotic systems. Rettenmeier et al. (2024) showed that combining AI-generated positioning data with optical assistance systems can make assembly activities much more efficient and make users more likely to accept them. Gualtieri et al. (2024) also updated design principles for cognitive ergonomics in collaborative robotics. They stressed how important it is to think about cognitive strain and user perceptions while designing the human-robot interface to make collaboration easier.

Industry 5.0 takes these human-centered prospects even farther by putting human-robot collaboration into manufacturing systems that are flexible, strong, and long-lasting. Longo et al. (2023) suggested using digital twins to drive cognitive training that would help workers learn new skills on the job, making it easier for them to work with robots on complex or unusual jobs. Romero et al. (2021) talk about the idea of "Resilient Operator 5.0," which stresses the need for smart manufacturing systems that are not only technologically advanced but also built with resilience and human-centered principles. This is supported by advanced human-machine interfaces and adaptive assistance tools. This concept fits with how exoskeletons are changing from only helping people physically to being built into cyber-physical production systems that can change based on what workers require and the situation.

Moreover, recent advancements focus on embedding the human-in-the-loop (HIL) paradigm into smart manufacturing, where human cognitive and physical capabilities continuously interact with AI and robotic systems. Kim et al. (2025) identified seven technological clusters and twenty-one key enabling technologies, including collaborative robotics and augmented reality, as essential for the implementation of HIL smart manufacturing. Yan et al. (2025) reinforced the importance of human-centric AI approaches that ensure reliability, safety, and trustworthiness in such systems.

The progression towards adaptive automation is also critical. Pollini et al. (2025) reviewed human-machine interaction design in adaptive automation technologies, proposing frameworks that dynamically allocate tasks based on real-time human and machine performance metrics to optimise collaboration and worker well-being.

Finally, digital twins and ergonomic surrogate modeling contribute to continuous assessment and customisation of workstations, enabling human-centred workplace reconfigurations that accommodate individual worker capabilities and reduce injury risks (Berti and Finco, 2022; Arkouli et al., 2024). These technological evolutions are coupled with ethical, social, and organisational considerations, ensuring the responsible integration of exoskeletons in future Industry 4.0 and 5.0 ecosystems.

For designers, managers, and regulators, the imperative is to prioritise human-centric and ethical development of exoskeleton technologies that respect worker dignity, privacy, and well-being while delivering measurable ergonomic benefits. Sustainable integration requires addressing social acceptance, equitable access, and comprehensive safety governance to realise the full potential of exoskeletons in augmenting workforce capability and preserving occupational health in evolving industrial contexts. As robotic technologies advance, exoskeletons have emerged as promising tools for rehabilitation and human augmentation (Ting et al., 2014). Exoskeleton robots are complex electromechanical devices engineered to bolster human motor skills, finding applications in motion amplification, rehabilitation, and therapy (Gull, 2022). Lower-limb exoskeletons, in particular, have garnered interest due to their capacity to aid individuals with paraplegia, hemiplegia, or monoplegia by assisting in walking and functional rehabilitation (Sadoun and Yacef, 2021). Upper limb exoskeletons reduce shoulder muscle activity depending on the workload (Plessis et al., 2021).

Technological advancements have enabled sophisticated control mechanisms, utilising methodologies such as force-based impedance control, which offers seamless human-robot interaction by adjusting to the user's movements and intentions (Kim et al., 2023). These advancements promote effective motor control restoration through complex, controlled rehabilitation treatments (Goffredo et al., 2020).

## **CONCLUSION**

This review highlights that exoskeleton integration in physically demanding workplaces offers substantial ergonomic and biomechanical benefits, including reduced muscular effort, improved load distribution, and enhanced task performance, which collectively contribute to enhanced worker safety and productivity. Despite these advantages, significant barriers remain, such as device fit, user comfort, functional limitations, psychosocial acceptance, and economic feasibility, which affect widespread adoption. Safety risks and regulatory gaps underline the need for comprehensive standards and tailored training protocols. Innovations in design and evaluation, coupled with participatory and human-centric approaches, are critical to overcoming these challenges. The incorporation of exoskeletons within Industry 4.0 and Industry 5.0 paradigms further expands their potential through advanced technologies and adaptive systems, promoting human-robot collaboration. Future research should prioritise addressing unresolved ergonomic issues, refining safety regulations, and exploring ethical considerations to facilitate sustainable and effective implementation of exoskeletons that enhance workforce health and operational resilience.

## REFERENCES

- Antwi-Afari, M. F., Li, H., Chan, A. H. S., Seo, J. O., Anwer, S., Mi, H. Y., Wu, Z., & Wong, A. Y. L. (2023). A science mapping-based review of work-related musculoskeletal disorders among construction workers. *Journal of Safety Research*, 85, 114–128. <https://doi.org/10.1016/j.jsr.2023.01.011>
- Arkouli, Z., Kokotinis, G., Michalos, G., Dimitropoulos, N., & Makris, S. (2021). AI-enhanced cooperating robots for reconfigurable manufacturing of large parts. *IFAC-PapersOnLine*, 54(1), 617–622. <https://doi.org/10.1016/j.ifacol.2021.08.072>
- Arkouli, Z., et al. (2024). Collaborative Human-Centred Design of Manufacturing Tasks: A Multi-User Immersive VR Experience. *Procedia CIRP*, Vol 128, 597-602.
- Bances, E., Wortmeier, A.-K., Bauernhansl, T., Garcia, B., Kropp, C., Schneider, U., & Siegert, J. (2022). Applicability of Exoskeletons in Timber Prefabrication: Actions for Exoskeleton Research. *Procedia CIRP*, 107, 1210–1215. <https://doi.org/10.1016/j.procir.2022.05.133>
- Benachour, Y., Rehman, M., & Flitti, F. (2025). Towards improved human arm movement analysis: Advanced feature engineering and model optimization. *Engineering Applications of Artificial Intelligence*, 156, 111194. <https://doi.org/10.1016/j.engappai.2025.111194>
- Berti, N., & Finco, S. (2022). Digital Twin and Human Factors in Manufacturing and Logistics Systems: State of the Art and Future Research Directions. *IFAC-PapersOnLine*, 55(10), 1893–1898. <https://doi.org/10.1016/j.ifacol.2022.09.675>
- Bogue, R. (2018). Exoskeletons – a review of industrial applications [Review of Exoskeletons – a review of industrial applications]. *Industrial Robot the International Journal of Robotics Research and Application*, 45(5), 585. Emerald Publishing Limited. <https://doi.org/10.1108/ir-05-2018-0109>
- Bonakdar, A., Riahi, N., Shakourisalim, M., Miller, L., Tavakoli, M., Rouhani, H., & Golabchi, A. (2025). Validation of markerless vision-based motion capture for ergonomics risk assessment. *International Journal of Industrial Ergonomics*, 107, 103734. <https://doi.org/10.1016/j.ergon.2025.103734>
- Bouffard, J., Campeau-Lecours, A., & Roy, J.-S. (2025). Arm supports for the prevention of work-related upper extremity disorders: A narrative review. *Journal of Hand Therapy*. <https://doi.org/10.1016/j.jht.2025.05.013>
- Bründl, P., Wegener, C., Stoidner, M., Bayer, J., Scheffler, B., Nguyen, H. G., & Franke, J. (2025). Designing worker assistance systems—Methodology development and industrial validation. *Journal of Manufacturing Systems*, 80, 272–293. <https://doi.org/10.1016/j.jmsy.2025.02.022>
- Cullen, L., Seaton, M., Janni, V., Pennathur, A., Pennathur, P., Blondin, M., & Stenger, K. (2025). Call to action to reduce the occupational hazard associated with patient handling for workforce preservation. *Nursing Outlook*, 73(3), 102402. <https://doi.org/10.1016/j.outlook.2025.102402>
- Di Natali, C., Mattila, J., Kolu, A., De Vito, P., Gauttier, S., Morata, M., Garcia, M., & Caldwell, D. (2023). Smart tools for railway inspection and maintenance work, performance and safety improvement. *Transportation Research Procedia*, 72, 3070–3077. <https://doi.org/10.1016/j.trpro.2023.11.856>
- Flor-Unda, O., Casa, B., Fuentes, M., Solórzano, S., Narváez, F., & Acosta-Vargas, P. (2023). Exoskeletons: Contribution to Occupational Health and Safety [Review of Exoskeletons: Contribution to Occupational Health and Safety]. *Bioengineering*, 10(9), 1039. Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/bioengineering10091039>
- Fosch-Villaronga, E., Calleja, C. J., Drukarch, H., & Torricelli, D. (2023). How can ISO 13482:2014 account for the ethical and social considerations of robotic exoskeletons? *Technology in Society*, 75, 102387. <https://doi.org/10.1016/j.techsoc.2023.102387>

- Goffredo, M., Infarinato, F., Pournajaf, S., Romano, P., Ottaviani, M., Pellicciari, L., Galafate, D., Gabbani, D., Gison, A., & Franceschini, M. (2020). Barriers to sEMG Assessment During Overground Robot-Assisted Gait Training in Subacute Stroke Patients. *Frontiers in Neurology*, 11. <https://doi.org/10.3389/fneur.2020.564067>
- Gonsalves, N., Afolabi, A., & Akanmu, A. A. (2025). Impact of social influence on construction workers' intention-to-use exoskeletons. *Smart and Sustainable Built Environment*, 14(4), 1073–1090. <https://doi.org/10.1108/SASBE-06-2023-0153>
- Gonsalves, N., Akanmu, A., Shojaei, A., & Agee, P. (2024). Factors influencing the adoption of passive exoskeletons in the construction industry: Industry perspectives. *International Journal of Industrial Ergonomics*, 100, 103549. <https://doi.org/10.1016/j.ergon.2024.103549>
- Gualtieri, L., Fraboni, F., & Dallasega, P., et al. (2024). Updating design guidelines for cognitive ergonomics in human-centred collaborative robotics applications: An expert survey. *Applied Ergonomics*, 117, 104246. <https://doi.org/10.1016/j.apergo.2024.104246>
- Gull, M. A. (2022). Design and bio-mechanical evaluation of upper-body exoskeletons for physical assistance. <https://doi.org/10.54337/au470866895>
- Gutierrez, N., Ojelade, A., Kim, S., Barr, A., Akanmu, A., Nussbaum, M. A., & Harris-Adamson, C. (2024). Perceived benefits, barriers, perceptions, and readiness to use exoskeletons in the construction industry: Differences by demographic characteristics. *Applied Ergonomics*, 116, 104199. <https://doi.org/10.1016/j.apergo.2023.104199>
- Heinold, E., Funk, M., Niehaus, S., Rosen, P. H., & Wischniewski, S. (2023). OSH related risks and opportunities for industrial human-robot interaction: results from literature and practice. *Frontiers in Robotics and AI*, 10. <https://doi.org/10.3389/frobt.2023.1277360>
- Joshi, A., Bartels, L., Viswanathan, S. H., Martínez, D. M., Sadeghi, K., Jaiswal, A. K., Collins, D., & Rykaczewski, K. (2023). Evaluation of thermal properties and thermoregulatory impacts of lower back exosuit using thermal manikin. *International Journal of Industrial Ergonomics*, 98, 103517. <https://doi.org/10.1016/j.ergon.2023.103517>
- Ke, J., Zhang, M., Luo, X., & Chen, J. (2021). Monitoring distraction of construction workers caused by noise using a wearable Electroencephalography (EEG) device. *Automation in Construction*, 125, 103598. <https://doi.org/10.1016/j.autcon.2021.103598>
- Khan, M., & Nnaji, C. (2025). Gender-specific effects of passive wearable exoskeletons (pwExo) on gait stability and fall risk in simulated construction tasks. *International Journal of Industrial Ergonomics*, 108, 103776. <https://doi.org/10.1016/j.ergon.2025.103776>
- Kim, D. B., Bajestani, M. S., Lee, J. Y., Shin, S.-J., Kim, G.-Y., Sajadieh, S. M. M., & Noh, S. (2025). Human-in-the-loop in smart manufacturing (H-SM): A review and perspective. *Journal of Manufacturing Systems*, 82, 178–199. <https://doi.org/10.1016/j.jmsy.2025.05.020>
- Kim, J., Ha, S., Shin, D., Ham, S., Jang, J., & Kim, W. (2023). Multitask Learning for Multiple Recognition Tasks: A Framework for Lower-limb Exoskeleton Robot Applications. 1530. <https://doi.org/10.1109/ro-man57019.2023.10309384>
- Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D., & Nussbaum, M. A. (2019). Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions. *IISE Transactions on Occupational Ergonomics and Human Factors*, 7, 185. <https://doi.org/10.1080/24725838.2018.1561557>
- Koopman, A. S., Näf, M. B., Baltrusch, S., Kingma, I., Rodriguez-Guerrero, C., Babič, J., Looze, M. P. de, & Dieën, J. H. van. (2020). Biomechanical evaluation of a new passive back support exoskeleton. *Journal of Biomechanics*, 105, 109795. <https://doi.org/10.1016/j.jbiomech.2020.109795>

- Lasota, A. (2020). A New Approach to Ergonomic Physical Risk Evaluation in Multi-Purpose Workplaces. *Tehnicki Vjesnik - Technical Gazette*, 27(2). <https://doi.org/10.17559/tv-20180312131319>
- Lee, K., Shin, J., & Lim, J. (2021). Critical Hazard Factors in the Risk Assessments of Industrial Robots: Causal Analysis and Case Studies. *Safety and Health at Work*, 12(4), 496. <https://doi.org/10.1016/j.shaw.2021.07.010>
- Longo, F., Padovano, A., De Felice, F., Petrillo, A., & Elbasheer, M. (2023). From “prepare for the unknown” to “train for what's coming”: A digital twin-driven and cognitive training approach for the workforce of the future in smart factories. *Journal of Industrial Information Integration*, 32, 100437. <https://doi.org/10.1016/j.jii.2023.100437>
- Ma, T., & Xiong, S. (2025). A novel biomechanical model for predicting ankle moments and assessing static balance in users of shoulder-support exoskeletons. *International Journal of Industrial Ergonomics*, 105, 103688. <https://doi.org/10.1016/j.ergon.2024.103688>
- Marcon, E., Soliman, M., Ayala, N. F., Sturgeon, T., & Frank, A. G. (2025). A system view of how balancing sociotechnical factors in Industry 4.0 implementation: Evidence from interviews and ethnographic research. *Computers & Industrial Engineering*, 203, 111047. <https://doi.org/10.1016/j.cie.2025.111047>
- Moencks, M., Roth, E., Bohné, T., Romero, D., & Stahre, J. (2022). Augmented Workforce Canvas: A management tool for guiding human-centric, value-driven human-technology integration in industry. *Computers & Industrial Engineering*, 163, 107803. <https://doi.org/10.1016/j.cie.2021.107803>
- Mukherjee, T. R., Tyagi, O., & Mehta, R. K. (2025). Differences in neural strategies explain exoskeleton-related benefits in performance over time during complex visuomotor wiring tasks. *Applied Ergonomics*, 127, 104532. <https://doi.org/10.1016/j.apergo.2025.104532>
- Musarat, M. A., Alaloul, W. S., & Khan, A. M. (2024). A survey-based approach of framework development for improving the application of internet of things in the construction industry of Malaysia. *Results in Engineering*, 21, 101823. <https://doi.org/10.1016/j.rineng.2024.101823>
- Nnaji, C., Okpala, I., Gambatese, J., & Jin, Z. (2023). Controlling safety and health challenges intrinsic in exoskeleton use in construction. *Safety Science*, 157, 105943. <https://doi.org/10.1016/j.ssci.2022.105943>
- Ojha, A., Gautam, Y., Jebelli, H., & Akanmu, A. (2024). Physiological impact of powered back-support exoskeletons in construction: Analyzing muscle fatigue, metabolic cost, ergonomic risks, and stability. *Automation in Construction*, 168, 105742. <https://doi.org/10.1016/j.autcon.2024.105742>
- Ojha, A., Gautam, Y., Jebelli, H., & Akanmu, A. (2025). Psychophysiological impacts of working with powered exoskeletons on construction sites. *Automation in Construction*, 177, 106312. <https://doi.org/10.1016/j.autcon.2025.106312>
- Park, J.-H., Madigan, M. L., Kim, S., Nussbaum, M. A., & Srinivasan, D. (2024). Wearing a back-support exoskeleton alters lower-limb joint kinetics during single-step recovery following a forward loss of balance. *Journal of Biomechanics*, 166, 112069. <https://doi.org/10.1016/j.jbiomech.2024.112069>
- Plessis, T. du, Djouani, K., & Oosthuizen, C. (2021). A Review of Active Hand Exoskeletons for Rehabilitation and Assistance [Review of A Review of Active Hand Exoskeletons for Rehabilitation and Assistance]. *Robotics*, 10(1), 40. Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/robotics10010040>
- Pollini, A., Giacobone, G. A., Zannoni, M., Pucci, D., Vignali, V., Falegnami, A., & Romano, E. (2025). Human–Machine Interaction Design in Adaptive Automation. *Procedia Computer Science*, 253, 1034–1044. <https://doi.org/10.1016/j.procs.2025.01.165>
- Preethichandra, D. M. G., Piyathilaka, L., Sul, J.-H., Izhar, U., Samarasinghe, R., Arachchige, S. D., & Silva, L. C. D. (2024). Passive and Active Exoskeleton Solutions: Sensors, Actuators, Applications, and Recent Trends [Review of Passive and Active Exoskeleton

- Solutions: Sensors, Actuators, Applications, and Recent Trends]. *Sensors*, 24(21), 7095. Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/s24217095>
- Pupkes, B., Petzoldt, C., & Freitag, M. (2025). User Expectations, Requirements, and Applications of Exoskeletons: Insights from a Survey. *Procedia CIRP*, 134, 91–96. <https://doi.org/10.1016/j.procir.2025.01.100>.
- Rettenmeier, M., et al. (2024). Model-driven evaluation of exoskeletons for efficient traction battery dismantling. *Procedia CIRP* 130 (2024), ScienceDirect.
- Romero, D. and Stahre, J. (2021). Towards The Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems. *Procedia CIRP*, 104, 1089–1094. <https://doi.org/10.1016/j.procir.2021.11.183>
- Rusu, C.-A., Constantinescu, C., & Marinescu, S.-C. (2021). A generic hybrid Human/Exoskeleton Digital Model towards Digital Transformation of Exoskeletons-integrated workplaces. *Procedia CIRP*, 104, 1787–1790. <https://doi.org/10.1016/j.procir.2021.11.301>
- Sadoun, M.-S.-N., & Yacef, F. (2021). Optimal Adaptive Control of a Knee Joint Exoskeleton for Lower Limb Functional Rehabilitation. 1. <https://doi.org/10.1109/icrami52622.2021.9585967>
- Schwerha, D. J., McNamara, N., Nussbaum, M. A., & Kim, S. (2021). Adoption potential of occupational exoskeletons in diverse enterprises engaged in manufacturing tasks. *International Journal of Industrial Ergonomics*, 82, 103103. <https://doi.org/10.1016/j.ergon.2021.103103>
- Siedl, S. M. and Mara, M. (2024). Am I still human? Wearing an exoskeleton impacts self-perceptions of warmth, competence, attractiveness, and machine-likeness. *Computers in Human Behavior: Artificial Humans*, 2(2), 100073. <https://doi.org/10.1016/j.chbah.2024.100073>
- Ting, C.-H., Yeo, W. H., King, Y.-J., Chuah, Y. D., Lee, J.-V., & Khaw, W.-B. (2014). Humanoid Robot: A Review of the Architecture, Applications and Future Trend [Review of Humanoid Robot: A Review of the Architecture, Applications and Future Trend]. *Research Journal of Applied Sciences Engineering and Technology*, 7(7), 1364. Maxwell Scientific Publications. <https://doi.org/10.19026/rjaset.7.402>
- Toxiri, S., Näf, M. B., Lazzaroni, M., Roa-Fernández, J., Sposito, M., Poliero, T., Monica, L., Anastasi, S., Caldwell, D. G., & Ortiz, J. (2019). Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends. *IISE Transactions on Occupational Ergonomics and Human Factors*, 7, 237. <https://doi.org/10.1080/24725838.2019.1626303>
- Weckenborg, C., Thies, C., & Spengler, T. S. (2022). Harmonizing ergonomics and economics of assembly lines using collaborative robots and exoskeletons. *Journal of Manufacturing Systems*, 62, 681–702. <https://doi.org/10.1016/j.jmsy.2022.02.005>
- Yan, J., Liu, Z., Leng, J., Zhao, J. L., Chen, C., Zhang, D., & Wang, Y. (2025). Human-centric artificial intelligence towards Industry 5.0: Retrospect and prospect. *Journal of Industrial Information Integration*, 47, 100903. <https://doi.org/10.1016/j.jii.2025.100903>.
- Zhu, Z., Dutta, A., & Dai, F. (2020). Exoskeletons for manual material handling – A review and implication for construction applications [Review of Exoskeletons for manual material handling – A review and implication for construction applications]. *Automation in Construction*, 122, 103493. Elsevier BV. <https://doi.org/10.1016/j>