EXOSKELETON FOR HEALTH AND SAFETY IN CONSTRUCTION WORKERS: A LITERATURE REVIEW

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Abstract: Health and safety in construction are critical concerns, and exoskeletons present a promising solution to mitigate these issues. Designed to improve the ergonomics of wearers, exoskeletons are increasingly used across various industries. While this technology is relatively new to the Sri Lankan construction sector, it is already employed in many developed countries. The research aims to develop a conceptual framework for implementing exoskeletons among construction workers in Sri Lanka. A comprehensive literature review was conducted to assess the impact of exoskeletons on worker health and safety, emphasizing their ergonomic benefits and potential barriers to adoption. Findings indicate that exoskeletons have significant potential in reducing work-related musculoskeletal disorders (WMSDs) when properly integrated into construction tasks. The study proposes a conceptual framework that assists managers in selecting suitable exoskeleton types and tasks, aiming to enhance worker safety and productivity. This framework contributes to the construction industry by offering a structured approach to implementing exoskeletons, thereby addressing unique sector challenges and improving overall occupational health outcomes. Future research should focus on practical implementations and further exploration of barriers and facilitators to optimize exoskeleton adoption in construction contexts.

Keywords: *Barriers, Benefits, Construction workers, Exoskeleton, H&S*

1. Introduction

Workers are exposed to a wide range of hazardous substances that have the potential to cause serious health and occupational diseases (Gupta, 2021). According to the Occupational Safety and Health Administration (2018), health hazards include chemical hazards, biological hazards (infectious diseases), physical hazards, and ergonomic risk factors (repetitive motions, heavy lifting, vibration). Accidents at construction sites can result in lasting physical injuries, illnesses, and deaths, and often cause construction workers to retire early due to overexertion and work-related musculoskeletal disorders (WMSD) (Anton, Mizner and Hess, 2013; Salim et al., 2017). As an approach to human-oriented work design, ergonomics is the study of human interaction with the surrounding environment to improve human safety (Golabchi et al., 2018). Furthermore, health and safety(H&S) problems impact productivity, cost for the companies, the quality of work, and the economy (Nnaji and Karakhan, 2020; Rosen and Isabella, 2022). Hence, there is a need to identify causes for H&S issues to implement the solution. Further, Ahamed et al. (2011) explain that operating without guidance, not wearing personal protective equipment, and working with moving machinery also cause these problems. Due to these reasons, it is obvious that health and safety must be properly managed using new technologies.

Therefore, Mihić et al. (2019) analyze the importance of considering innovative models for construction place safety. Accordingly, building information modelling (BIM) (Martínez-Aires, López-Alonso and Martínez-Rojas, 2018), and 4D computer-aided design (4D CAD) (Mihić, Vukomanović and Završki, 2019) can be implemented as solutions for these issues. In addition, Bock et al. (2012), Petrullo et al. (2017), and Teizer (2015) highlighted that digital technologies include Virtual reality (VR), unmanned aerial vehicles, online databases, geographic information systems (GIS), exoskeletons and sensor-based technology such as accident prevention and on-site safety. Exoskeletons can reduce physical demand and fatigue of body parts and achieve high user acceptance (Gonsalves et al., 2021). Therefore, exoskeleton ergonomics is a great solution to mitigate health and safety problems (Kim et al., 2019; Okpala et al., 2022; Rosen and Isabella, 2022).

Anastasi et al. (2019) define exoskeletons which were invented by the Russian scientist “Nicholas Yang” in 1890 as electromechanical devices worn by a human operator designed to enhance or assist physical activity by generating forces or torques on human joints. The exoskeleton increases performance through ergonomics support which improves performance through human-machine interaction with load-carrying capacity, decreasing metabolic expenditure, or running at a faster pace (Bridger, 2008; Anastasi *et al.*, 2019; Rosen and Isabella, 2022). Bogue (2018) explains the exoskeleton's primary purpose is to prevent occupational injuries and associated financial consequences. The lighter weight,

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smaller size, and less hardware are vital in working with them (Mertz, 2012). A fully automated system can be the solution to this problem, nevertheless, a fully automated system is that it is not always possible, since it is not suitable for all the work and is expensive (de Looze *et al.*, 2016).

There is research conducted by Gunasekara et al. (2012) on the "Control methodologies for upper limb exoskeleton robots" for the manufacturing industry in Sri Lanka. However, there is a lack of research on exoskeletons for construction workers' health and safety in the Sri Lankan context. Therefore, this research aims to develop a framework for exoskeleton implementation for construction workers. The structure of the paper is as follows: It begins with an outline of the methodological approach. This is followed by the presentation of research findings, derived from an extensive literature review. Finally, the paper concludes with a summary and suggestions for future research.

2. Methodology

A background study was undertaken to explore the potential of utilizing exoskeletons to improve health and safety conditions for construction workers. This preliminary investigation highlighted the necessity of conducting a detailed study focused on implementing exoskeleton technology within the construction industry to enhance health and safety standards. As part of this process, a comprehensive literature review was conducted to synthesize existing research, since it helps establish the theoretical foundation and contextual background necessary for the study (Creswell, 2009). Thus, to have a thorough grasp of exoskeleton ergonomics, this research is based on the results of a literature analysis. Further, to summarize the results, the literature was critically assessed. To identify the idea of exoskeleton, applications, available types, benefits, and barriers in the construction sector, comprehensive literature research was undertaken by consulting books, papers, theses, journals, magazines, and conference proceedings. Thus, literature review followed a stringent screening process, concentrating on studies pertinent to 'exoskeletons in construction', 'ergonomics', and 'safety benefits'. Peer-reviewed articles, theses, and conference proceedings accessible through databases such as Scopus, Google Scholar, Emerald, and Science Direct were included. Approximately 150 sources were examined to ensure relevance and high quality, with outdated or non-peer-reviewed materials excluded from consideration. The collected data from the literature review was analysed using the content analysis method since this method has a straightforward criterion for categorising data to improve the contextual significance (Kyngäs, 2020). A conceptual framework was developed from the findings since it acts as an important research element that assists further investigations on the research area (Martín et al., 2019).

3. Results & Findings

3.1 HEALTH AND SAFETY IN THE CONSTRUCTION INDUSTRY

Mihić et al. (2019) highlighted that the construction industry is one of the most dangerous industries to work in and H&S is the most critical aspect. Due to hazardous work environments on construction sites, workers are frequently exposed to potential safety and health risks throughout the construction process. Giri (2020) defines health as the protection of the body and mind of people from diseases brought about by the materials, methods, or processes used in work. Safety is about protecting people from physical injury. Further, safety is defined as protecting people from physical injury (OSHA, 2021). These two terms are usually combined to express concern for the employee's physical and mental health at work (Giri, 2020). According to the Occupational Safety and Health Administration (OSHA) (2021), H&S in construction is a set of practices, regulations, and measures for protecting the well-being and safety of workers, contractors, and the public during construction activities. The boundary between H&S is ill-defined and the two words are usually used together to refer to the concern for the physical and mental well-being of the individual in the workplace (Huges & Ferrett, 2016). This understanding transitions seamlessly into a focused exploration of its applications within the construction industry.

The scope of H&S has grown continuously, considering changes in the economy, technology, politics, and society. Since each employee shares this commitment, everyone will gain from a safe work environment (Khoso *et al.*, 2017). Therefore, the critical importance of health and safety in construction lies in its fundamental role in safeguarding workers' well-being and mitigating risks, emphasizing the necessity of a comprehensive framework for a secure construction environment.

3.2 INTRODUCTION TO EXOSKELETON

The field of human factors plays a crucial role in studying, assessing, and improving the exoskeleton design to improve the human-exoskeleton interface (Kuber and Rashedi, 2021). Wearable robots known as Exo interact closely with humans both physically and cognitively (Pons, 2010). These are rigid robotic exoskeletal structures that typically operate alongside human limbs (Pons, 2008). According to Constantinescu et al. (2019), the main objective of EXO is the optimization of human ergonomics and the production system. An exoskeleton is a mechanical apparatus designed to enhance the ergonomic and biomechanical performance of the wearer while reducing the physical strain associated with specific tasks or activities (Rosen and Isabella, 2022). Figure 1 demonstrates how construction workers in developed countries use exoskeletons to make material handling work efficient and safe.

Figure 1: Exoskeleton application for the construction industry (*Source:* Timken World, 2022*)*

The primary objectives of an exoskeleton are to improve user comfort, reduce the risk of injury, enhance physical capabilities, and optimize efficiency in a range of applications, from manual labour to medical rehabilitation. Therefore, this review article employs human factors principles to identify, classify, and offer potential design improvements in exoskeletons, considering the ergonomics between the wearer and the device. The main benefit of the application of an exoskeleton above any type of robot system (classical robots, full-automation systems, or humanoid robots), would be that, specifically in dynamic environments, one will fully profit from the human's creativity and flexibility, while there is thus no need for robot programming or teaching of robots (de Looze et al., 2016). These products are often heavy and used for longer periods, increasing the risk of causing fatigue and strain disorders. WMSDs are costly for companies and negatively impact the worker's quality of life. Golabchi et al. (2018) suggest that to increase the safety of the workplace, investigating how ergonomic aids could be used and developed for this industry is necessary. The exploration of ergonomic exoskeletons naturally segues into an in-depth examination of the various types available, fostering a comprehensive understanding of the diverse landscape within this innovative field.

3.3 TYPES OF EXOSKELETONS

Exoskeletons come in different types, powered for enhanced strength, passive for mechanical support, full-body or partial designs, and contrast between soft, flexible models and rigid, solid structures (Ren *et al.*, 2021). The two primary categories of exoskeletons are typically passive and active exoskeletons (Rosen and Isabella, 2022). McFarland and Fischer (2019) highlighted that the effectiveness and efficiency of exoskeletons can be strengthened, and samples representative of industrial workers can be included to improve the quality of the research. A passive exoskeleton relies on the user providing the energy necessary to maintain postures or movements, whereas an active exoskeleton has external sources, like batteries, that supply extra energy (Rosen and Isabella, 2022). Compared to active exoskeleton systems, these passive exoskeleton systems do not require force to support the human body, and thus, are lighter in weight and present fewer safety risks to users (Rosen & Isabella, 2022).

According to their purpose of use, there are two types of exoskeletons available: load augmentation and gait assistance. Another name for load augmentation is strength augmentation which is a wearable robotic device intended to improve a wearer's physical strength and capabilities, especially when it comes to tasks that require an able-bodied person to lift heavy objects for extended periods (Singla et al., 2016). Gait assistance for able and disabled persons enables them to perform various mobility tasks for normal daily living activities independently (Singla, Virk and Dhand, 2016). This technology aims to provide support, stability, and improved mobility to users who may experience difficulties with walking due to various reasons, such as injury, disability, or age-related issues.

Additionally, there are two other types of exoskeletons: back supporting and upper/lower limb exoskeletons. Back-supporting exoskeletons are used to reduce the risk of lower back pain and injury for workers in various possible application sectors, including assembly in automotive and aerospace, logistics, construction, healthcare, and agriculture (Anastasi *et al.*, 2019). Upper limb exoskeletons are used to minimize workers' mechanical exposure to both short-term and long-term occupational risk factors and to guarantee that manual labour complies with ergonomic principles (Spada et al., 2017).

3.4 THE POTENTIAL BENEFITS OF EXOSKELETON ERGONOMICS IMPLEMENTATION FOR CONSTRUCTION WORKERS

The construction industry is labour-intensive and construction workers are frequently involved in manual handling tasks for material lifting or hauling, plastering, paving, surfacing, scaffolding, and other activities. The continual engagement in such physically demanding tasks exposes the workers to significant risk for WMSDs (Bennett et al., 2023). According to the study of Kim et al. (2019), exoskeletons held the promise of helping individuals complete their tasks more quickly and with less physical exertion, ultimately making their work more manageable. Moreover, almost all believed that using exoskeletons could significantly reduce the incidence of musculoskeletal injuries and disorders Babalola et al. (2023), which, in turn, could play a crucial role in retaining workers within the industry. Babalola et al. (2023) investigate that exoskeletons

can address issues such as heavy lifting, twisting, and repetitive turning, making the workplace more ergonomically sound and allowing workers to work at a faster pace while maintaining their health and longevity. According to the authors main benefit workers achieve is the reduced maximal activity of trunk extensor Figure 2 shows how construction workers use exoskeletons for different applications.

Figure 2: Exoskeleton application for the construction industry *(Source:* (HILTI Production, 2023*)*

As Figure 2 exoskeletons can provide valuable support and assistance to maintain proper body postures and facilitate movements while working, workers are expected to perform their tasks more easily and effectively. muscles during repetitive lifting (Kim et al., 2018; Alemi et al., 2020; Zhu, Dutta and Dai, 2021). Therefore, Exoskeletons have proven invaluable in enhancing the health and safety of construction workers by addressing ergonomic challenges (Rosen and Isabella, 2022). Table 1 highlights the potential effects of these technologies on improving overall working conditions in the construction industry by demonstrating how exoskeletons can improve ergonomic conditions and thus improve the safety and well-being of construction workers.

Table 1: Benefits of Exoskeletons to construction workers

No	Construction Worker	Benefits	References
1	Electrician	Lowering the peak loading on the shoulders	[1]
		Reducing overall muscle activity for static/repetitive overhead task	[5], [6]
		Address body tension from twisting and reaching overhead, contact stress on the knees, and forceful effort when using a particular tool.	[5], [6]
2	Carpenter	Lowering the peak loading on the shoulders	[1]
		Lowering the peak loading on the knees, forceful exertion while assembling, dissembling, lifting & carrying	[2], [3], [9]
3	Heating A/C mechanic	Repetitive bending, working with hands and arms above shoulder level, and exertion when handling heavy equipment be addressed.	[1]
4	Labourer	Address repetitive bending, forceful exertion, and repetitive motion in manual material handle, & contact stress in kneeling	[1], [3], [9]
5	Plumber	Alleviate muscle strain and sprain due to heavy lifting, pulling, pushing, pipe fitting, and considerable work overhead	[1], [3]
		Safety at heights and adaptability to operate in small, tight spaces	[5], [6]
6	Welder	Alleviate long-time use of metal inert gas (MIG) guns, forceful pushing, pulling, and heavy lifting, and contact stress of knees.	[1], [3]
		void's flammability and adaptability to operate in a small area	[5], [6]
7	Brickman	Reducing peak activity of trunk extensor muscles in repetitive lifting	[1], [2]
		Assist masonry workers in lifting and carrying heavy bricks and blocks, reducing the risk of back injuries & muscle strain	[2]
8	Plasterer	Assist in working above shoulder & reaching overhead, working below knee level, and working when kneeling	[1]
9	Concreter	Reduce Back pain, shoulder, wrist region, and neck	[1]
[1] - (Zhu, Dutta and Dai, 2021), [2] - (Alemi et al., 2020), [3] - (Alabdulkarim and Nussbaum, 2019), [4] - (Marino, 2019), [5] - (Van Engelhoven et al., 2019), [6] - (Kim et al., 2018), [7] -(Rosman and Mahmud, 2021), [8] - (Gopura et al., 2023), [9] - (Gutierrez et al., 2024)			

Table 1 outlines the benefits of implementing Exo for various construction worker roles. Each row represents a different occupation, detailing the advantages of EXOs in addressing particular ergonomic challenges. According to the table main benefit workers achieve is the reduced maximal activity of trunk extensor muscles during repetitive lifting (Kim et al., 2018; Alemi et al., 2020; Zhu, Dutta and Dai, 2021). Therefore, Exoskeletons have proven invaluable in enhancing the health and safety of construction workers by addressing ergonomic challenges (Rosen and Isabella, 2022).

3.5 BARRIERS TO EXOSKELETON ERGONOMICS ON H &S IN CONSTRUCTION WORKERS

Exoskeletons provide significant benefits such as augmenting physical force, offering support, facilitating task completion, reducing muscle exertion, and enhancing overall performance. However, several barriers must be addressed to ensure their effective implementation (Kuber & Rashedi, 2021). Currently, there are no established safety inspection protocols for exoskeletons to ensure the safe use of these devices. According to Bennett et al. (2022), if a device fails while performing a task, there may be severe safety consequences. When a worker is constantly performing heavy-duty work while wearing an exoskeleton, a worker might develop a misconception regarding his/her capability. This misconception about personal augmented capability might lead to the worker intuitively performing heavy work when not wearing an exoskeleton, which could result in injury (Bennett et al., 2022). An issue that was raised was that it looked like the harnesses that are worn when working at higher heights, which often are considered uncomfortable to wear. Although it was described that they get used to wearing it after some time, many people are still hesitant to wear it (Rosen and Isabella, 2022).

Another significant barrier is financial barriers. In practical terms, the costs associated with the equipment, automation, and training necessary for exoskeleton implementation can limit their widespread adoption (Okpala et al., 2022). As exoskeletons have not been widely used in the construction industry, the potential returns on investment (ROI) and even how to estimate ROI are unknown. For this reason, the industry is hesitant about investing in exoskeletons without having a proven ROI. Further, if the device's use requires learning, is time-consuming or space-consuming, loads are within the operator's strength, movement is restricted, or any of these reasons, the operator may choose not to use it (Kuber & Rashedi, 2021).

One notable drawback lies in the inherent restriction of movement imposed by the exoskeleton design which limits a person’s ability to perform various common activities such as running and stair descent, decreasing locomotion performance (Yandell, Tacca and Zelik, 2019). The rigid structure, while offering support, can pose limitations on the natural range of motion, potentially hindering the fluidity of certain tasks. Additionally, users may experience discomfort attributable to the exoskeleton's structure, as prolonged wear may lead to pressure points or chafing, highlighting the importance of ergonomic considerations in the design (Okpala et al., 2022). Nnaji & Karakhan (2020) explains that the process of donning the devices can be complicated, demanding additional time and effort from users. Simplifying this aspect can significantly contribute to the seamless integration of exoskeletons into various work environments.

The weight of devices is a relevant concern (Okpala et al., 2022). Designed to increase human capabilities, the added weight can become a contributing factor to user fatigue over long periods. Addressing this aspect by exploring lightweight materials or optimizing structural design can improve user comfort and extend the duration of effective use (Bennett et al., 2022). Recognizing the challenges associated with exoskeleton technology underscores the importance of implementing strategic approaches to overcome these barriers (Bennett et al., 2022). By proactively addressing these challenges through strategic advancements, we can tailor exoskeleton to better align with our intended purposes, ensuring that these devices not only meet industry needs but also provide a seamless and user-friendly solution for enhanced productivity and occupational well-being.

3.6 STRATEGIES FOR EXOSKELETON ERGONOMICS TO IMPROVE H &S IN CONSTRUCTION WORKERS

The implementation of exoskeleton ergonomics faces obstacles that warrant exploration, particularly concerning the health and safety of construction workers. To overcome these barriers, several areas need improvement, and various strategies can be employed to address these barriers. Huysamen et al. (2018) suggest a longer training phase could be implemented before the use of the device so that users are more familiar and comfortable with the exoskeleton. Testing protocols are essential to ensure the safety of exoskeleton devices and prevent accidents when performing tasks with them (Jia-Yong et al., 2020). A specific inspection and maintenance schedule may be desirable to detect wear and tear and malfunctions promptly and perform necessary repair and replacement activities to ensure exoskeleton safety (Bennett et al., 2022).

Compounding these form-factor concerns is the potential issue of artificial joints in exoskeletons, which, if misaligned, can negatively impact user performance and comfort (Yandell et al., 2019). Therefore, innovative designs have been developed to reduce physical bulk and range-of-motion restrictions. Another potential solution is to offer manufacturers partnership training programs with trade schools, contractors, associations, and apprentice training programs to increase awareness and knowledge of exoskeletons and their use in industry (Bennett et al., 2022). Providing workers with opportunities to utilize exoskeleton products beyond conventional workplaces, such as in home remodelling projects, can yield substantial benefits. When workers can apply exoskeletons in varied contexts, they acquire invaluable hands-on experience that transcends the limitations of their typical work environments (Constantinescu et al., 2019). Bennett et al. (2022) describe this exposure not only allows them to familiarize themselves with the capabilities and limitations of the technology but also encourages a more nuanced understanding of its practical applications. In addition, this approach fosters

a sense of ownership and comfort with the technology, contributing to a seamless integration of exoskeletons into their professional repertoire (Bennett et al., 2022). Exoskeletons can be incorporated into high school and college curricula to build awareness among students before they join the workforce as professionals upon graduation. Providing students with access to exoskeletons will enable them to study, experiment with, and evaluate the technology. This approach will ultimately help bridge the knowledge gaps regarding the use of exoskeletons and enhance the development of exoskeleton products, thereby making them more viable for application in the construction industry (Okpala et al., 2022).

Further, encourage research and development to make exoskeletons more cost-effective through advancements in materials, manufacturing processes, and economies of scale (Jia-Yong et al., 2020). Implement awareness campaigns highlighting the positive impact of exoskeletons on health, safety, and productivity. Showcasing successful case studies and testimonials can effectively demonstrate the benefits and practical applications of exoskeletons (Bennett et al., 2022). Additionally, construction businesses can deepen their understanding of exoskeleton technology by collaborating with exoskeleton experts, who can also facilitate trials within companies (Bennett et al., 2022).

3.7 CONCEPTUAL FRAMEWORK

Through the literature survey, it became apparent that there is a need to identify the potential of exoskeletons for construction workers. The conceptual framework, shown in Figure 3, was developed based on the findings from the literature review and aims to address the barriers and strategies identified. This framework provides a structured approach to understanding and implementing exoskeletons in the construction industry, with components derived directly from key findings.

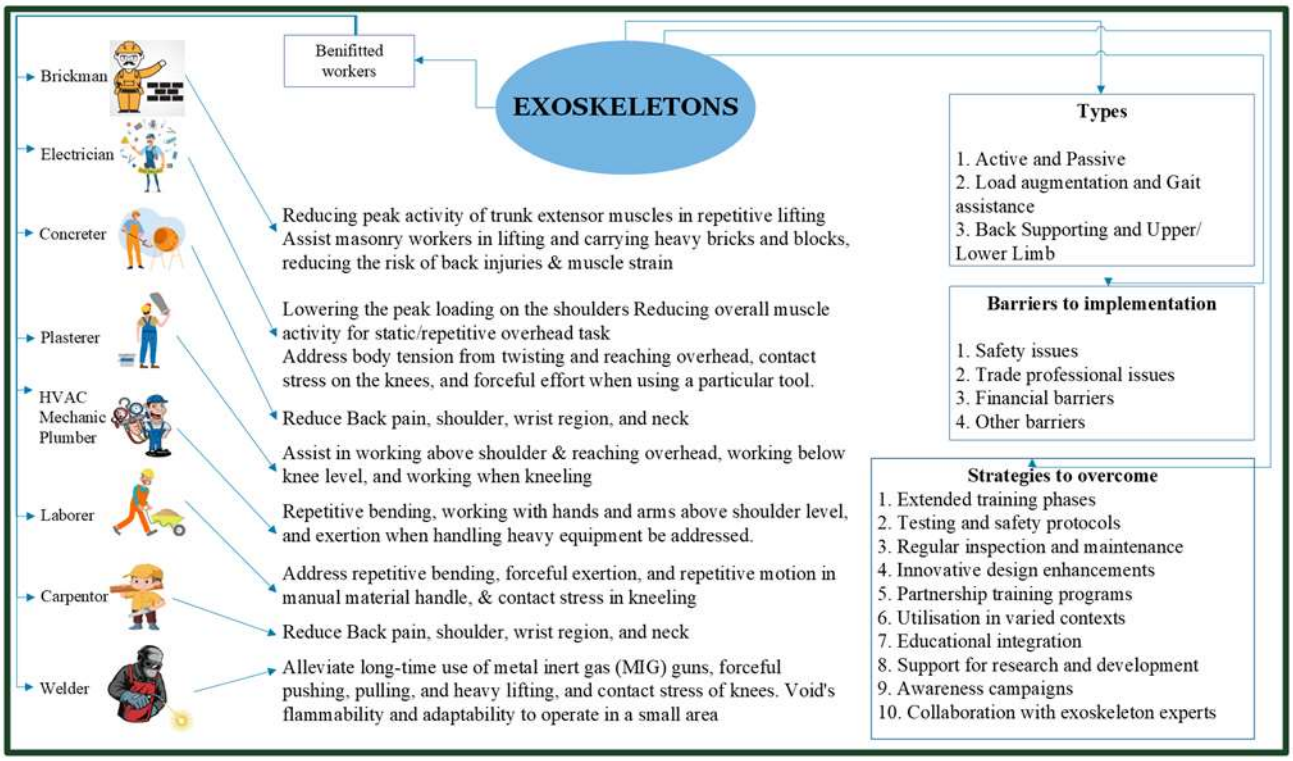

Figure 3: Conceptual Framework

This framework provides a comprehensive approach to understanding and implementing exoskeletons in the construction industry to enhance health and safety outcomes. It categorizes various construction trades, including bricklayers, electricians, and plumbers, and highlights the specific benefits and potential barriers to exoskeleton implementation for each group. The framework addresses multiple barriers to implementation, such as safety concerns, trade professional issues, financial constraints, and other challenges. Further, it suggests strategies to overcome these obstacles, such as utilizing exoskeletons solely for intended tasks, providing robust evidence of their benefits, developing inspection protocols, and establishing best practices for regulation and safety.

4. Conclusion

In conclusion, the use of exoskeletons in the construction industry has demonstrated significant potential in reducing WMSDs, with their effectiveness being closely tied to ergonomic design and compatibility with natural worker movements. Health and safety are prioritized over productivity, underscoring the need for exoskeletons to address lifelong injuries faced by construction workers. This study has developed a framework aimed at implementing exoskeleton ergonomics to minimize health and safety issues, assisting managers in selecting suitable exoskeleton types and applications for specific

tasks. By evaluating the positive influence of exoskeletons on enhancing health and safety within the industry, the proposed conceptual framework aims to enhance worker safety and productivity, leveraging the benefits of exoskeleton technology to address the unique challenges of the construction sector.

The conceptual framework consolidates insights from the study's findings and serves as a guide for further research and practical applications, particularly for implementing exoskeletons to address ergonomic challenges within construction. Furthermore, future researchers need to comprehend the enablers, barriers, and strategies for exoskeleton applications practically to address the research gap in employing exoskeleton applications to improve the health and safety of the construction industry. Understanding these factors will facilitate the successful integration of exoskeleton technology, ultimately enhancing the well-being of construction workers and advancing industry practices. Practically, the study provides valuable insights for industry practitioners on utilising exoskeletons in construction projects. It highlights the importance of adhering to innovative concepts such as biomimicry inspirations, which positively impact worker health and safety. Despite the numerous benefits, several barriers to exoskeleton implementation need addressing to ensure successful adoption. Further research is necessary to identify appropriate solutions for these barriers, with additional studies recommended to practically assess exoskeleton applicability in construction. Future research should focus on a detailed exploration of enablers, barriers, and strategies for effectively applying exoskeletons to overcome health and safety issues in the construction industry.

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