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A Framework for Evaluation and Adoption of Industrial Exoskeletons

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Abstract: Work-related Musculoskeletal Disorders (WMSDs) account for a significant portion of worker illnesses and injuries, resulting in high costs and productivity losses to employers globally. In recent years, there has been an increased interest in the use of exoskeleton technology to reduce rates of WMSDs in industrial worksites. Despite the potential of exoskeletons to mitigate the risks of WMSDs, the required steps to properly assess and implement the technology for industrial applications are not clear. This paper proposes a framework that can help organizations successfully evaluate and adopt industrial exoskeletons. Through a focus group of industry professionals, researchers, and exoskeleton experts, and by building on existing literature, an overarching adoption framework is developed. The identified stages and tasks within the framework enable an organization to evaluate and adopt exoskeletons through a systematic approach and to identify the existing gaps in their technology adoption process. The findings also highlight the areas where further studies are needed to promote the adoption of industrial exoskeletons, including large-scale field studies and long-term monitoring.

Keywords: exoskeleton; technology adoption; framework; industrial exoskeleton; work-related musculoskeletal disorders

1. Introduction

Work-related musculoskeletal disorders (WMSDs) are defined as a group of injuries to the muscles, tendons, cartilage, ligaments, bone, and nerves caused by fixed or constrained body positions, repetitive movements, the concentration of forces on the body, or due to a work pace that does not allow for sufficient recovery (Workplace Musculoskeletal Disorders, 2017). As described by U.S. Bureau of Labor Statistics (2020), the industries with the highest rates of WMSDs resulting in days away from work include the transportation, health care and social assistance, retail trade, agriculture, manufacturing, and construction. Furthermore, WMSDs account for 25.4% of all injuries and illnesses requiring days off in private industry in the United States, making it a common work-related health problem (U.S. Bureau of Labour Statistics, 2020). Historically, exoskeletons were developed for rehabilitation and military use; however, there has been an increased interest in exoskeletons being applied in industrial fields involving substantial manual handling or sustained awkward postures to reduce and prevent the incidence of WMSDs (Del Ferraro et al., 2020; Bogue, 2019).

Exoskeletons for industrial use are designed to support the worker's body, primarily the lower back and upper extremities, to improve or sustain work performance (Murashov et al., 2019). ASTM standard F3323(2021) defines exoskeletons as "wearable devices that augment, enable, assist, and/or enhance physical activity through mechanical interaction with the body" (p.1). Exoskeletons can be typically classified as either active (i.e., requiring an external power source) or passive (i.e., not requiring an external power source) (Zhu et al., 2021). Semi-active exoskeletons also exist, which involve a combination of passive and active components; however, this paper will primarily focus on the adoption considerations necessary for passive and active exoskeletons (Del Ferraro et al., 2020).

Previous studies evaluating the use of passive exoskeletons have shown the positive effects of using exoskeletons on muscle and metabolic activity (Kong et al., 2023; So et al., 2022; Alemi et al. 2020; Baltrusch et al. 2020). Kong et al. (2023) demonstrated that using passive upper limb exoskeletons led to a substantial reduction in muscle activity (29.3-58.1%) in the arm and shoulder of participants while performing overhead tasks. So et al., (2022) investigated the impact of a passive back-support exoskeleton on muscle activity and kinematics of participants in a repetitive lifting and carrying task. The exoskeleton decreased trunk muscle activity (3-7%) and the kinematic parameters also exhibited improvements, specifically in terms of the peak flexion angles. Alemi et al. (2020) showed that two different passive back-support exoskeletons were able to significantly reduce peak activity of the trunk extensor muscles of the participants by ~10%–28% during different conditions of repetitive lifting. They also quantified the impact of exoskeletons on the energy expenditure by measuring O2 and CO2 uptake rates and reported a 4%–13% decrease. Also, von Glinski et al., (2019) investigated influence of an active back-support exoskeleton on lower back muscle activity during repetitive lifting tasks where the exoskeleton was able to reduce lumbar muscle activity by 14%.

Despite the benefits of using exoskeletons as reported in previous academic studies, the evaluation methods used in exoskeleton related studies are not always comprehensive or consistent (Golabchi et al., 2022; Hoffmann et al., 2021), which limits the generalizability and applicability of the results to various and novel work setups. For example, many studies only focus on a specific metric (e.g., muscle activity) for a single target task (e.g., manual handling task) without taking into consideration the body posture adopted (e.g., squat, stoop), or the other tasks typically carried out in the field by the same user. Also, there have been cases where one study reports a significant reduction in a metric such as muscle activity, while another study of a similar nature may report issues with discomfort and usability (Luger et al. 2021; Baltrusch et al. 2019). Conflicting outcomes of studies can lead to inaccurate decisions regarding effectiveness of exoskeleton. however, these effects are not well documented in the literature (Howard et al., 2020). While the current body of literature is promising, a more comprehensive evaluation is needed to determine the effectiveness of exoskeletons for industrial applications.

Another notable limitation affecting the implementation of exoskeletons within industrial environments is the lack of studies examining and testing exoskeletons in job sites (de Looze et al., 2016). Many laboratory studies have been documented in scientific papers; however, the applicability of the results of these studies in an industrial environment is limited. Comparatively, field studies have been limited by small sample sizes, and results have been focused primarily on subjective metrics (Crea et al., 2021). Furthermore, most research focuses on evaluating the effects of specific exoskeletons on the body, with little research focusing on the practical impact of exoskeletons (e.g. productivity of the user). Crea et al. (2021) concluded that large-scale deployment of exoskeleton technology would require a stepwise knowledge-based approach. Some previous studies have tried to propose frameworks for exoskeleton evaluation and the human experience associated with the use of exoskeletons. For example, Moyon et al. (2019) developed an acceptance model for the early phase adoption of exoskeletons in the field. While they used an ecological approach, they did not include the economical and practical aspects of exoskeleton adoption in the industry such as cost effectiveness and feasibility of implementation. Also, Torricelli et al.

(2020) proposed a benchmarking framework for the evaluation of exoskeletons for effective adoption by end-users. However, the study was not focused on industrial exoskeletons. Elprama et al. (2022) also identified factors influencing the use of industrial exoskeletons based on literature and proposed a framework to study user acceptance, although their framework mainly focused on passive exoskeleton studies.

The above-noted limitations in the literature demonstrate that industrial exoskeletons cannot be blindly applied to all settings. Rather, a comprehensive framework for evaluation, adoption and implementation should be used to determine if exoskeletons are a good fit for an organization, and if so, guide the proper adoption cycle. This paper proposes such a framework for use within industrial environments. This study contributes to the existing literature by proposing an adoption framework that will facilitate the development of large-scale field studies and long-term monitoring. This paper includes a step-by-step breakdown of each stage of the adoption framework. Once all factors within a step have been addressed, a defined output (as shown in Figure 1) will lead to the next stage of the framework. The goal of this framework is the successful evaluation, adoption and implementation of exoskeletons within an organization.

2. Methods

A qualitative design was used to understand the top needs, concerns, and considerations regarding the adoption of industrial exoskeletons. A focus group approach was chosen to ensure the development of each stage of the adoption process was informed by researchers and professionals. Compared to other methods such as surveys, observational studies, and content analysis, a focus group allows for more in-depth and nuanced feedback, which in turn provides useful insights into whether the adoption framework is comprehensive, realistic, and has the potential to be utilized and implemented by organizations (Agan et al., 2008; Kontio et al. 2008).

Participants were recruited through targeted sampling. Existing networks and professional associations were assessed and evaluated to identify individuals who meet the inclusion criteria for the focus group. Through this screening process, researchers determined whether potential participants within these networks and associations possessed the desired characteristics or experiences necessary to contribute valuable insights during the focus group discussions. Inclusion criteria included experience in a relevant field and a working knowledge of exoskeletons. Participants were chosen to reflect a diversity of experience, education, and industrial backgrounds, and included a mix of researchers and industry professionals. The focus group consisted of 8 research experts from mechanical engineering, biomechanics, ergonomics, electrical engineering, and construction fields, with their experience ranging from 7 years to more than 30 years (mean=12.1, SD=8.5), as well as 8 industry professionals including company executives, health and safety professionals, ergonomists, and occupational therapists with job experiences ranging from 4 years to more than 30 years (mean=13.3, SD=8). The focus group discussion was divided into three sessions, facilitated by a neutral moderator who followed a structured approach. In the first session, participants engaged in a high-level brainstorming session, exploring various aspects of exoskeleton adoption. The session was recorded, and the information was transcribed and categorized based on the different aspects discussed. During the second session, in-depth discussions were held to delve into each general category identified in the previous session. To enhance the research findings, a comprehensive literature review was conducted after the second session to validate the information collected and fill in any gaps. The third session served as a final verification stage, allowing participants to review and validate the information gathered throughout the process. This approach ensured a systematic and rigorous examination of the topic, combining participants' insights, findings of previous studies, and collective verification to generate comprehensive and reliable outcomes.

3. Industrial Exoskeleton Adoption Framework

The proposed exoskeleton adoption framework is presented in Figure 1. The framework comprises of six stages: feasibility assessment, task selection, exoskeleton selection, implementation logistics, trial phase, and long-term adoption. The framework is developed based on best practices for technology implementation while also considering mitigating potential negative effects on workers. Each stage includes multiple evaluation steps. Once all steps within a stage have been evaluated and the desired output has been achieved, the organization can move on to the next implementation stage. While the framework is depicted as a linear structure, it also recognizes the existence of feedback loops and the important interplay between the outlined steps, which are explained throughout the paper. These feedback loops enable continuous improvement and interaction, enhancing the overall effectiveness of the framework. The goal of the adoption framework is the successful long-term adoption of exoskeletons within the organization.

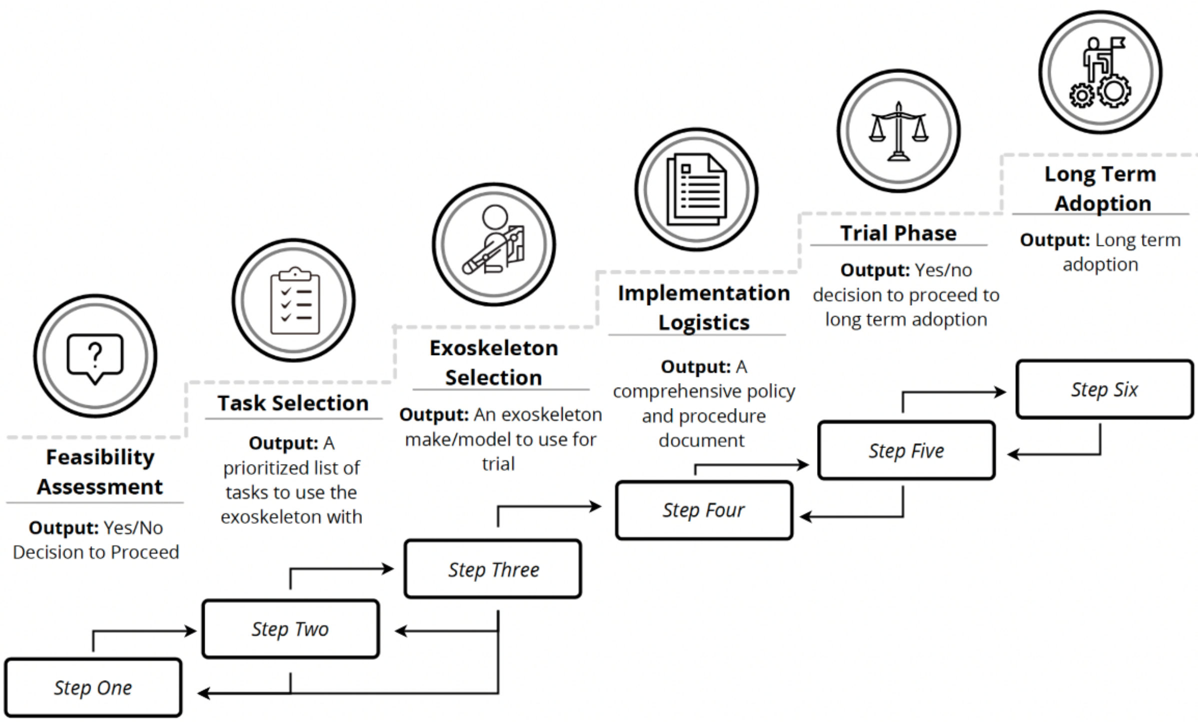

Figure 1. Industrial Exoskeleton Adoption Framework

3.1. FEASIBILITY ASSESSMENT

The first step of adopting any technology in an organization is to evaluate the feasibility of its implementation (Henderson & Ruikar, 2010). Thus, this phase aims to determine whether exoskeletons are a feasible solution for the organization. The high-level steps involved in this phase, shown in Figure 2, include obtaining working knowledge about exoskeletons to understand the implications of the implementation and determining the organizational fit. The output of the feasibility assessment is a yes/no decision regarding moving to the next stage.

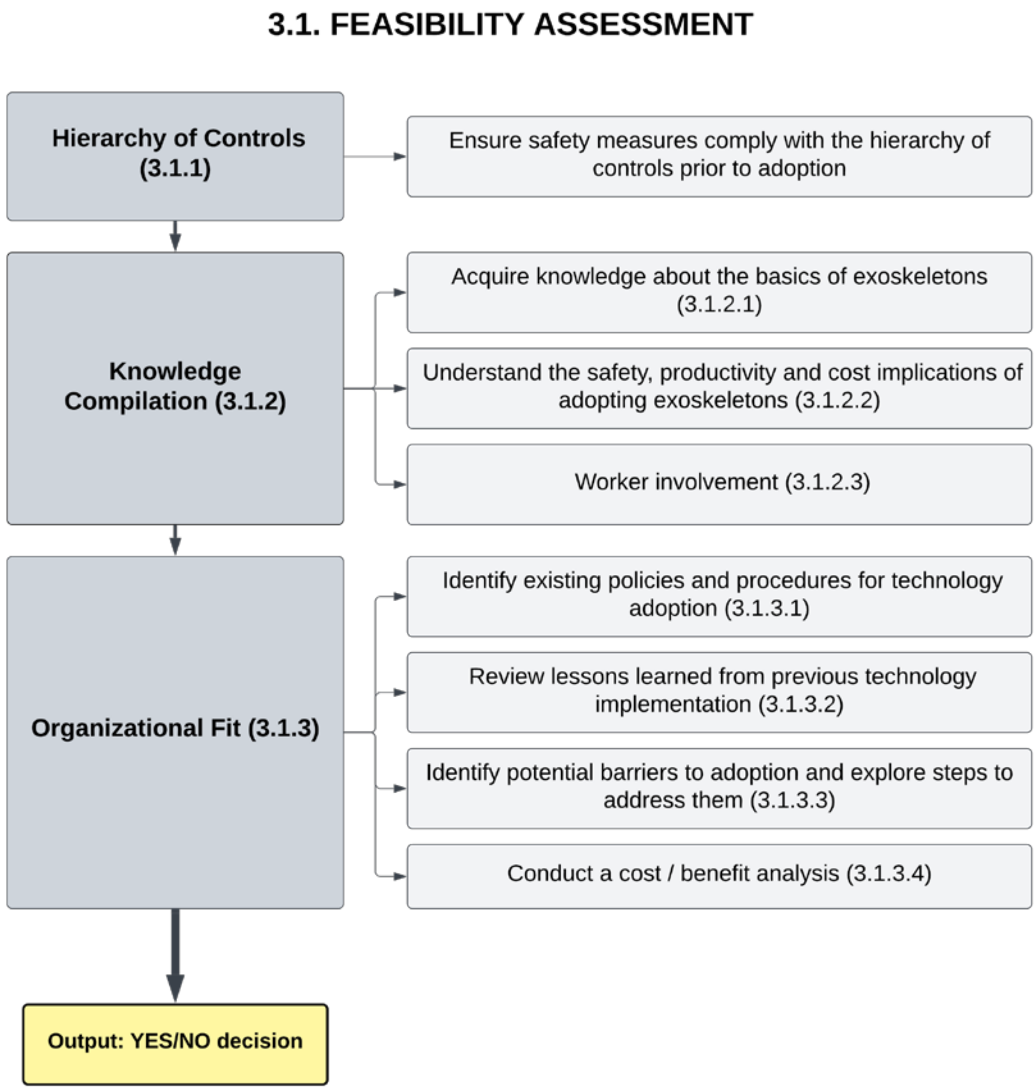

Figure 2. Feasibility Assessment Stage of Exoskeleton Adoption

3.1.1 Hierarchy of Controls - Ensure safety measures comply with the hierarchy of controls prior to adoption

Since exoskeletons can be considered as a type of Personal Protective Equipment (Butler et al., 2019; Acosta-Sojo & Stirling, 2021), other strategies in the hierarchy of controls should be considered before using exoskeletons. The hierarchy of controls states that the most effective controls should be implemented first, with less effective controls only being considered if a control is not feasible or practical. Elimination is the most effective control, followed by substitution, engineering controls, administrative controls, and PPE (Burt & Dickerson, 2021). Thus, it is important to adopt exoskeletons only once all other applicable and feasible controls have been exhausted. In addition, it is crucial to ensure all stakeholders, including the workers, view exoskeletons as PPE.

3.1.2 Knowledge Compilation

3.1.2.1 Acquire knowledge about the basics of exoskeletons

Prior to implementation, it is imperative to study the impacts and implications of adopting exoskeletons (Hill et al., 2017). Basic knowledge of exoskeletons is required to determine if the exoskeleton is a viable workplace injury control method for the organization (de Looze et al., 2016). This knowledge can be acquired from public domain databases and case studies, which provide insight into the challenges and opportunities associated with exoskeleton use (Wang et al., 2017). Academic studies are also useful for examining the impacts of exoskeleton use on workplace injury rates and productivity; however, most studies to date have examined this impact through short-term experiments in laboratory settings rather than long-term, longitudinal field studies (Zhu et al., 2021). Therefore, the experiences and reviews from organizations with prior involvement in adopting exoskeletons should be consulted as an important source of information. Academic studies should also be used to complement information from in-field studies. Due to the rapid progress in this field, it is imperative this knowledge is current and reflects the most recent advancements.

3.1.2.2 Understand the safety, productivity and cost implications of adopting exoskeletons

Adopting exoskeletons can impact an organization's safety, productivity and cost (Cho et al., 2018). These factors and the interactions between each factor should be identified and accounted for as part of the feasibility assessment. For example, active exoskeletons can potentially reduce muscle activity by up to 80% (compared to 10 - 40% for passive exoskeletons), thus mitigating the underlying factors associated with work-related musculoskeletal injuries (de Looze et al., 2016). However, these exoskeletons are generally more expensive, bulkier and heavier. The interaction of the exoskeletons with their surrounding environment should also be explored (e.g., the effects of temperature, working near equipment, and interactions with other PPE) (Kim et al., 2019). In addition, while some studies attribute the use of exoskeletons to higher long-term productivity levels (Zhu et al., 2021), an initial decrease is expected due to the learning curve (Kim et al., 2018, part II). Finally, while initial adoption will impose upfront costs, the increase in productivity could reduce labour costs over time (Poh & Chen, 1998). Thus, it is imperative to evaluate the organization’s specific job site conditions and to understand the impact of the adoption on safety, productivity, and expenditure, both in the short term and in the long term.

3.1.2.3 Worker involvement

Including workers' feedback in the feasibility assessment stage is crucial as their expertise and experiences provide valuable insights, ensuring the technology meets their needs, enhances safety and well-being, and boosts morale and engagement. Through facilitated open discussions and structured surveys, workers' opinions, concerns, and expectations regarding usability, comfort, heat, impact on job performance, and potential health and safety considerations can be collected.

3.1.3 Organizational Fit

3.1.3.1 Identify existing policies and procedures for technology adoption

Before adopting a new technology such as exoskeletons, it is important to examine the existing organizational policies and procedures for adopting new technologies. A well-established procedure will facilitate the adoption of exoskeletons and enable the identification of the individuals, teams, and departments that need to be informed, involved, and held accountable for each stage of the adoption. A lack of procedure, or a procedure that is not fully developed, may indicate the need for increased upfront planning regarding the adoption process.

3.1.3.2 Review lessons learned from previous technology implementation

Any lessons learned from previous technology adoption by the organization should be reviewed to identify potential barriers and challenges and ensure proper adoption of new technologies such as exoskeletons (Reid, 2014).

3.1.3.3 Identify potential barriers to adoption and explore steps to address them

Challenges associated with adopting technology in industrial settings are more often human behaviour problems than technological ones (Henderson & Ruikar, 2010). For example, leadership may be wary of the commitment required to implement exoskeletons (Kim et al., 2019). In addition, previous studies show workers may have low acceptance of exoskeletons due to concerns related to ease of use or level of comfort (Zhu et al., 2021), and peer acceptance (Kim et al., 2019; Schwerha et al., 2021). Thus, proper steps must be taken before implementation to ensure all stakeholders, including workers, will be receptive to the technology. Leadership should be provided with sufficient and timely information concerning the adoption process, and training and information sessions must be provided to address workers' concerns (Zhu et al., 2021). Workers more receptive to new technology can encourage hesitant co-workers (Butler & Sellbom, 2002). It is highly recommended to follow the principles of organizational change management from the feasibility assessment stage to complete adoption to ensure effective uptake of the exoskeleton technology (Jones et al., 2005). Adopting a participatory approach can be beneficial for the acceptance of exoskeletons by workers as it fosters employee engagement, ownership, and empowerment. By involving workers in the decision-making process, addressing their concerns, and soliciting their feedback, organizations can build trust, increase acceptance, and ensure successful adoption of the exoskeleton technology. This approach enhances worker satisfaction, promotes a positive work environment, and maximizes the potential benefits of exoskeleton implementation (Quinlan-Smith, 2022; Canadian Standards Association 2013).

3.1.3.4 Conduct a cost/benefit analysis

The cost of adoption and the potential for long-term cost savings are important factors that must be considered before adoption. Table 1 outlines the cost implications and potential cost savings when using exoskeletons. The costs associated with adoption include initial purchase costs, cleaning and storage costs, maintenance costs, and training costs. On the other hand, there are potential cost savings due to reduced work-related injuries and increased productivity (Gorgey, 2018). Comparing cost implications and potential saving sources can help decide and justify the adoption of exoskeletons (Kim et al., 2018, part I). Although some studies have shown that industry professionals believe in a long-term return on investment (ROI) when adopting exoskeletons, the short-term ROI is also an important factor in the decision-making process (Kim et al., 2019). It is imperative to ensure that the organization has identified tasks that can effectively benefit from exoskeleton implementation as failing to do so may result in misallocation of funds and resources. It should be noted that the high-level analysis conducted in this step is considered preliminary and a more precise and comprehensive analysis needs to be conducted once the specific task for adoption of exoskeletons and the appropriate exoskeleton model have been identified.

Table 1. Potential Saving Sources and Cost Implications of Exoskeleton Adoption (identified by the focus group)

Potential Saving Sources	Cost Implications
• Reduced injury rates • Reduced costs associated with injuries • Reduced days lost at work due to injury • Reduced fatigue • Increased productivity • Higher worker retention • Higher work satisfaction • Lower number of workers required	• Initial purchase price • Maintenance/upgrading costs • Cleaning and storage cost • Time spent training • Time spent implementing exoskeletons • Designated personnel to manage exoskeletons • Expense of unintended consequences of mismatch between exoskeletons and task/PPE

Once proper knowledge is acquired regarding exoskeletons, barriers to adoption have been identified and addressed, the cost implications are justified, and all stakeholders are on board with the decision to proceed, the organization can move to the task identification stage.

3.2. Task Identification

Before implementing a trial phase at step five of the adoption framework, it is imperative to systematically identify the tasks that can benefit from using exoskeletons. To identify suitable tasks, relevant data must be collected, productivity and safety implications must be considered, and the hierarchy of controls must be addressed, as shown in Figure 3. The output of the task identification stage is a prioritized list of tasks suitable for the pilot phase.

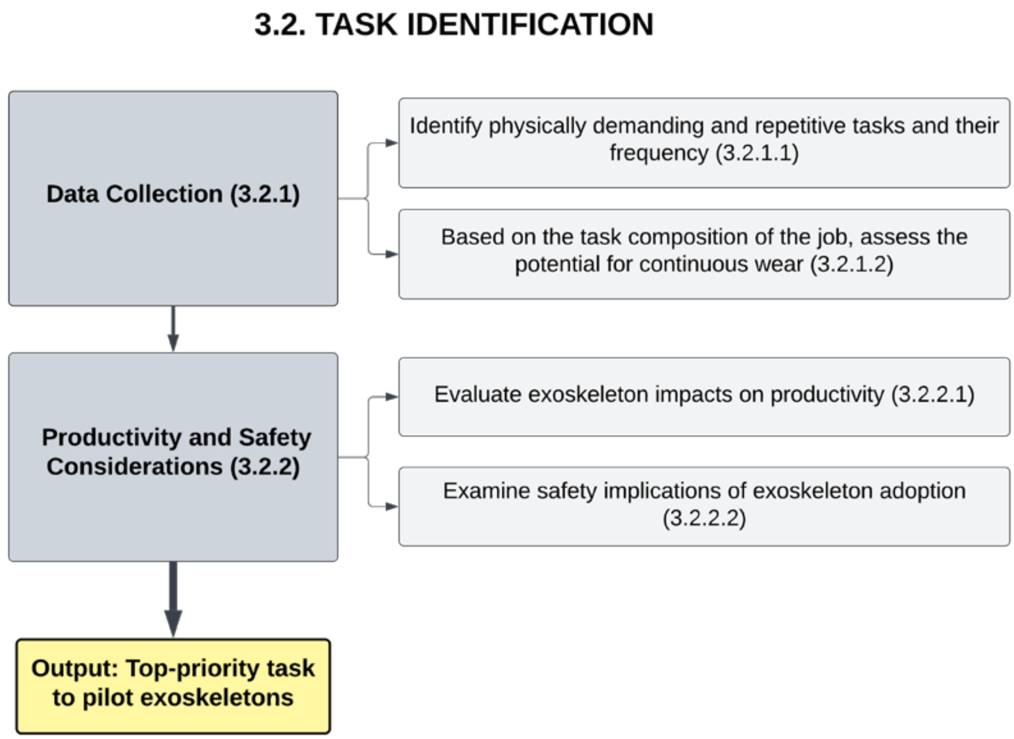

Figure 3. Task Identification Stage of Exoskeleton Adoption

3.2.1 Data Collection

3.2.1.1 Identify physically demanding and repetitive tasks and their frequency

Industrial exoskeletons are typically suited for tasks that require high repetition and are carried out in unnatural postures with heavy workloads (Hoffmann et al., 2021). The scoring system of ergonomic risk assessment tools, such as REBA (Hignett & McAtamney, 2000), can be used to identify tasks where exoskeletons can be most beneficial (Butler & Gillette, 2019). The ergonomic risk score is determined by considering the number of workers exposed to the risk, the number and levels of risk existing within the task, energy expenditure, workload, and posture (Shamsan & Qasem, 2020). It is imperative to involve workers in the task selection process as they have the most familiarity and expertise in the tasks. Any worker discomfort and injury reports, physical demand analysis (PDA) reports, and reports of existing medical conditions should also be reviewed before implementation. Ergonomic experts can also be consulted during this phase to ensure the proper selection of tasks and workers. Once possible tasks have been identified, the task frequency should also be considered. To justify exoskeleton use, the task must have a substantial ergonomic risk over an extended period (Butler & Gillette, 2019). The more physically demanding a task is, the less time is needed to justify using an exoskeleton as concentration of forces on the body is among the main causes of WMSDs. In contrast, if less strain is put on the body, high frequency of the task can also justify the use of an exoskeleton, as prolonged repetitive movements also lead to WMSDs. The frequency can be easily identified in cyclic tasks (such as manufacturing); however, it can be more challenging in work environments that require the completion of dynamic tasks, such as construction. Additionally, it is important to consider the frequency of tasks over extended periods of time, such as months or years, as some tasks may only be required for a limited period.

3.2.1.2 Based on the task composition of the job, assess the potential for continuous wear

Many job descriptions involve a variety of manual tasks. When assessing the potential for continuous wear, the task composition should be considered to determine whether the exoskeleton can be worn for the entire job or needs to be deactivated or doffed for some tasks. Additionally, the effect of the exoskeleton on the range of motion must be examined to ensure that workers will not be negatively affected when wearing the exoskeleton for other tasks (Capitani et al., 2021; Schwerha et al., 2021). After this step, the process of using the exoskeleton for different job tasks should be laid out.

3.2.2 Productivity and Safety Considerations

3.2.2.1 Evaluate exoskeleton impacts on productivity

Adopting an exoskeleton will have various positive and negative influences on productivity through setup time, task execution and process-related impacts (Dahmen & Constantinescu, 2020). Setup time impacts result from the time required to don and doff the exoskeleton, as well as transit times (e.g., moving between workstation and storage area to retrieve or return the exoskeleton), which can lead to a loss of productivity (Dahmen & Constantinescu 2020). On the other hand, introduction of exoskeletons can lead to an increase in productivity due to decreased fatigue of the worker being supported by the exoskeleton (Spada et al., 2017a); however, the productivity would differ for each particular task and in some cases might be adversely affected due to the discomfort experienced by the workers (Luger et al. 2021). At this preliminary stage, the assessment of the impact of exoskeletons on productivity is limited. However, valuable insights can be gained by drawing upon the experiences of organizations that have previously adopted exoskeletons, as well as academic studies that have investigated specific tasks. Thus, the productivity implications should be carefully considered prior to the adoption of exoskeletons.

3.2.2.2 Examine safety implications of exoskeleton adoption

Safety considerations related to the working conditions and environment must be considered when adopting exoskeletons. For example, working in extreme temperatures may impact task and exoskeleton selection. In hot environments, a lightweight exoskeleton may be required to prevent overheating, while in cold environments, outer layers may be required over or under the exoskeleton to maintain warmth. Working around heavy machinery and moving parts could also affect task selection, as a part of the exoskeleton could be caught in machines and harm the workers (Kim et al., 2019). The interaction with machinery or tools, could lead to possible damage to the equipment or the products being manufactured or handled as well. Other potential limiting factors include working around electric and magnetic fields with exoskeletons made of metal components as well as chemicals and flammable material (Schwerha et al., 2021). The existing safety standards on adoption of exoskeleton such as ISO 10218, ISO 13482, and ASTM F3527 should be consulted during this stage. Given their familiarity with the tasks, it is also imperative to consult workers to identify additional safety considerations for the adoption of exoskeletons. Their insights can provide valuable input and help address potential safety concerns that might arise in the specific work environment. Overall, the working conditions of any selected task should be carefully reviewed to ensure that the adoption of the exoskeleton is safe.

Once the tasks that could benefit from exoskeleton use have been identified and productivity and safety impacts have been considered the organization can move on to the next stage.

3.3. Exoskeleton Selection

The next stage of the exoskeleton adoption process is exoskeleton selection. First, the body parts requiring support must be identified, and the type of exoskeleton (i.e., active or passive) must be chosen. The available brands and models can then be evaluated for working conditions, compatibility with other PPE, and any identified worker requirements. The steps for exoskeleton selection are shown in Figure 4. The output of this stage is the selection of a specific exoskeleton brand and model suitable for the task that will be used during the pilot phase.

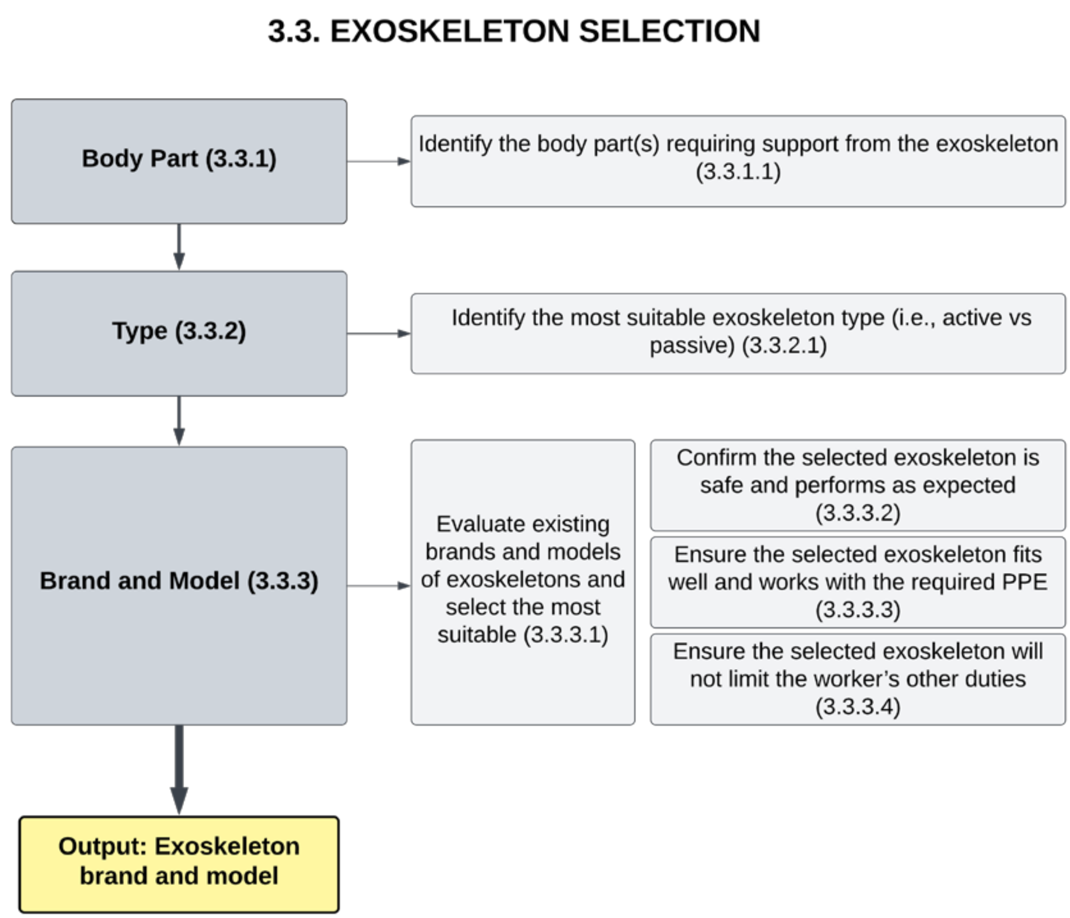

Figure 4. Exoskeleton Selection Stage of Exoskeleton Adoption

3.3.1 Body Part

3.3.1.2 Identify the body part(s) requiring support from the exoskeleton

The body parts most impacted by injuries can be determined using information collected from the task identification stage (Stage 2). Most industrial exoskeletons support the lower back, shoulders, or lower limbs. Some models also support the neck, arms, hands, or fingers, and there are models available that can hold a tool for the user. A lower body exoskeleton aids in sitting, standing, walking, balancing, and squatting (Wang et al., 2017) and can support the knee, hip, lower back, and ankle (de Looze et al., 2016). Similarly, an upper body exoskeleton assists in reaching, grasping, and lifting (Wang et al., 2017). Some models are also developed to allow for simultaneous support, for example, simultaneously supporting the lower back, shoulder, and lower limbs.

3.3.2 Type

3.3.2.1 Identify the most suitable exoskeleton type (i.e., active vs passive)

Exoskeletons are classified by their power source. An exoskeleton that requires an external power source is classified as active, while an exoskeleton that does not use an external power source is classified as passive (Zhu et al., 2021). While active exoskeletons use a power supply to augment the user's performance, passive exoskeletons typically store the energy of the user's movements and return it in the form of support. While active exoskeletons are usually bulkier, heavier, and more expensive than passive exoskeletons, their design has been improving over time and they also have greater potential to provide physical support (de Looze, 2016), particularly for tasks that require higher level of forces. Currently available commercial passive exoskeletons are typically better suited for industrial applications due to their smaller size, lighter weight, and ease of implementation. When determining the most appropriate exoskeleton type, the working environment, length of time worn, and loads on the worker's body must be considered.

3.3.3 Brand and Model

3.3.3.1 Evaluate existing brands and models of exoskeletons and select the most suitable

Suitable brands and models should be identified and compared from the information gathered in the previous stages. Table 2 summarises the manufacturer and exoskeleton characteristics that should be considered when choosing an exoskeleton. Available online catalogues, such as the Commercial Exoskeletons Catalog (Marinov, 2016), can be used to access a database of commercially available exoskeletons. Comprehensive studies such as (Zhu et al., 2021; Voilqué et al., 2019) that highlight the function of available exoskeletons and recommend suitable exoskeleton types for different trades could be consulted as well.

Table 2. Characteristics to be evaluated during exoskeleton selection (identified by the focus group)

Exoskeleton Characteristics	Manufacturer Characteristics
• Evidence based studies	• Support from a vendor during trial period
• Cost	• Training provided by vendor
• Reviews from previous users	• Repair policy of vendor
• Success stories	• Technical support
• Sizing and fit	• Warranty period
• Pace of donning and doffing	• Location of vendor
• Impact on productivity	• Return policy
• Safety of operations	• Inspection and follow-up
• Suit limitations	• Reviews from previous customers
• Power supply	• Information transparency
• Joint flexibility	• Company size
• Dependability	

3.3.3.2 Confirm the selected exoskeleton is safe and performs as expected

After a specific exoskeleton model is chosen, Step 3.2.2.2 (i.e., examine the safety implications of adopting exoskeletons) should be repeated to ensure the selected exoskeleton can perform well and is safe to use for the identified tasks (e.g., hot or cold environments, work around equipment or moving parts, magnetic fields, chemicals, and fire hazards). Workers and supervisors should also be consulted in this stage as they are most familiar with the working environment. Additionally, it is essential to review the impact of the environment on exoskeleton function and whether the exoskeleton has been tested or adopted in various working environments (Zoss et al., 2006). During the assessment of the exoskeleton, it is essential to screen the characteristics of individual workers to ensure a proper fit that aligns with their anthropometry and does not worsen any existing medical conditions such as back pain, joint disorders, cardiovascular issues, respiratory conditions, and neurological conditions. Consulting with medical professionals, such as occupational health specialists or physicians, can ensure that the chosen exoskeleton is well-suited to the workers' specific needs and medical conditions.

3.3.3.3 Ensure the selected exoskeleton fits well and works with other required PPE

Although existing studies have not thoroughly evaluated the impact of other PPE on using exoskeletons or vice versa, it is critical to evaluate this impact when selecting an exoskeleton. Some exoskeletons may be incompatible with existing PPE such as fall harnesses or supplied air devices (Schwerha et al., 2021) and some may negatively affect pre-existing PPE (Kim et al., 2019). Also, some exoskeletons might restrict the worker's range of motion (Capitani et al., 2021) which impacts the ability of the worker to don and doff additional PPE that is required. To determine the compatibility of exoskeletons with task-specific PPEs, organizations should first consult the manufacturers of the exoskeletons to assess their design and specifications. Secondly, they should explore the possibility of obtaining different models of exoskeletons for a trial in real-world settings to evaluate how they interact with their PPE and identify any potential issues or limitations.

3.3.3.4 Ensure the selected exoskeleton will not limit the worker’s other duties

Once a specific exoskeleton model is chosen, Step 3.2.1.2, should be repeated to ensure the additional size and weight of the selected exoskeleton and its subsequent effects on the wearer do not limit the safe and efficient completion of other duties. It is also crucial to seek the feedback of the workers as the end users regarding whether the exoskeleton will impose limitations on their ability to perform other tasks as part of their job.

Once the body parts requiring support and the type of exoskeleton have been determined, and the brand and model of the exoskeleton have been selected, the organization can move to the next stage. To achieve the highest level of accuracy and relevance, it is essential to revisit the cost/benefit analysis conducted at step 3.1.3.4. This analysis should be repeated with the full information on the specific task for implementing exoskeletons and the selection of the most suitable exoskeleton model. This will allow for an updated and refined version of the analysis that aligns with the latest available information.

3.4. Implementation Logistics

This stage covers the logistics of implementing exoskeletons. It includes defining roles and responsibilities, fit and use procedures, maintenance and monitoring requirements, and finally safety, training and implementation policies, as shown in Figure 5. The output of this section is a comprehensive implementation policy and procedure document. It is important to keep the scope of the logistics phase to the essential components required, to ensure staff time and resources are not wasted if the exoskeleton trial is concluded not to be worth pursuing. It is advisable to delay comprehensive updates and finalization of the documents until a positive outcome is achieved in the trial phase. This ensures that the finalized documents accurately reflect the successful results and incorporate any necessary modifications or enhancements based on the trial's findings.

3.4. IMPLEMENTATION LOGISTICS

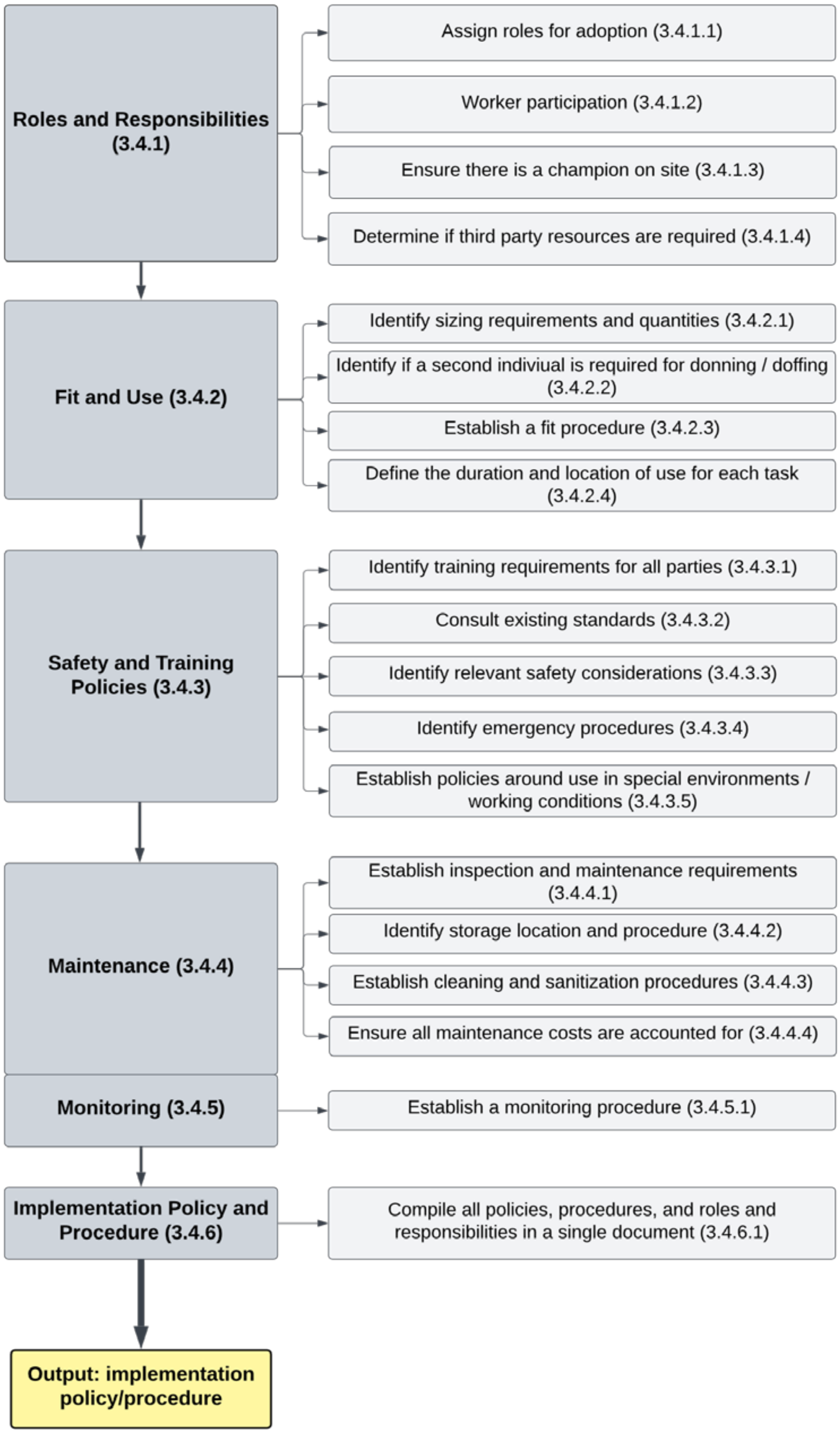

Figure 5. Implementation Logistics Stage of Exoskeleton Adoption

3.4.1 Roles and Responsibilities

3.4.1.1 Assign roles for adoption

It is important to establish a leader in the adoption process and identify all individuals and groups that will be involved (Eastwood et al., 2017). Roles and responsibilities must be established on an individual and group basis and communicated within the organization to ensure the adoption process goes smoothly (Leonard-Barton & Deschamps, 1988). Roles and responsibilities should be assigned for each implementation logistics step discussed in the following sections.

3.4.1.2 Worker participation

Workers are an indispensable asset in the successful implementation of exoskeleton technology, and their active involvement throughout the adoption process is crucial. Specifically, during the implementation logistics steps, their deep understanding of the details and nuances of their tasks and working environment becomes invaluable. This knowledge can be effectively utilized in the implementation logistics steps discussed in the following sections. This participatory approach not only enhances the overall effectiveness of exoskeleton implementation, but also fosters a sense of ownership and commitment among the workforce, leading to a more seamless and successful adoption of the exoskeleton technology (Quinlan-Smith, 2022).

3.4.1.3 Ensure there is a champion on site

Assigning a knowledgeable and supportive champion of new technology can significantly enhance acceptance of the technology by workers (Gupta et al., 2006). Since one of the main concerns in adopting exoskeletons is the willingness of workers to use the technology (Zhu et al., 2021), assigning a champion on the job site to promote and support the use of the technology is essential. Champions are innovative risk-takers that exhibit a transformational leadership style (Howell & Higgins, 1990). The champions should be individuals who interact with workers daily, with whom the workers are comfortable (Leonard-Barton & Deschamps, 1988).

3.4.1.4 Determine if third-party resources are required

Implementing new technology requires dedicated human resources (Ensminger et al., 2004). If the pre-existing resources are inadequate for the adoption process, a third party may be needed. Advantages of internal human resources include a full-time dedicated task force that often leads to quicker implementation (Zhang & Wu, 2017), while involving a third party could provide the specific expertise and skill set that is missing in the organization and is needed to advocate for and assist in the adoption (Sauvage, 2003). Potential third parties that may assist in the adoption process include researchers, ergonomists, and health and safety professionals.

3.4.2 Fit and Use

3.4.2.1 Identify sizing requirements and quantities

It should be noted that the sizing requirements have already been considered in step 3.3.3.1 and this step is about final confirmation and decision making on the quantity of the exoskeletons. Some exoskeletons are available as one-size-fits-all and designed with adjustable straps and components

(Spada et al., 2017b), while others are available for purchase in different sizes. If the chosen exoskeletons are one-size-fits-all products, the number of suits required for the trial phase can be easily determined. However, if sizing varies, the size requirements of workers participating in the pilot must be considered to ensure an adequately sized suit is available when needed. Overall, a sufficient number of suits should be obtained so that workers are not required to share suits, at least not on the same work shift. It will also be imperative to establish a workable schedule regarding the shared use of the exoskeleton (Howard et al., 2020).

3.4.2.2 Identify if a second individual is required for donning and doffing

Some exoskeletons may require a second individual to assist with the donning and doffing of the suit. In this scenario, the additional labour required to assist in donning and doffing the suit must be considered (Dahmen & Constantinescu, 2020). It should also be determined if a buddy system will be established between workers or if a designated individual will assist all users. The training materials should incorporate the procedure for donning and doffing with a second individual.

3.4.2.3 Establish a fit procedure

Establishing a proper fit is vital in using exoskeletons since an improper fit can be counterproductive (Kuber & Rashedi 2021) and even lead to injury (Xu & Qiu, 2013, May). Also, proper fit and comfort of an exoskeleton have been shown to be critical to successful adoption (Schwerha et al., 2021). Thus, a procedure for fitting the exoskeleton must be established based on guidance and support provided by the manufacturer, and all users should be trained on this fit procedure. Exoskeleton use should also be closely monitored during the first few weeks of adoption to ensure adherence to proper use and fitting procedures. Monitoring requirements are further discussed in Section 3.4.5.

3.4.2.4 Define the duration and location of use for each task

Based on the previous information collected during the task and exoskeleton selection stages, it should be established, documented, and communicated when, for how long, and by whom the exoskeleton will be worn for each task.

3.4.3 Safety and Training Policies

3.4.3.1 Identify training requirements for all parties

Training requirements must be determined for all parties involved based on existing standards for exoskeletons such as the ASTM standard F3444 (2020) and the organization’s operating procedures for implementing new technologies (Helpman & Rangel, 1999). Training topics include the process for donning and doffing the suits, proper fit instructions, postural considerations, safety considerations, maintenance, storage requirements, etc. (Golabchi et al. 2023; Hickman et al., 2007). Additionally, exoskeleton safety “dos and don’ts” must be included within the training materials to provide workers with insight into what the exoskeleton is and is not capable of achieving (Cho et al., 2018). Training regarding the proper use of exoskeletons is important since incorrect use can lead to workplace injury (Samper-Escudero et al., 2021).

3.4.3.2 Consult existing standards

With the recent advancements made in the adoption of exoskeletons, more standards and guidelines are being developed to guide the adoption process. For example, ASTM F48 is a task force specifically created to help develop standards related to exoskeleton adoption (Lowe et al., 2019). Previous standards that have been published include ISO 13482, ISO/DTR 23482-1, ASTM F3323, and ASTM F3358. These standards include design requirements, hazard sources, safety compliance criteria, terminology, and labelling (Howard et al., 2020). Standards that are currently in progress aim to cover the wearing of exoskeletons, care and maintenance, load handling, optimal environmental conditions for utilization, safety considerations for design and selection, system training assessment, recommendations on usability, utilization of digital human modelling, designing for population accommodation, standard test methods, and exoskeleton ergonomics (ASTM International F48 (2021); Howard et al., 2020). These standards are being constantly updated and should be reviewed frequently to ensure that the adoption process follows current standards.

3.4.3.3 Identify relevant safety considerations

With the increasing global interest in the adoption of industrial exoskeletons, several safety standards such as ASTM F3527, F3540, and F3578 have been developed. It is critical to incorporate all harm scenarios, applicable safety considerations, and rules and regulations in the exoskeleton training material. Examples include emergency procedures and day-to-day safety requirements (Howard et al., 2020). Training workers to recognize and address adverse health effects of wearing exoskeletons including heat illness, skin irritation, and psychological impacts such as a feeling of being trapped is also essential. Finally, the training should align with any existing safety policies in the organization.

3.4.3.4 Identify emergency procedures

The most likely emergency to occur while wearing an exoskeleton is getting caught in moving machinery or equipment (Kim et al., 2019). Other emergencies that may occur while working with the exoskeleton include workplace accidents leading to a fire or the release of chemicals, which require immediate evacuation. Any existing release mechanisms and the procedure for disengaging/doffing the suit should be identified, documented, and included in the training.

3.4.3.5 Establish policies around use in special environments/working conditions

Using some exoskeletons can be limited by the environments they can safely and effectively operate in. For example, food manufacturing facilities can not use exoskeletons with exposed Velcro™ due to food safety standards, and facilities with lead-based products might not be able to effectively decontaminate the exoskeleton (Schwerha et al., 2021). Environmental limitations must be identified and documented, and policies and procedures established. These policies should identify the conditions in which an exoskeleton can safely operate before reaching environmental thresholds (Kim et al., 2019). Additionally, the effectiveness and safety of using exoskeletons in special conditions, such as in proximity to magnetic fields and moving equipment, should be discussed. Lastly, policies should identify the space requirements for exoskeleton use and any potential interactions with chemicals or fire.

3.4.4 Maintenance

3.4.4.1 Establish inspection and maintenance requirements

Inspection and maintenance requirements for the exoskeleton can be determined using information and guidelines provided by the manufacturer and the organization's existing procedures. Also, existing standards such as ASTM F3392 on care and maintenance of exoskeletons should be consulted. Factors that affect the frequency of inspection and maintenance include components of risk-based inspection planning, such as the likelihood and consequence of failure (Ablitt & Speck, 2005). Some items that should be included in an inspection and maintenance procedure are inspection frequency, indications of damaged suits, reporting requirements, maintenance frequency and process, and roles and responsibilities. Any recommendations or guidelines provided by the manufacturer should be followed, and if required, any clarifications regarding this information should be made before the adoption. Proper inspection procedures for each instance of use should be established and communicated, similar to PPE. For example, fall arrests require an inspection prior to donning to ensure that there is no damage to the harness or clasps (Kurniati et al., 2015). The frequency of inspection, random checks, and maintenance tasks can differ based on the task the exoskeleton is being used for. The inspections would be performed by the inspector assigned during the step 3.4.1.1. The frequency of inspection and checks should be greater for high-risk tasks where the failure of the exoskeleton can increase the risk for injury; however, the frequency of inspection and checks can potentially be lower for low-risk tasks (Jovanovic, 2003).

3.4.4.2 Identify storage location and procedure

The storage location and procedure can be determined based on the number of exoskeletons and the selected exoskeletons' size, power source, and composition. This procedure needs to include where the exoskeletons will be stored, how they will be stored, and any special considerations required for storage. In case of active exoskeletons, it is also important to establish a charging procedure that includes determining the charging location and duration, as well as assigning a person responsible for charging, inspecting, and replacing the batteries. Also, it should be determined whether the exoskeletons require a special storage area, whether they should be kept away from certain materials and equipment, or whether they can safely be stored with other PPE. Security concerns should also be considered when determining the storage location and procedure.

3.4.4.3 Establish cleaning and sanitization procedures

To prevent skin irritation and other sanitization concerns, cleaning procedures must be established and communicated within the organization (Zhu et al., 2021). The type of cleaning solution should also consider any existing sensitivities and allergies. These procedures should designate who is responsible for cleaning and how frequently cleaning should occur. For suits that are shared by multiple workers, the rate and frequency of cleaning and sanitation must be increased to prevent infectious diseases (Howard et al., 2020). In contrast, for suits that a single worker wears atop of outer clothing, the cleaning frequency may not need to be as frequent (e.g., bi-weekly, weekly) (Ringen et al., 1995).

3.4.4.4 Ensure all maintenance costs are accounted for

When implementing new technology, such as exoskeletons, all maintenance costs should be considered prior to implementation to ensure that the benefits of use outweigh the costs (Stasiak-Betlejewska & Potkány, 2015). Additionally, an adequate budget for maintenance costs must be established to ensure successful adoption.

3.4.5 Monitoring

3.4.5.1 Establish a monitoring procedure

The use of new technologies, such as exoskeletons, must be closely monitored to ensure they are being used safely and properly (Ablitt & Speck, 2005). Prior to implementation, a monitoring procedure should be created outlining, at minimum, the frequency of monitoring, the monitoring process, and the roles and responsibilities related to the monitoring process. The workers using the exoskeletons should also be responsible for ongoing monitoring. The information collected during the monitoring period must be defined, and data collection forms should be created as necessary. The requirements for monitoring in the pilot and long-term adoption phases are discussed in further detail in Steps 3.5.2 and 3.6.3, respectively.

3.4.6 Implementation Policy and Procedure

3.4.6.1 Compile all policies, procedures, roles, and responsibilities in a single document

All of the information collected in stages 3.4.1 to 3.4.5 should be compiled into a single policy and procedure document that is readily available for reference within the organization (Lobato et al., 2010). This document will not only serve as an essential guide for the safe and productive use of exoskeletons but will also serve as a living document for future improvements and reference. As this document will be shared with all relevant stakeholders, items that must be clearly documented include the policies, procedures, training requirements, and the roles and responsibilities for exoskeleton use. The document should include general information as well as standard operating procedure. A breakdown of the requirements of each section in the document is provided in Table 3. This document should be updated throughout the project as necessary.

Table 3. Information to be documented in the Implementation Policy and Procedure (identified by the focus group)

General Information and Procedures	Standard Operating Procedures

● Safety policies concerning use
● Contact information of those responsible for adoption
● Roles and responsibilities of
   o Workers
   o Supervisors
   o Managers
   o Contractors
   o External parties
● Communication and reporting requirements
● Training requirements
● Monitoring requirements
● Exoskeleton information provided by manufacturer
	● Daily operational requirements
	● Emergency procedures
	● Instruction on proper use
	● Limitations of exoskeleton use
	● Donning and doffing instructions
	● Cleaning requirements
	● Training requirements

Once the roles and responsibilities have been established, maintenance and inspection requirements have been determined, safety and training policies have been created, a proper fit and use procedure has been established, the monitoring requirements have been decided, and all implementation policy and procedures are made available to stakeholders in one document, the organization can move onto the trial phase.

3.5. Trial Phase

To determine whether exoskeleton adoption is a good fit for an organization, a trial phase wherein the technology can be piloted and introduced to the organization and workforce is highly recommended. Introducing new technologies without conducting a trial phase and proper preparation could lead to resistance to change by staff, safety risks, reduced efficiency, and wasted resources in case of inappropriate exoskeleton-task matching. This phase involves pilot phase preparation, data collection procedure preparation and implementation and analysis of the findings as shown in Figure 6. The output of this trial period is a yes/no decision regarding whether the long-term adoption phase should be initiated.

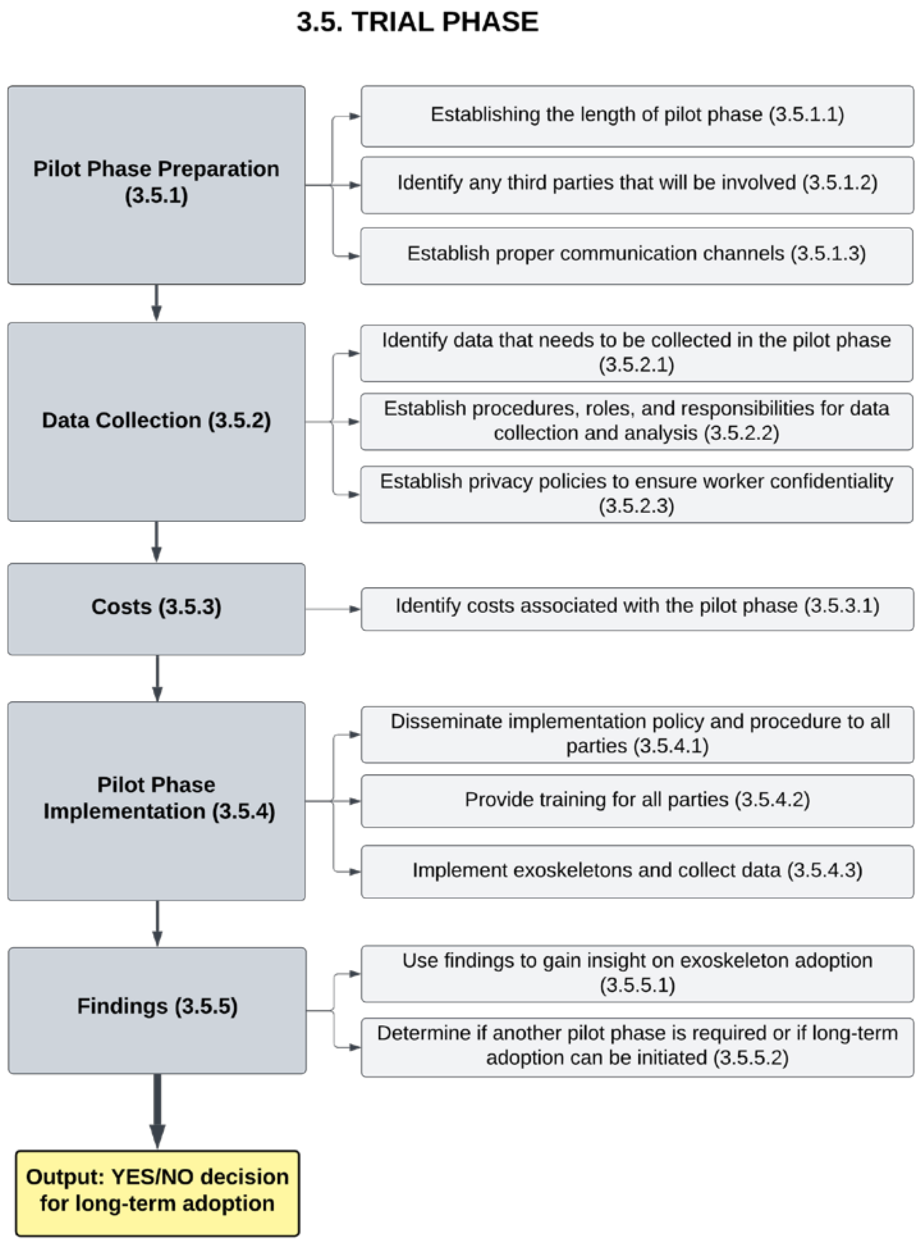

Figure 6. Trial Phase Stage of Exoskeleton Adoption

3.5.1 Pilot phase preparation

3.5.1.1 Establishing the length of the pilot phase

A pilot phase must be long enough to ensure users can overcome the learning curve of trialling new technology (Adler & Clark, 1991). Additionally, it must be long enough to provide the organization with sufficient insight into the impacts of adopting the technology. However, if a pilot phase is too long and is ultimately unsuccessful, it will negatively impact cost and productivity. The length of the pilot period will depend on several factors, including the number of tasks involved, the number of workers, and the organization's size.

3.5.1.2 Identify any third parties that will be involved

The pilot phase will require monitoring to ensure that the adoption of the technology has a positive and desirable impact on the organization (Thabane et al., 2010). Involving additional parties in the monitoring phase to complement internal expertise can help ensure the effectiveness of the pilot. Ergonomists, safety professionals, exoskeleton adoption experts, and researchers are among the third parties that can help to facilitate the effective implementation of the exoskeletons during the pilot phase. Involving academic partners who are actively working with exoskeleton technology can assist in not only ensuring trial success but also in publishing and disseminating findings from the pilot to allow other organizations to learn from the adoption process and further the development of future exoskeletons (In, 2017).

3.5.1.3 Establish proper communication channels

Improper technology implementation can result if stakeholders are unclear about the adoption process or have unaddressed concerns (Leonard-Barton & Deschamps, 1988). To counteract this, an easily accessible communication channel supplying information concerning exoskeleton use and implementation must be provided to all groups involved in the project. The selection of communication channels should prioritize technologies that are familiar to and affordable for all stakeholders. Additionally, it is essential to ensure that the level of communication is understandable to all groups involved in the project. Providing an open forum during the pilot phase, where participants can freely discuss concerns, enables the organization to effectively address any issues and carry out effective problem-solving processes. Information regarding the communication channel should be added to the implementation policy and procedure document.

3.5.2 Data Collection

3.5.2.1 Identify data that needs to be collected in the pilot phase

During the pilot phase, different types of data collection will be required. This data is typically categorized into objective and subjective data. Subjective data is based on individuals' perceptions (Schachter, 2010). In contrast, objective data is collected from objective measures and scales (Schachter, 2010). During the pilot phase, subjective and objective data must be collected to ensure workers are satisfied with the use of the exoskeletons and that their use has measurable and positive impacts on safety and productivity. The types of objectives and subjective data that will be collected are shown in Table 4. It should be noted that collection of some of the objective data listed in Table 4 may not be possible in the field (e.g., camera motion capture) and may require simulated in lab tests by a third party (e.g., researcher labs). Less technical measures such as task completion time and subjective feedback of the users can be completed by the assigned organization personnel (assigned in step 3.4.1.1).

3.5.2.2 Establish procedures, roles and responsibilities for data collection and analysis

A clear understanding of the impact of exoskeleton use cannot be determined until all relevant data is collected and analyzed. While the analysis of less technical data can be done by organization personnel, more technical data such as EMG and IMU require third party professionals. As such, roles and responsibilities for data collection and analysis need to be clearly established and communicated to stakeholders. The procedure for data analysis must also be clearly established to ensure accurate results (Hsu, 2005).

3.5.2.3 Establish privacy policies to ensure worker confidentiality

The data that is collected from users must be anonymized prior to data analysis to ensure worker confidentiality and limit biases (Thabane et al., 2010). By collecting anonymous data, participants will be able to provide honest feedback, leading to more accurate results (Schomakers et al., 2020). Privacy policies must therefore be established to ensure that data is protected and correctly handled by those involved (Lin et al., 2004). This data privacy and security policy should be reflected in the implementation policy and procedure document.

Table 4. Objective and Subjective Data to be Evaluated when Adopting Exoskeletons (identified by the focus group)

Objective Data	Subjective Data
● Impact on task duration ● Don and doff timing ● Muscle activity (electromyography (EMG) measurements) ● Muscle fatigue (electromyography (EMG) measurements) ● Posture (camera motion capture & IMU measurements) ● Joint forces and moments ● Range of motion (camera motion capture & IMU measurements) ● Postural Balance ● Energy expenditure (Heart rate, Oxygen consumption and CO_2 production) ● Weight of load ● Speed of work ● Work height, distance, and orientation ● Precision ● Support provided by the suit ● Rest break frequency	● Worker overall feedback ● Worker discomfort ● Rate of Perceived Exertion (RPE) ● Safety/Productivity concerns ● Interference with other activities ● Fit concerns ● Impact on PPE ● Skin irritations ● Usability and future intention to use ● Perceived task difficulty ● Rate of fatigue ● Perceived balance

3.5.3 Costs

3.5.3.1 Identify costs associated with the pilot phase

A short-term pilot phase often has a more significant cost impact than long-term adoption due to additional costs resulting from frequent monitoring, data collection (Thabane, 2010), and potential losses in productivity. It should also be noted that the organization must consider the costs associated with hiring third parties. These additional costs must be quantified prior to the pilot phase, as the organization must be able to adequately allocate the resources required to run the pilot before initiation.

3.5.4 Pilot Phase Implementation

3.5.4.1 Disseminate the implementation policy and procedure to all parties

At the beginning of the pilot phase, the implementation policy and procedure must be communicated to all groups involved in the adoption process (In, 2017). The level of communication should be understandable for all involved groups. As previously mentioned, the implementation policy and procedure are considered living documents and will evolve as the adoption proceeds.

3.5.4.2 Provide training for all parties

All individuals involved in the pilot phase should receive adequate training in the use, safety, and maintenance of the exoskeleton (In, 2017), as discussed in Step 3.4.3. The training should be delivered in a manner that ensures clear understanding and accessibility for all participants, regardless of their background or prior knowledge. This training will ensure that the exoskeletons are correctly worn and used and all safety standards are met.

3.5.4.3 Implement exoskeletons and collect data

Once training has been provided, exoskeletons can be implemented. Data should be collected throughout the pilot phase in accordance with the data collection policies and procedures established in Section 3.5.1.

3.5.5 Findings

3.5.5.1 Use findings to gain insight into exoskeleton adoption

Following data collection and analysis, the findings need to be reviewed to determine the impact of adopting the exoskeleton technology (Thabane et al., 2010). Analysis of the data will help to evaluate the cost-effectiveness of exoskeleton adoption as well as the effects on organizational productivity and whether any potential safety concerns or shortcomings need to be addressed. If the organization cannot impartially or accurately analyze data, third-party experts can be consulted to ensure an unbiased data analysis. The findings should enable the identification of (1) areas where exoskeleton use has been the most and least effective in reducing the risk of WMSDs and improving productivity; (2) challenges in exoskeleton adoption and how best to address these challenges; (3) opportunities wherein exoskeletons can be used for other tasks; (4) feasibility of long-term implementation; (5) and potential changes needed to ensure feasibility for long-term adoption (e.g., different type, brand, or the number of exoskeletons). Sharing the results with all stakeholders, including frontline workers, is essential to promote transparency and maintain effective communication throughout the process.

3.5.5.2 Determine if another pilot phase is required or long-term adoption can be initiated

From the pilot phase findings, a determination can be made whether the results are positive, negative, or inconclusive regarding long-term adoption (Haas & Mittelmeier, 2014). If results are inconclusive, another pilot phase with changes may be warranted. Suppose findings are negative, and it is determined that exoskeleton use is not an appropriate fit for the organization. In that case, further steps to secure exoskeleton adoption for the long term should not be initiated. However, if the results are positive, the organization can proceed to long-term adoption.

Once the length of the pilot has been defined, data has been collected and analyzed, findings have been discussed with the stakeholders, and if the results are positive, the organization can move to the next stage. At this stage the documents on implementation policy need to be updated based on the findings during the pilot phase to ensure they accurately reflect the outcomes including any required adjustments or improvements.

3.6. Long-Term Adoption

This section provides a framework for long-term adoption. It includes updating policies and procedures, data collection and analysis procedures, and monitoring requirements, as shown in Figure 7. The output of this stage is successfully adopting the exoskeleton technology and identifying lessons learned.

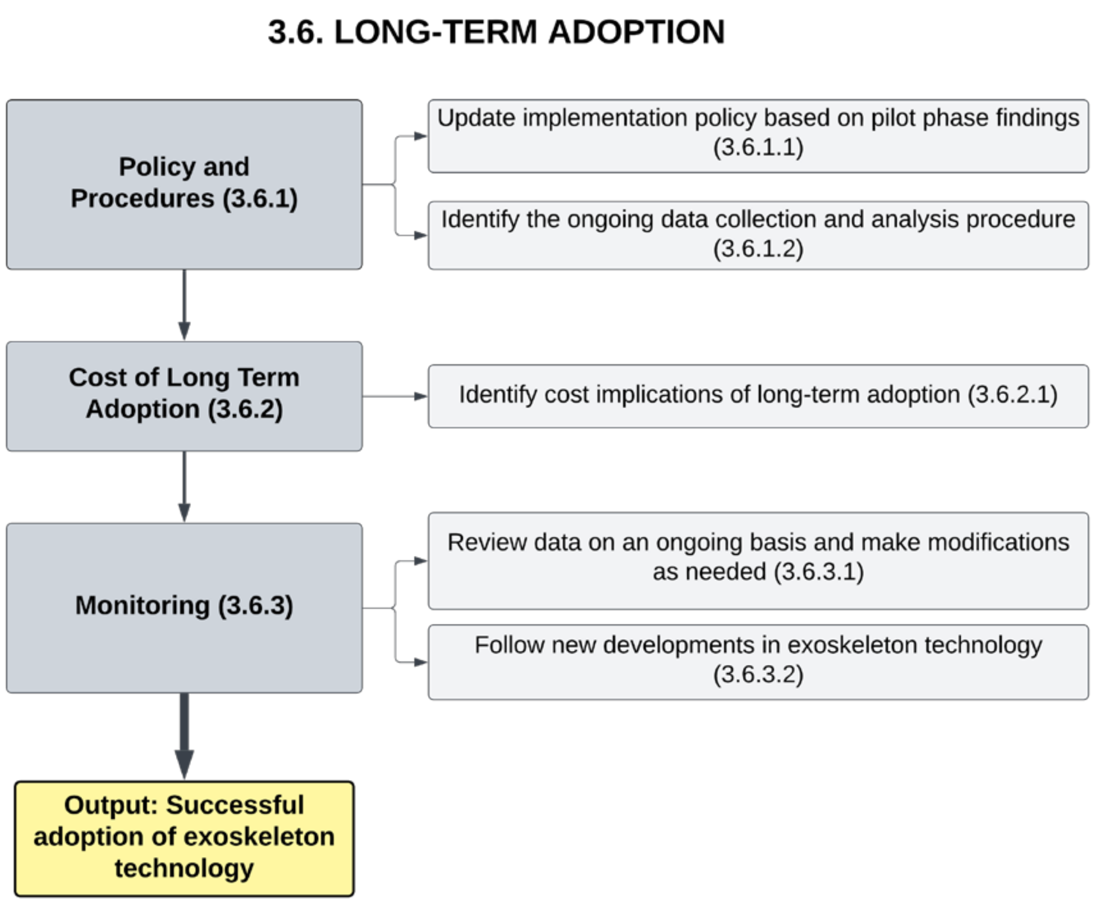

Figure 7. Long-term Adoption Stage of Exoskeleton Adoption

3.6.1 Policy and Procedures

3.6.1.1 Update implementation policy based on pilot phase findings

The findings from the pilot phase should inform the framework for long-term adoption (In, 2017). In particular, findings should be used to update the implementation policy and procedure developed in Step 3.4.6 with respect to the adoption plan, roles and responsibilities, training requirements, and monitoring procedures.

3.6.1.2 Identify the ongoing data collection and analysis procedure

Information should be continuously collected throughout the long-term adoption phase to ensure the technology remains beneficial to the organization (Van Teijlingen & Hundley, 2002). A subset of the data collected during the pilot phase, including feedback from workers, imposed risks and hazards, and the impacts of exoskeletons on safety and productivity, need to be collected and analyzed on an ongoing basis. Based on the results of evaluations, appropriate modifications to the data collection process should be implemented to optimize its relevance and usefulness. Data collection and analysis frequency will depend on the number of workers using exoskeletons and the duration of use. The procedure, roles, and responsibilities of all those involved in the data collection and analysis should be documented and properly communicated to stakeholders (Hausman & Stock, 2003).

3.6.2 Cost of Long-Term Adoption

3.6.2.1 Identify the cost implications of long-term adoption

As the cost implications of long-term adoption will differ from the pilot phase, the findings of the pilot phase should be used to inform additional costs or potential cost savings associated with long-term adoption. The long-term maintenance requirements will also affect the costs of long-term adoption. Based on the cost analysis, the organization should ensure that all resources required to adopt new technology for long-term success can be allocated (Gibson et al., 2007). This includes taking into account the costs associated with replacing and updating outdated equipment.

3.6.3 Monitoring

3.6.3.1 Review data on an ongoing basis and make changes as needed

Using the trial phase findings as a baseline, the long-term cost, productivity, and safety implications of adopting exoskeletons can be tracked. The collected data should cover changes to productivity (e.g., task duration), cost, injury and discomfort rates, and feedback from the workers.

The data collected during the long-term adoption phase can be utilized to ensure that the benefits of the adoption outweigh the disadvantages in the long run (Ablitt & Speck, 2005; Aborisade, 2013). By reviewing the collected data on an ongoing basis, the positive and negative aspects of the adoption can be determined, which enables the ability to make modifications to the adoption plan to ensure effectiveness. Any procedure changes should be reflected in the implementation policy and procedure document and communicated to stakeholders. New technologies consistently evolve within an organization (Smith & Carayon, 1995); this evolution must be tracked to ensure that adoption remains beneficial.

3.6.3.2 Keep up to date with exoskeleton technology advancements

With the current rate of advancement in exoskeleton technology, it will be critical to closely follow new information, including updates from manufacturers, industry, and academic researchers (Jang et al., 2021). This information enables continuous improvement of the adoption process.

Once long-term adoption has been implemented, permanent policies and procedures have been documented, and data collection and monitoring are ongoing, the adoption of exoskeleton technology can be considered successful.

4. Conclusion

As evidenced by the literature, there is an increasing interest in implementing exoskeletons within industrial environments due to their potential to prevent WMSDs and increase productivity. However, there is still limited information on the steps to properly adopt this technology within industrial settings. This study presents an industrial adoption framework consisting of six stages: feasibility assessment, task selection, exoskeleton selection, implementation logistics, trial phase, and long-term adoption. Each stage of the adoption framework results in an output used as a checkpoint to ensure the successful completion of the phase before moving on to the subsequent adoption phase.

While the proposed framework was developed in collaboration with industry professionals and researchers in the exoskeleton field, the proposed framework has not been implemented in an industrial setting for long-term validation yet. Another limitation of this study is the lack of available research on exoskeleton adoption within an industrial environment. Although some research has been completed, there is insufficient evidence to conclusively state whether exoskeletons can be successfully integrated into industrial environments as a long-term solution. Thus, future research directions include implementing the proposed framework in industrial settings, proposing adjustments to the design of passive and active exoskeletons for successful adoption in industrial job sites, and examining workers' performance and acceptance level regarding the long-term use of industrial exoskeletons.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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