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Research Article

A Theory-Informed Framework for Implementing Passive Back-Support Exoskeletons in Construction

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Abstract

Passive exoskeletons hold significant promise for reducing work-related musculoskeletal disorders in construction, yet clear, theory-informed guidance on how organisations should adopt and sustain them remains limited. This study presents Exo-Implant, a multi-stage implementation framework grounded in Normalisation Process Theory and tailored to the operational, organisational, and cultural characteristics of construction workplaces. The framework was developed through literature review, expert validation, and iterative refinement using construction-specific adoption factors. Its evaluation employed a scenario-based case study with professionals from a construction firm, integrating a usability questionnaire with a facilitated focus-group analysis to assess practicality, clarity, and perceived value. Results indicated that participants viewed Exo-Implant as useful, trustworthy, and role-relevant, though moderately complex to navigate due to the number of interconnected steps and information flows. Identified facilitators included early feasibility assessment, stakeholder engagement, and clear procedures for training, operational planning, and iterative learning. Key barriers centred on plan complexity, limited embedded prompts or examples, insufficient detail on repair-tracking and usage monitoring, and the variability of cost–benefit evaluation practices across firms. This study contributes to existing knowledge by providing a transferable, construction-specific implementation framework; extending Normalisation Process Theory with industry-specific insights into organisational readiness, workforce engagement, and continuous learning; and offering guidance for researchers and practitioners seeking to implement exoskeleton adoption in construction and other labour-intensive sectors. Exo-Implant demonstrates how theory-informed, context-sensitive strategies can bridge the persistent gap between exoskeleton promise and real-world organisational practice.

Keywords: Passive Exoskeletons; Exoskeleton adoption; Implementation plan; Normalisation Process Theory; Construction industry

Highlights

- A theory-informed framework guides sustainable adoption of passive exoskeletons in construction.
- Organisational readiness and workforce engagement drive successful exoskeleton implementation.
- Usability, trust, and iterative monitoring are critical to long-term exoskeleton sustainability.

1 Introduction

Workforce health and safety remain critical concerns in the construction industry, which continues to rank among the most hazardous sectors due to persistent exposure to ergonomic and physical risks (Anwer, Li, Antwi-Afari, & Wong, 2021). These risks stem from the highly physical, variable, and dynamic nature of construction tasks, which frequently involve manual material handling, repetitive movements, and awkward postures (CPWR, 2018). Such conditions contribute substantially to work-related musculoskeletal disorders (WMSDs), particularly low back pain which is the most common nonfatal injury in the sector accounting for approximately 42% of all construction-related WMSDs (BLS, 2023). Despite efforts to mitigate these risks through worker training (Roy, 2022), mechanical handling devices (Kumar, Agrawal, & Kumari, 2016), and workstation redesign (Albers, Estill, & MacDonald, 2005), many interventions remain insufficient for addressing the rapid task-specific variability and constantly changing conditions of construction work. This persistent gap highlights the need for practical, adaptable ergonomic innovations tailored to the unique characteristics of construction environments.

Exoskeletons are increasingly being explored across sectors such as healthcare, manufacturing, and agriculture to augment human performance and reduce physical strain (Delgado et al., 2019). They typically fall into two broad categories: passive systems, which use mechanical structures such as springs or counterweights, and active systems, which incorporate powered actuators and sensors (Govaerts et al., 2024). Passive back-support exoskeletons (e.g., BackX shown in Figure 1) offer several advantages for construction, including lighter weight, lower cost, reduced maintenance requirements, and independence from electrical power, making them particularly appealing for highly mobile, outdoor, and resource-constrained job sites (Okunola, Akanmu, & Yusuf, 2023). Prior research demonstrates that passive devices can reduce trunk muscle activity, spinal loading, and perceived exertion during lifting and sustained bending tasks (Baltrusch, Van Dieën, Van Bennekom, & Houdijk, 2018; Bosch, van Eck, Knitel, & de Looze, 2016). Given the substantial economic burden of WMSDs and the relatively accessible cost of passive exoskeletons, construction firms increasingly view these devices as potential ergonomic solutions that balance practicality, affordability, and expected benefit (Wang et al., 2018). However, growing evidence of the benefits of exoskeletons have not been matched by comparable progress in understanding how construction organisations should adopt, implement and sustain their use. Existing research identifies barriers, including cost concerns, safety perceptions, training gaps, and worker resistance, as well as facilitators such as leadership support and worker participation (Kim et al., 2019; Mahmud et al., 2022; Okunola, Afolabi, Akanmu, Jebelli, & Simikins, 2024). Yet, most studies evaluate exoskeleton performance in laboratory or limited pilot settings (Baltrusch et al., 2018; De Looze, Bosch, Krause, Stadler, & O'sullivan, 2016), with far less attention to the organisational, cultural, and managerial processes required for widespread and sustained adoption. This gap is especially problematic in construction, where transient crews, project-based workflows, and tight cost–time pressures complicate the introduction of new technologies (Maali, Lines, Smithwick, Hurtado, & Sullivan, 2020). While regulatory bodies such as American Society for Testing and Materials (ASTM) and International Organisation for Standardisation (ISO) are developing exoskeleton standards (Howard, Murashov, Lowe, & Lu, 2020; Lowe, Billotte, & Peterson, 2019), standards alone do not translate into organizational readiness or implementation capability.

As a result, construction organisations continue to face uncertainty regarding how passive back-support exoskeletons should be introduced, coordinated, and sustained within everyday work practices. Although prior studies have documented biomechanical benefits and identified isolated adoption barriers, many firms still lack practical guidance for translating promising pilot results into organisational routines that accommodate shifting job-site conditions and workforce structures. Consequently, adoption decisions are often ad hoc, fragmented across projects, or abandoned after limited trials. While other high-risk industries, such as manufacturing and logistics, have begun formalising implementation approaches for wearable interventions, comparable construction-specific strategies remain scarce. This disconnect between demonstrated device potential and practical organisational implementation highlights the need for theory-informed frameworks capable of explaining how exoskeleton use becomes meaningful, workable, and sustainable in construction operations.

Although frameworks such as the Technology Acceptance Model (TAM) and Diffusion of Innovations have informed related studies (Davis, 1989; Ngai, Law, & Wat, 2008), these theories primarily emphasise individual-level acceptance or innovation attributes, rather than the collective, practice-level processes through which new technologies become normalised in construction operations. As a result, they offer limited insight into how exoskeleton use is coordinated, reinforced, and embedded into daily work routines. Normalisation Process Theory (NPT) addresses this gap by examining the social and organisational mechanisms through which new technologies become embedded and sustained in practice (May & Finch, 2009; May, Finch, & Rapley, 2020). NPT emphasises four constructs: coherence (making sense of a new practice), cognitive participation (engaging key actors), collective action (implementing the practice), and reflexive monitoring (evaluating and refining use). These constructs offer a structured yet flexible lens for understanding how exoskeletons can be meaningfully integrated into construction workflows. Despite its relevance, NPT has rarely been applied to construction technology implementation, and no prior study has implemented it to guide exoskeleton adoption in this domain.

To address these gaps, this study developed Exo-Implant, an NPT–based implementation plan adapted to passive back-support exoskeletons in construction organisations. The study is guided by two research questions (RQs):

- RQ1: What components constitute an effective implementation strategy for passive back-support exoskeletons in construction?
- RQ2: Which organisational, operational, and workforce factors influence the adoption, use, and long-term sustainability of such a strategy?

The remainder of the paper is organized as follows: Section 2 presents the background and conceptual foundations motivating Exo-Implant; Section 3 describes the multi-method approach used to develop and evaluate the plan; Section 4 presents results from the usability assessment and qualitative analysis; Section 5 discusses the implications of findings in relation to NPT and construction practice; and Section 6 presents the conclusions, limitations, and directions for future research. This study contributes to existing knowledge by developing a construction-specific implementation framework that addresses the persistent absence of practical guidance for exoskeleton integration; extending NPT with industry-derived insights into organisational readiness, workforce engagement, and iterative learning; and providing guidance for researchers and practitioners seeking to implement passive back-support exoskeletons in construction.

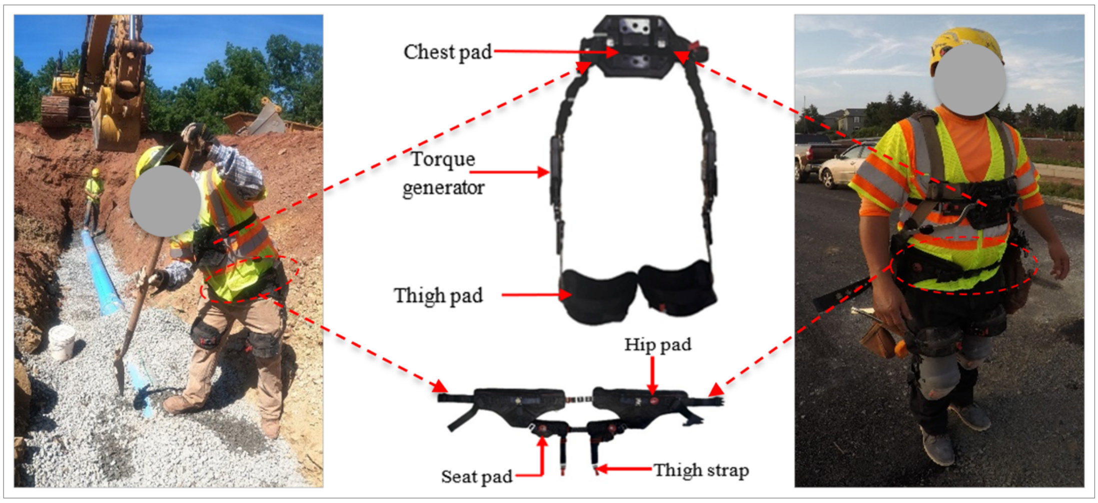

Figure 1: BackX: An example of passive back support exoskeletons (BackX, 2022).

2 Background

2.1 Persistent Burden of Work-Related Musculoskeletal Disorders in Construction

Work-related musculoskeletal disorders remain one of the most persistent and costly occupational health issues in the construction industry. Construction workers experience disproportionately high rates of WMSDs due to the physical demands of tasks such as lifting, carrying, repetitive movements, and working in awkward postures (CPWR, 2018; Santos et al., 2025). According to the U.S. Bureau of Labour Statistics (BLS, 2023), WMSDs account for nearly one-third of all nonfatal injuries in construction, with low back pain comprising approximately 42% of these cases. The impact of WMSDs extends beyond individual health outcomes to broader organisational and economic burdens, including lost workdays, decreased productivity, elevated workers' compensation claims, and long-term disability costs, all of which can escalate across project-based, subcontractor-driven organisational structures (Punnett & Wegman, 2004; Rosado, Baptista, Guilherme, & Guedes, 2022). Although ergonomic training, tool redesign, and mechanical handling devices have contributed to incremental improvements (Albers et al., 2005; Kumar et al., 2016; Roy, 2022), these measures often fall short in dynamic, uncontrolled environments where task demands shift by project phase, crew skill level, and environmental conditions. This persistent gap highlights the need for task-specific, easily deployable ergonomic innovations that can flexibly support workers across diverse construction tasks rather than isolated activities.

2.2 Exoskeletons as Emerging Solutions for Workforce Ergonomics

Exoskeletons are wearable mechanical devices designed to augment human performance or reduce physical strain. These devices have emerged as a promising innovation in occupational ergonomics (De Looze et al., 2016). Within construction contexts, research has increasingly focused on passive back-support exoskeletons due to their mechanical simplicity and compatibility with dynamic, outdoor work environments. Studies have shown that these devices can reduce trunk muscle activity, spinal loading, and perceived fatigue during lifting tasks and prolonged static postures (Ahn, Jung, Moon, Kwon, & Ahn, 2025; Reimeir, Calisti, Mittermeier, Ralfs, & Weidner, 2023; Schwartz, Desbrosses, Theurel, & Mornieux, 2023). Pilot studies in industrial and construction contexts suggest that passive exoskeletons contribute to both injury reduction and productivity improvements. Additionally, regulatory bodies such as ASTM and ISO have begun establishing technical standards to guide safe deployment, reflecting the growing legitimacy of exoskeletons as industrial tools (Howard et al., 2020; ISO, 2022). Despite these advances, adoption in construction remains uneven and constrained by cost uncertainty, usability concerns, concerns about interference with workflow, inconsistent worker acceptance, and the absence of structured, construction-specific implementation guidance (Mahmud et al., 2022; Schwartz et al., 2023). Conversely, facilitators include leadership support, clear demonstration of benefits, and the role of innovation champions among frontline workers (Bunce et al., 2020; Kim et al., 2019). These findings highlight the need for implementation strategies that go beyond device-level performance assessments and address the organisational, social, and managerial dimensions of technology integration in construction.

2.3 Research Gaps

Although passive exoskeletons demonstrate biomechanical benefits, there is a substantial gap between evidence of device efficacy and guidance on how organisations should adopt and sustain them within construction workflows. Existing research has largely focused on laboratory-based evaluations or short pilot demonstrations with limited scope, giving limited attention to the multi-layered organisational, cultural, and logistical challenges that influence long-term adoption. The construction industry's distinctive characteristics mean that generic technology-adoption frameworks do not adequately capture the cyclical, distributed, and socially coordinated nature of construction work. Although models such as TAM and Diffusion of Innovations have been used to explain perceptions of new technologies, these frameworks primarily focus on individual-level acceptance or innovation attributes rather than the collective work processes required to embed a new practice into everyday routines. NPT offers a valuable lens for studying construction technology implementation. Its focus on coherence, cognitive participation, collective action, and reflexive monitoring provides a structured mechanism to analyse how new technologies become implemented, legitimised, and sustained across diverse roles, work settings, and project cycles. Despite its relevance, scarce prior study has implemented NPT to build a construction-specific exoskeleton implementation strategy, leaving practitioners with fragmented guidance and limited tools for structured adoption. In parallel, construction organisations have relied on alternative ergonomic interventions such as job rotation and worker training to mitigate musculoskeletal risk. While these approaches provide incremental benefits, they often struggle to accommodate the task variability, environmental uncertainty, and transient crew structures characteristic of construction projects. In other high-risk industries, including healthcare, manufacturing, and logistics, implementation frameworks emphasise feasibility assessment, stakeholder engagement, and iterative evaluation as prerequisites for successful ergonomic intervention deployment. However, these frameworks are rarely adapted to construction's project-based delivery model, highlighting the need for a construction-specific, theory-informed implementation strategy. Responding to these gaps, this study introduces Exo-Implant, an NPT–based, construction-oriented implementation framework designed to support the coordinated and sustainable adoption of passive back support exoskeletons.

3 Methodology

This study adopted a multi-method, theory-informed design to develop and evaluate Exo-Implant, an implementation plan for passive back-support exoskeletons in the construction industry. The methodological approach unfolded through four interconnected phases: identifying existing implementation strategies; adapting and contextualising these strategies using empirical evidence and NPT; validating the emerging framework with experts and industry representatives; and conducting a scenario-based case study to assess usability and identify adoption-related factors. The use of multiple, complementary methods enabled the study to integrate conceptual rigour, empirical grounding, and practical relevance. This combination is particularly critical given the limited maturity, fragmented findings, and lack of standardised implementation guidance in construction-focused exoskeleton research. The study was approved by the Virginia Tech Institutional Review Board (IRB 22-017), and all participants provided informed consent. Figure 2 presents an overview of the methodology.

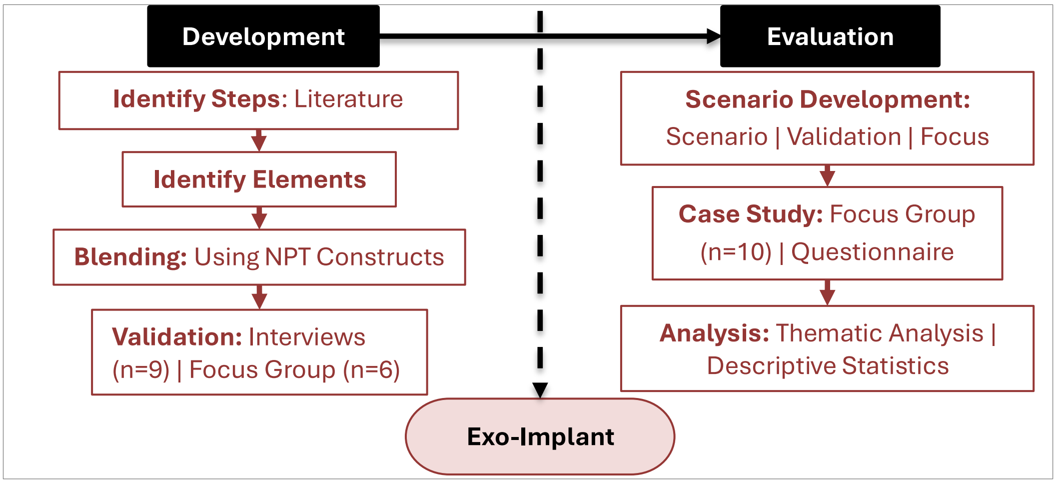

Figure 2: Research methodology.

3.1 Development of the Implementation Plan

The development of Exo-Implant followed a four-stage process: (1) identifying key steps from existing implementation plans; (2) identifying elements associated with each step; (3) refining these steps for construction-specific constraints, workforce characteristics, and organisational structures; and (4) validating and adapting the steps through iterative feedback. The subsections below describe each stage in detail.

3.1.1 Identification of Key Steps of Implementation Plans

The first stage involved conducting a review of published implementation strategies in construction and adjacent industries such as healthcare, logistics, and manufacturing. Searches of major academic databases were performed, focusing on peer-reviewed journal articles, conference papers, and industry reports. The review revealed that implementation strategies commonly follow a recurring sequence beginning with (1) an organizational commitment to adopt a new technology (Peansupap & Walker, 2005), (2) preparation for initial use (E. Ngai et al., 2010), (3) stakeholder engagement and awareness building (Ruikar, Anumba, & Carrillo, 2006), (4) training (Arayici, Khosrowshahi, Ponting, & Mihindu, 2009), (5) operational planning (Stewart, Mohamed, & Daet, 2002), (6) deployment (Feldmann, Kaupe, & Lucas, 2020), and (7) monitoring and evaluation (Arayici et al., 2011). While this synthesis provided an initial foundation for Exo-Implant, further refinement was necessary to account for the nature of construction work, which is not adequately captured in generic implementation models.

3.1.2 Identification of Step-Level Elements

After identifying the core steps, the study examined how these steps could be implemented within construction settings. The Consolidated Framework for Implementation Research (Damschroder et al., 2009) and the recommendations of Breimaier, Heckemann, Halfens, and Lohrmann (2015) guided this stage. The analysis emphasised two processes: identifying workplace factors that influence intervention uptake and clarifying the responsibilities of stakeholders who would participate in or support implementation. Findings from Gonsalves, Akanmu, Shojaei, and Agee (2024), which examined construction industry perceptions of passive exoskeletons, were also incorporated to ensure that Exo-Implant reflected construction-specific decision-making practices, cultural dynamics, usability concerns, crew selection considerations, and training needs. This integration of conceptual frameworks with domain-specific evidence ensured that each step included construction-relevant components rather than generalised principles.

3.1.3 Integration of the Implementation Steps with the Construction Context Using NPT

To enhance theoretical coherence and ensure that Exo-Implant addressed the social and organisational processes underlying technology normalisation, the emerging steps and elements were aligned with NPT. NPT highlights four key mechanisms (i.e., coherence, cognitive participation, collective action, and reflexive monitoring) that describe how new technologies or practices become embedded within everyday routines (May et al., 2020). Step 1 and Step 2 were aligned with coherence by emphasising the need for organisations to understand why exoskeletons are needed and how they fit within organisational priorities. Step 3 improved cognitive participation by fostering stakeholder engagement through demonstrations, communication, and early involvement. Steps 4, 5, and 6 implemented collective action by establishing detailed procedures for creating manuals, training workers, coordinating deployment, and supporting daily use. Step 7 incorporated reflexive monitoring through ongoing evaluation, feedback loops, and iterative refinement. Mapping every step to an NPT construct ensured that the plan addressed not only procedural activities but also the cognitive, relational, and organisational mechanisms that determine whether exoskeletons become normalised in construction practice. Table 1 presents this mapping.

Table 1: NPT constructs, steps and supporting elements of Exo-Implant.

NPT Constructs	Steps	Supporting elements within Exo-Implant
Coherence	1	Identifying documented benefits, evaluating cost–benefit indicators, and relevant stakeholders; assessing organisational readiness and strategic alignment.
	2	Conducting an exploratory (or feasibility) study; evaluating task–technology fit, site constraints, workflow patterns, and procurement options (purchase/rental).
Cognitive participation	3	Providing lectures, toolbox talks, demonstrations of exoskeletons, developing multilingual and culturally tailored communication materials, and offering trial opportunities.
Collective action	4	Developing manuals, guidelines, and streamlined observation sheets; establishing storage, maintenance, and operational procedures.
	5	Developing training module; conducting training sessions; evaluating workers' learning; engaging innovation champions; ensuring manufacturer-led trainer preparation.
	6	Executing pilot deployment; collecting field observations; coordinating supervisor–worker feedback cycles; leveraging peer champions.
Reflexive monitoring	7	Collecting periodic feedback; contacting manufacturers for potential updates to exoskeleton design; conducting cost-benefit analysis; revising training materials; tracking repairs, documenting usage hours, updating operational procedures, and scheduling three-year reassessment of implementation decisions.

3.1.4 Validation and Iterative Refinement of the Implementation Plan

The preliminary version of Exo-Implant was iteratively refined through two stages of validation, reflecting best practices in implementation science that emphasise participatory design, stakeholder engagement, and iterative adaptation (Damschroder et al., 2009; May et al., 2020). The first stage involved semi-structured interviews with nine experts, including construction technologists, safety managers, ergonomists, and academic researchers specialising in exoskeletons and implementation science. Semi-structured interview is widely recognised as an effective method for probing conceptual clarity, surfacing contextual assumptions, and refining theoretical models (Kallio, Pietilä, Johnson, & Kangasniemi, 2016). Each interview lasted approximately one hour and focused on examining the conceptual appropriateness of each step, the clarity of associated elements, and the logical sequencing of activities. Feedback from these sessions resulted in key refinements, including clearer terminology, expanded feasibility assessment procedures, and strengthened justification for major decision points, consistent with iterative co-design approaches recommended in complex intervention development (Alicia et al., 2019). The second validation stage consisted of a facilitated focus group with six stakeholders representing management, safety, ergonomics, experienced field workers, and regulatory agencies. Focus groups are particularly well-suited for implementation research because they capture collective reasoning, illuminate divergent interpretations, and reveal practical constraints that individual interviews may not surface (Hennink, 2013). Participants reviewed each step and element, assessing alignment with construction workflows and identifying additional considerations that needed to be incorporated.

3.2 Evaluation of Exo-Implant

Given that few construction firms currently deploy exoskeletons, a field-based implementation study was unfeasible for an early-stage framework. Instead, the evaluation phase employed a scenario-based case study, which is suited for emerging technologies because it enables researchers to explore decision-making processes, organisational interactions, and implementation challenges in a structured yet controlled environment (Badham et al., 2019). Scenario methods have been used in safety research, human-technology interaction studies, and organisational decision-making to simulate real-world complexity without exposing participants to physical or operational risks (Carroll, 2003). The goal of the evaluation was to determine whether Exo-Implant was usable, understandable, practically relevant, and aligned with construction workflows, consistent with usability evaluation practices in implementation science (Davis, 1989; Lewis, 2014).

3.2.1 Scenario Development and Validation

A detailed scenario was developed describing how a hypothetical mid-sized construction firm ("Company A") identified rising WMSD rates, selected passive exoskeletons as an intervention, and applied Exo-Implant to guide adoption. The scenario incorporated management deliberations, formation of an Exo-Project Team, feasibility assessments, manufacturer coordination, training sequences, buy-in activities, pilot deployment processes, and feedback mechanisms. Developing scenarios with this level of procedural detail aligns with recommendations for scenario construction in organisational and systems research (Badham et al., 2019). The scenario underwent validation through a focus group involving a safety manager, superintendent, corporate manager, ergonomist, experienced worker, and OSHA representative. Focus group participants evaluated whether the scenario realistically represented construction operations, decision hierarchies, and communication flows. Their feedback prompted refinements such as incorporating procurement timelines, clarifying task-device compatibility assumptions, and specifying responsibility for equipment maintenance.

3.2.2 Case Study with Construction Professionals

The validated scenario formed the basis for a case study involving ten participants: one exoskeleton manufacturer and nine construction professionals, including general managers, project managers, safety leaders, field supervisors, and risk managers. Case study methodology is used to examine socio-technical implementation processes and to capture multi-perspective interpretations of an intervention (Stake, 1995; Yin, 2018). Participants were assigned scenario-specific roles and asked to enact implementation steps collaboratively as if the scenario were unfolding within their own firm. Participants were purposively selected to represent key organisational roles involved in technology adoption and safety decision-making, including management, safety leadership, supervision, and field operations, consistent with practices in exploratory implementation research aimed at capturing diverse perspectives (Palinkas et al., 2015; Proctor et al., 2011). This method generated insights into how stakeholders perceived the feasibility and clarity of each step, how they interpreted their responsibilities within the framework, and how organisational realities shaped the perceived usefulness of Exo-Implant. The case study format provided both evaluation metrics, including usability ratings grounded in technology acceptance measures (Davis, 1989), and qualitative depth, enabling analysis of sensemaking, role alignment, and potential barriers to adoption. This mixed approach is consistent with recommendations for assessing implementation readiness and acceptability in the early stages of technology introduction (Palinkas et al., 2015; Proctor et al., 2011).

3.3 Data Analysis

The study employed integrated qualitative and quantitative analysis to examine the usability of Exo-Implant and identify factors influencing adoption. Qualitative analysis drew on transcripts from the expert interviews and focus groups. These data were analysed using an inductive thematic approach following the procedures of Vanover, Mihas, and Saldaña (2021). Two researchers independently coded the data, compared interpretations, and reconciled discrepancies through discussion. The resulting inter-rater reliability ($\kappa = 0.75$) reflected strong agreement. Themes were synthesised to refine the plan and to generate the list of facilitators and barriers presented in the Results section. Quantitative data were obtained from a usability and user-acceptance questionnaire administered during the scenario-based case study. Participants rated their perceptions of ease of use, usefulness, trust, attitude, and intention to use Exo-Implant using a five-point Likert scale adapted from the Technology Acceptance Model (Davis, 1985). Descriptive statistical analysis was conducted to summarise these perceptions. The integration of qualitative and quantitative findings enabled a better understanding of how construction professionals interacted with Exo-Implant, how they interpreted its relevance, and which features supported or hindered its perceived usability.

4 Results

This section is organised to address the two research questions guiding the study. The components of an effective implementation strategy for passive back-support exoskeletons in construction (RQ1) are presented in Section 4.1, which details the development of Exo-Implant and describes each step of the proposed implementation plan. The organisational, operational, and workforce factors that influence adoption, use, and sustainability (RQ2) are presented in Section 4.2 through an evaluation of the plan's usability and an analysis of step-specific facilitators and barriers.

4.1 Developed Implementation Plan (Exo-Implant)

This section describes each step of the Exo-Implant, illustrating how its components implement the constructs of NPT and address the practical considerations identified during validation. Figure 3 presents the visual structure of the plan while the following subsections explain the logic, purpose, and operational features of each step.

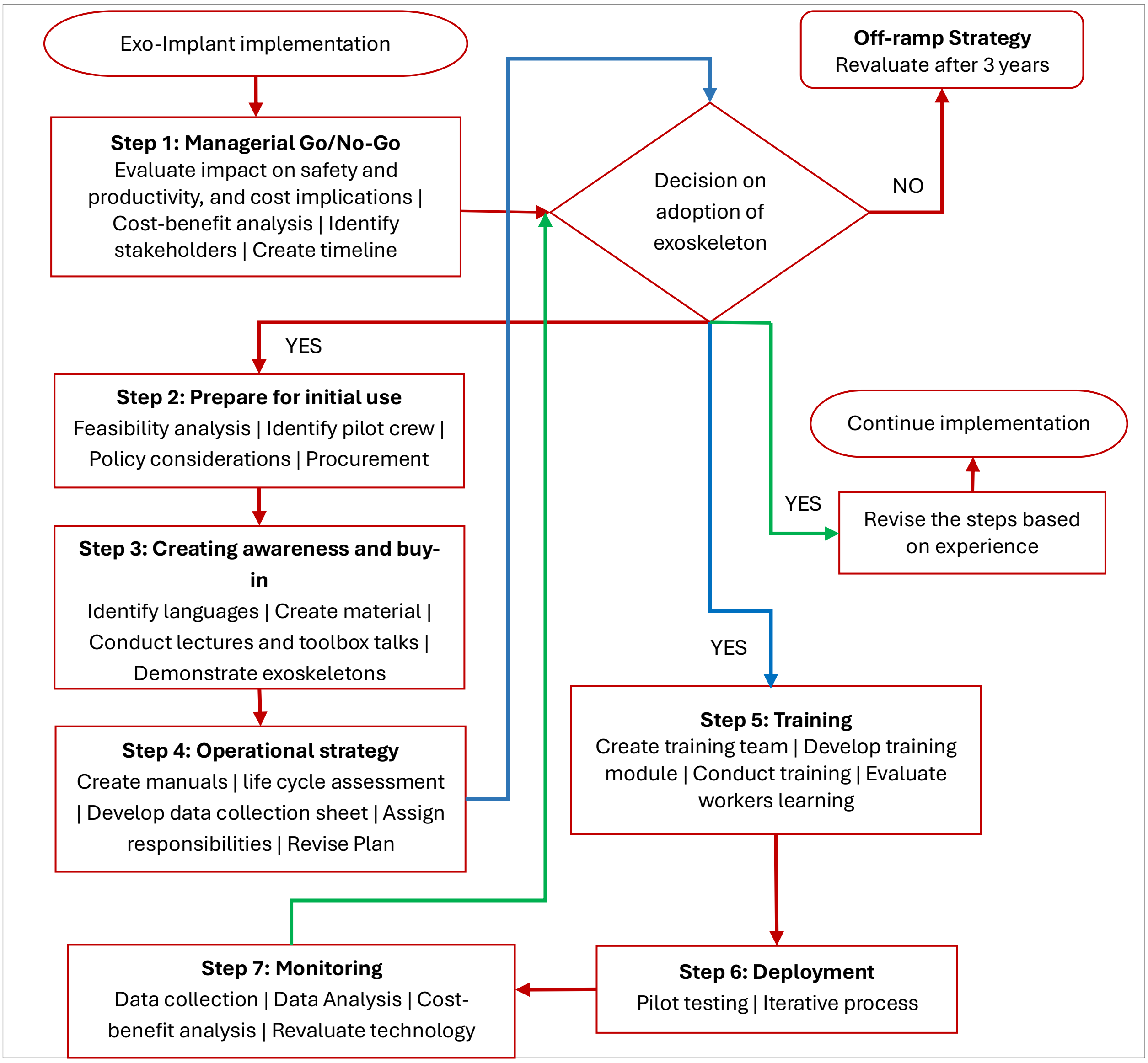

Figure 3: Exo-Implant.

4.1.1 Step 1: Managerial Go/No-Go Decision on the Adoption of Exoskeletons

Step 1 establishes managerial commitment and early organisational sensemaking as fundamental prerequisites for successful implementation. In this step, corporate leadership evaluates whether passive back-support exoskeletons align with the firm's strategic, financial, and safety priorities. Decision makers review documented benefits, including potential reductions in injury rates, improvements in worker well-being, productivity gains, and decreases in workers' compensation claims, and relate these benefits to broader organisational objectives such as talent retention, competitive advantage during bidding, and alignment with evolving expectations for safety innovation. Managers also assess the practicality of implementation, considering compatibility with common jobsite tasks, the extent to which exoskeletons integrate into existing workflows, and the availability of manufacturer support. A cost-benefit analysis clarifies anticipated returns and resource requirements. Early identification of relevant stakeholders supports later stages of workforce engagement, operational planning, and training. By the end of this step, the organisation has established a clear understanding of need, feasibility, and strategic fit, resulting in either a 'Go' decision to advance to Step 2 or a 'No-Go' decision triggering the Off-Ramp Strategy.

4.1.2 Step 2: Preparing for the Initial Use of Exoskeletons

Step 2 transitions the organisation from managerial approval to the detailed groundwork required for implementation. This step emphasises feasibility assessment, interdisciplinary coordination, and logistical readiness. After a 'Go' decision, an Exo-Project Team is formed, bringing together representatives from management, safety, ergonomics, project supervision, and experienced field workers. The involvement of multiple organisational roles ensures that early decisions reflect operational realities as well as strategic objectives. The team conducts a feasibility assessment that examines ergonomic risk profiles, crew structures, workflow sequences, environmental constraints, tool-use patterns, personal protective equipment compatibility, and the physical demands of targeted tasks. Participants emphasised that overlooking these variables can lead to practical disruptions during later deployment. The team also analyses storage needs, cleaning and inspection areas, and supervisory capacity to support initial rollout. Procurement pathways are evaluated to include rental options, trial agreements, bulk purchasing, and manufacturer-supported pilots, recognising that construction firms frequently prefer low-risk avenues for testing new technologies. Budget cycles, project timelines, and training windows are reviewed to ensure organisational alignment. Through these activities, Step 2 develops from a preparatory task list into a coordinated readiness process that establishes the foundations for subsequent workforce engagement in Step 3.

4.1.3 Step 3: Creating Awareness and Buy-In

Step 3 addresses the role of workforce engagement in shaping adoption, acknowledging that worker perceptions strongly influence implementation success. Awareness efforts begin by situating WMSDs, particularly low-back injuries, as persistent and costly problems in construction. Participants noted that workers respond more receptively when the need for the intervention is communicated clearly and linked to their own experiences. Communication materials are tailored to the linguistic and cultural diversity of construction crews to ensure accessibility and comprehension across literacy levels. Demonstrations constitute the centrepiece of engagement, providing opportunities for workers to wear the device, experiment with movement patterns, and address concerns related to mobility restrictions or discomfort. Additional communication channels, including mobile-app videos, recorded testimonials, and posters, help normalise the device and integrate it into the visual landscape of the jobsite. A voluntary trial period allows workers to test the exoskeleton prior to formal deployment. Participants identified these hands-on trials as pivotal moments for acceptance, particularly when supported by peer endorsement from respected workers. These activities build shared understanding, foster early commitment, and reduce uncertainty by providing direct and meaningful exposure to the technology.

4.1.4 Step 4: Operational Strategy

Step 4 establishes the operational systems necessary to support consistent, reliable use of exoskeletons. The Exo-Project Team developed a handling and storage manual tailored to jobsite conditions, addressing temperature variations, humidity, dust, and irregular work-shift durations, which require adjustments beyond standard manufacturer instructions. The maintenance manual is expanded to include inspection procedures, wear indicators, cleaning processes, repair workflows, and warranty considerations. A life-cycle assessment enables organisations to anticipate replacement intervals, service needs, and long-term budgeting implications. The operational strategy also includes a streamlined observation sheet designed to capture information on comfort, exertion, workflow compatibility, environmental constraints, and device fit. Participants emphasised that a concise format improves compliance among supervisors and field personnel. Environmental compatibility is assessed explicitly, as cold-weather operability and precipitation were identified as important determinants of device performance. Role responsibilities are clearly delineated to clarify which workers maintain personal or shared devices, who conducts inspections, and who oversees day-to-day deployment. This approach ensures that exoskeleton use is supported by stable routines, clear expectations, and mechanisms for consistent oversight.

4.1.5 Step 5: Training

Step 5 focuses on developing the technical and behavioural competencies required for safe and effective exoskeleton use. Training begins with the formation of a Training Team composed of safety leaders, ergonomists, engineers, and frontline supervisors. Trainers undergo manufacturer-led instruction to ensure technical accuracy, consistency, and the capacity to address workers' concerns. A multi-stage training module is developed to cover donning and doffing, proper fit adjustments, device modes, and safety precautions. In addition to these technical components, the training incorporates behavioural-change principles addressing readiness, perceived usefulness, and common sources of resistance. Hands-on practice is a central feature, allowing workers to perform common construction tasks while receiving feedback on posture, movement, and device handling. Experienced "innovation champions" are incorporated into training to model appropriate use and offer peer-level support. Training materials are designed for multilingual communication, using diagrams and simplified terminology to enhance accessibility. Training concludes with a brief assessment to verify comprehension and certify workers who demonstrate safe, proficient use. This process cultivates confidence and establishes a shared baseline of knowledge across users and supervisors.

4.1.6 Step 6: Deployment

Step 6 marks the transition to real-world use under routine jobsite conditions. Deployment is treated as an iterative process characterised by continuous learning and incremental scaling. Pilot crews, typically those performing high-risk or high-flexion tasks, are selected to use the exoskeletons for a defined period. Supervisors and safety professionals use the observation sheet from Step 4 to document comfort, usability, workflow impacts, productivity implications, and emerging constraints. Participants emphasised the importance of debriefs, routine check-ins, and open communication between workers and the Exo-Project Team. These interactions allow for rapid problem resolution, such as adjusting sizing, modifying storage processes, or refining training content. Participants also highlighted that deployment patterns often follow trade-specific norms rather than isolated crew units, reinforcing the value of coordinating across multiple crews simultaneously. The pilot concludes with an evaluation meeting in which the Exo-Project Team determines whether to expand, adjust, or pause implementation. Successful deployments are communicated throughout the organisation to build momentum and encourage broader adoption. Through these cycles of feedback, testing, and refinement, Step 6 facilitates the transition from initial rollout to sustained operational use.

4.1.7 Step 7: Monitoring

Step 7 establishes ongoing evaluation processes that support long-term integration of exoskeletons into organisational routines. Monitoring captures both quantitative and qualitative indicators, including comfort, ease of movement, exertion levels, durability, and productivity effects. Participants emphasised the importance of tracking repair history, frequency of use, device failures, and environmental performance as part of routine oversight. Worker feedback is solicited through periodic conversations, mobile reporting options, and supervisor-initiated check-ins. Monitoring is framed as a two-way communication process in which workers actively contribute to understanding device performance and identifying new barriers or risks. Cost-benefit analyses are conducted periodically to assess whether the program continues to provide value, incorporating both direct and indirect outcomes. Monitoring data informs updates to earlier steps, including training revisions, operational adjustments, and procurement strategies. Through these iterative cycles, Step 7 supports continuous alignment between organisational needs and exoskeleton practices.

4.1.8 Off-ramp Strategy

The Off-Ramp Strategy outlines a pathway for organisations that choose not to adopt exoskeletons or elect to pause implementation. If the Exo-Project Team or management determines that adoption is not feasible, due to cost, safety concerns, workflow incompatibility, or workers' resistance, the rationale is documented in a report capturing feasibility findings, worker feedback, and trial performance. A three-year reassessment window ensures that organisations reevaluate their decision in light of technological improvements, pricing changes, and shifting organisational needs. This cyclical reassessment prevents premature long-term rejection and ensures that organisations remain attentive to emerging opportunities.

4.2 Evaluation of the Developed Implementation Plan

The evaluation phase assessed Exo-Implant's usability, clarity, and perceived practicality in a simulated organisational environment. This section integrates quantitative usability ratings with qualitative interpretations to show how participants engaged with the plan and how they perceived its feasibility. The subsections below present these findings in detail.

4.2.1 Usability

Figure 4 summarises participants' ratings across the five usability constructs: ease of use, perceived usefulness, trust, attitude, and intention to use.

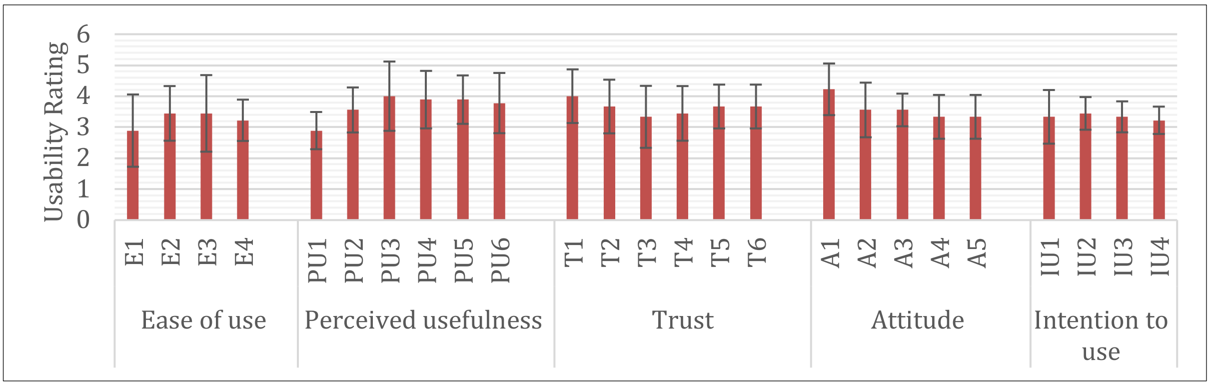

Figure 4: Ease of use, perceived usefulness, trust, attitude and intention-to-use Exo-implant.

Ease of use

Participants provided a near-moderate level of agreement (E1: 2.89 ± 1.17) that Exo-Implant was easy to use. They noted that while individual steps were clear, navigating the full plan required effort, particularly for first-time users. Learning the plan and understanding its content received higher ratings (E2: 3.44 ± 0.88; E3: 3.44 ± 1.24), suggesting that familiarity improves usability. Participants also moderately agreed that the plan helped them identify role-specific responsibilities (E4: 3.22 ± 0.67). These findings indicate that clarity at the step level is a strength, while overall comprehensiveness introduces cognitive load.

Perceived usefulness

Perceived usefulness was rated positively across all items. Participants moderately agreed that Exo-Implant would support timely completion of the implementation process (PU1: 2.89 ± 0.60) and felt that its structured format could streamline decision-making once users became familiar with it. They agreed that the plan would ease exoskeleton adoption (PU2: 3.56 ± 0.73) and improve implementation effectiveness (PU4: 3.89 ± 0.93). Participants also reported moderate-to-high agreement that Exo-Implant would guide them through the implementation process (PU6: 3.78 ± 0.97), indicating perceived value as a decision-support and procedural reference tool. The highest usefulness rating (PU3: 4.00 ± 1.12) reflected agreement that the plan was clearly relevant to their professional roles. Overall usefulness received a near-high score (PU5: 3.89 ± 0.78). These results indicate strong perceived value, particularly in supporting role-specific decision making.

Trust

Trust ratings were consistently moderate to high. Participants strongly agreed that the plan provided reliable information (T1: 4.00 ± 0.87) and moderately agreed that it addressed user needs (T2: 3.67 ± 0.87), was practical (T3: 3.33 ± 1.00), and would be used consistently during implementation (T4: 3.44 ± 0.88). They also agreed that Exo-Implant contained the necessary information for effective adoption (T5: 3.67 ± 0.71) and that they trusted it as a guidance tool (T6: 3.67 ± 0.71). Trust emerged as one of the plan's strongest usability attributes.

Attitude

Participants expressed a positive overall attitude toward Exo-Implant. They rated using the plan as a "good idea" (A1: 4.22 ± 0.83) and indicated favourable views of the plan (A2: 3.56 ± 0.88). They believed the plan would support implementation (A3: 3.56 ± 0.53) and expressed willingness for their organisation to use it (A4: 3.33 ± 0.71). They also agreed that organisational adoption of Exo-Implant would be beneficial (A5: 3.33 ± 0.71). These findings reflect broad conceptual acceptance of the plan.

Intention to use

Participants reported moderate intention to use the plan. They indicated a moderate likelihood of using it frequently (IU1: 3.33 ± 0.87), referring to it during implementation (IU3: 3.33 ± 0.50), and using it throughout the adoption process (IU2: 3.44 ± 0.53). The lowest, but still moderate, rating reflected their intent to use the plan as often as the company adopted exoskeletons (IU4: 3.22 ± 0.44). These results suggest that while the plan is valued, its complexity may limit spontaneous use unless supported by organisational frameworks.

4.2.2 Factors Influencing the Adoption of Exo-Implant

Qualitative analysis identified facilitators and barriers that shaped how participants interpreted each step of Exo-Implant. Table 2 summarises these factors, while the following details how the factors shaped participants' perceptions of feasibility, acceptability, and practicality.

Table 2: Facilitators and barriers influencing the adoption of Exo-Implant.

Steps	Facilitators	Barriers
1	Feasibility study; Impact assessment; Pilot testing; Modifications; Stakeholders; Manufacturer's support; Competitive advantage; Cost-benefit analysis; Implementation approach; Buy-in; strategic alignment; early assessment of procurement options; device–task compatibility analysis.	Rotational injuries; Difficulty in measuring site safety; Compatibility with PPE and tasks; Device weight; Customisation for the workplace; Adjustability for different sizes; Timeline for execution; Limited early-stage information on repair/service needs; Uncertainty about long-term costs.
2	Crew identification; Renting plan; Manuals; workflow analysis; site-condition assessment; Evaluation of procurement lead times.	Service life; Key performance indicators; Redundancy of some elements; Unclear ownership models (personal vs. shared devices).
3	Crew composition; Language consideration; Workers' testimonials; Demonstration; Manufacturers' support;	Inclusion of other communication aids (videos, mobile apps, prompts); Include trial opportunities; Buy-in through

	Toolbox talks; Mobile-app videos; Culturally adapted materials; Structured trial opportunities.	productivity benefits; Perceived stigma; Resistance due to unfamiliarity or discomfort.
4	Developing manuals; Weather compatibility; Operational strategy; Life cycle assessment; Workers' responsibilities; Parts procurement; Maintenance requirements; Customised storage/handling protocols; streamlined data collection tools.	Device protection accessories; Assignment of responsibilities; Psychological considerations; Data collection and processing support; Environmental limitations (heat/cold); Workflow disturbances.
5	Champions; Manufacturer's support; Hands-on training; Training module; Trainer certification; Multilingual materials.	Multi-lingual trainers; Time constraints for training; Variability in trainer competence.
6 and 7	Size considerations; Iterative process; Data collection; Implementation approach; Peer champion influence; repair/usage tracking; Continuous monitoring loops; Trade-level deployment.	Large-scale implementation; Simple data collection; Data on repair/use; Worker fatigue with repeated surveys; Lack of automated data tools.
Overall	Includes necessary elements; Theoretically grounded; Flexible and adaptable; Aligned with construction workflows.	Condense plan; Provide more description; Need to simplify; Potential cognitive overload; Need for visual aids and role-specific modules.

Step 1: Managerial Go/No-Go decision

Participants identified cost feasibility, injury-prevention potential, and insurance implications as major facilitators. They noted that general contractors increasingly require subcontractors to adopt advanced safety technologies, suggesting that exoskeletons may soon represent a competitive advantage. Participants also explained that workers may resist adoption because benefits accrue over long time horizons. They emphasised that many injuries stem from twisting motions, not only flexion, highlighting the need for collaboration with manufacturers to expand device capabilities. Participants recommended addressing warranty terms, training needs, and availability at this early stage so that managers can make fully informed decisions.

Step 2: Preparing for the initial exoskeleton use

Participants viewed feasibility assessment, crew identification, and rental options as strong facilitators. They noted that service life, maintenance frequency, and key performance indicators should be considered earlier in the decision-making sequence. Many suggested moving these elements to Step 1 to support a clearer Go/No-Go decision. Participants emphasised the importance of determining whether exoskeletons would be personally assigned or shared, as this influences hygiene protocols, maintenance expectations, and worker acceptance. Failure to clarify these factors early was viewed as a potential barrier.

Step 3: Creating awareness and buy-in

Participants stressed that awareness strategies must reflect workforce diversity in language, culture, and job-site experience. Hands-on demonstrations, testimonials from workers with prior injuries, and multilingual content were identified as particularly effective engagement tools. Additional communication formats, such as mobile-app prompts and printed flyers, were recommended to increase visibility. Participants also noted that highlighting productivity gains, in addition to injury prevention, would enhance buy-in among project teams. These factors were seen as essential to cultivating early acceptance.

Step 4: Operational strategy

Participants agreed that the operational strategy provided strong support for reliable use but emphasised the need to clearly integrate storage, maintenance, and handling procedures with decision-making timelines. They recommended customising manufacturer manuals to reflect site-specific conditions and incorporating weather-compatibility assessments and life-cycle considerations. Participants raised concerns about workers' reluctance to handle maintenance tasks and emphasised the importance of clearly defined accountability structures. They also suggested simplifying data collection tools and addressing psychological barriers, such as discomfort with being visibly differentiated on-site.

Step 5: Training

Participants identified training as a critical driver of successful implementation. They emphasised the importance of leveraging innovation champions, involving manufacturers directly in training delivery, offering multilingual instruction, and providing extensive hands-on practice. Training should address maintenance and cleaning procedures, reflect culturally relevant jobsite examples, and incorporate clear strategies for addressing resistance. Participants consistently noted that strong training practices could offset many early-stage barriers.

Steps 6 and 7: Deployment and monitoring

Participants suggested that deployment and monitoring naturally operate together during field use and could be conceptually linked. They recommended organising deployment by trade rather than individual crews to align with common construction practices. Participants emphasised the need to simplify data collection, track repairs and usage frequency, and create tight feedback loops to enable rapid problem solving. Deployment was seen as an opportunity to test, refine, and standardise procedures across diverse crews.

Overall

Participants agreed that Exo-Implant contained the essential components of a comprehensive implementation framework. They encouraged condensing the plan to improve readability and incorporating supportive visuals such as flowcharts and illustrations. Participants emphasised that despite its complexity, the framework provides a valuable structure for guiding exoskeleton adoption in real-world construction environments.

5 Discussion

Back-support exoskeletons offer a promising approach to reduce WMSDs in construction. However, despite growing biomechanical evidence of their benefits, the industry still lacks clear, structured, and context-sensitive implementation processes capable of supporting their integration into everyday work practices. This study directly addresses that gap by developing and evaluating Exo-Implant, a theory-driven and empirically informed framework designed specifically for construction organisations. The incorporation of NPT provided a lens for organising implementation activities, clarifying stakeholder roles, and conceptualising adoption as a dynamic and ongoing process rather than a one-time technological intervention. By foregrounding the social and organisational mechanisms that influence normalisation, Exo-Implant demonstrates how exoskeleton adoption depends as much on shared understanding, interaction, and role coordination as it does on technical performance. The plan was evaluated through a scenario-based case study to examine its usability, stakeholder acceptance, and adoption drivers.

5.1 Usability of Exo-Implant

Overall, participants found Exo-Implant comprehensible, well-structured, and relatively easy to learn, which is critical in construction environments where stakeholders often come from diverse educational and cultural backgrounds (Fischer & Amekudzi, 2011). The clarity of step-level descriptions and the explicit assignment of roles were identified as strengths that supported rapid comprehension. However, they reported only moderate ease of use, primarily due to the plan's extensive, multi-step structure, which requires navigation across organisational, operational, training, and monitoring domains. This finding reflects an inherent trade-off between completeness and usability in multi-stakeholder implementation frameworks, particularly in complex project-based industries such as construction. Despite this challenge, participants rated the plan as highly useful, a perception strongly associated with sustained use of organisational interventions (Malik & Annuar, 2021). Importantly, trust in Exo-Implant was rated as moderately high, reflecting confidence in its reliability, completeness, and alignment with real-world construction processes. Trust plays a decisive role in adoption because it reduces uncertainty and strengthens the likelihood that stakeholders will rely on the tool during decision-making (Gefen, Karahanna, & Straub, 2003; Sari, Isnayanti, Ikhsan, Sayoga, & Pradhani, 2021). Participants also expressed a consistently positive attitude toward the plan, aligning with findings that perceived usefulness, trust, and positive attitudes significantly influence intention to adopt new technologies (Sari et al., 2021). These results suggest that although Exo-Implant's complexity may challenge seamless adoption, its perceived credibility and relevance are likely to sustain long-term interest and organisational use.

5.2 Factors Influencing Adoption of Exo-Implant

Feasibility analysis was identified as a key facilitator for adopting Exo-Implant. By evaluating crews and their risk exposure, construction companies can identify which crews to target for pilot testing and select appropriate exoskeleton types. Factors such as task compatibility, weather conditions, and work environments will inform these decisions. This approach aligns with Feldmann et al. (2020), who emphasised feasibility assessments as a critical first step in exoskeleton implementation in logistics environments. In this study, feasibility analyses also supported early identification of operational constraints that, if unaddressed, could undermine later stages of deployment.

Stakeholder engagement, particularly through the identification of critical actors and innovation champions, also emerged as a major facilitator. Ensuring that managers, supervisors, and experienced workers are involved strengthens ownership and legitimacy (Crea et al., 2021). The plan's integration of peer champions reflects evidence that workers' attitudes are strongly shaped by trusted colleagues rather than top-down directives (Bunce et al., 2020). Champion involvement also played an important role in reframing exoskeletons as practical tools rather than management-driven mandates.

Worker buy-in, however, remained a central challenge. Resistance to new technologies is common in construction (Ngai et al., 2010), but raising awareness about WMSD risks and providing tangible demonstrations of exoskeleton benefits can significantly reduce resistance. This aligns with the Change Model (Grol & Wensing, 2004), which stresses the importance of problem recognition as a precursor to behavioural change. Pilot testing played a crucial facilitative role by providing real-time evidence of cost-effectiveness, safety, comfort, and productivity implications, similar to findings in intralogistics (Feldmann et al., 2020). Workers were more willing to try the exoskeleton after hearing positive testimonials from peers, reinforcing the importance of social influence mechanisms (Bunce et al., 2020). Continuous monitoring and feedback loops supported iterative refinement and organisational learning, echoing prior implementation research (Arayici et al., 2009; Ngai et al., 2010).

Several barriers emerged as well. First, participants noted that without embedded reminders or decision cues, users may lose momentum or skip critical steps, indicating a need for integrated behavioural nudges or digital prompts (Sunstein, 2014). They also explained that Exo-Implant's comprehensiveness, while valuable for reliability, could overwhelm users. This reveals a trade-off between depth and usability. Simplifying the plan into role-specific modules could mitigate cognitive overload. Another barrier involved gaps in standardised procedures for capturing maintenance and repair data, which are essential for estimating life-cycle cost and long-term viability (De Looze et al., 2016). Finally, the absence of industry-wide cost-benefit tools complicates financial evaluation, as construction firms typically rely on highly variable financial decision models (Shenhar, Dvir, Lechler, & Poli, 2002).

6 Conclusions, Limitations and Future Work

Passive back-support exoskeletons have shown considerable potential to reduce musculoskeletal disorders and improve productivity among construction workers, leading to increased interest in their organisational deployment in recent years. Despite this potential, most construction firms still lack formalised, context-specific, and evidence-based processes to support safe, consistent, and sustainable integration of exoskeleton technologies into everyday work practices. This study responded to this need by developing Exo-Implant, a theory-informed implementation plan tailored to construction environments. The plan was grounded in a systematic review of implementation frameworks and industry adoption factors, and its utility was examined through a scenario-based case study involving a mid-sized construction company. Results showed that stakeholders viewed Exo-Implant as useful, trustworthy, and role-relevant, though somewhat complex. Participants recommended refinements including visual aids, clearer sequencing, and enhanced guidance on feasibility evaluation. This study advances the limited but growing body of research on exoskeleton implementation in construction. First, it provides a structured, theoretically grounded, and empirically validated framework that organisations can apply or adapt when planning exoskeleton deployment. Second, it extends the use of NPT within construction technology research by demonstrating how coherence-building, role alignment, collective action, and reflexive monitoring can structure large-scale adoption. Third, it contributes guidance for practitioners and establishes a methodological foundation for future studies on wearable and human-assistive technologies.

While this study advances understanding of exoskeleton implementation, several limitations must be acknowledged. The case study involved participants from a single mid-sized construction company, limiting generalizability to firms with different sizes, resources, or organisational structures. The scenario-based evaluation, selected due to limited field deployments, provided controlled insight but may not fully capture the complexity, production pressures, and environmental variability of live implementation. Accordingly, the findings reflect perceived feasibility and usability rather than observed long-term operational performance. Additionally, Exo-Implant was designed specifically for passive exoskeletons, which are mechanically simpler than active systems. Active devices introduce additional considerations such as power requirements, sensor calibration, digital interfaces, and expanded safety protocols, which may necessitate future modifications. Future research should validate Exo-Implant across diverse construction contexts, including varying company sizes, project types, and contractual arrangements, to assess scalability and adaptability. Longitudinal field studies are needed to examine real-world adoption trajectories, workforce responses, productivity effects, and organisational change processes over time. Extending Exo-Implant to active exoskeletons represents another important direction, as does developing risk-assessment tools and performance indicators to support implementation. A particularly promising frontier involves integrating Exo-Implant with digital technologies; for example, a digital-twin version of the framework could support real-time monitoring, predictive analytics, simulation of deployment strategies, and adaptive organisational learning. Cross-industry applications may also be explored, given that manufacturing, logistics, warehousing, and healthcare face similar ergonomic and adoption challenges. Adapting the framework for these sectors could broaden its impact and support the wider advancement of wearable technology implementation research.

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Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics.

Data Availability Statement

Data can be made available upon request to the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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