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Organized biennially by the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), in collaboration with the University of Stuttgart's Institute of Industrial Manufacturing and Management (IFF) and the Wearable Robotics Association (WearRA), a global interest group based in Phoenix, Arizona (USA), WearRAcon Europe aims to showcase the latest findings, trends, and innovations in wearable robotics across Europe, with a particular emphasis on occupational exoskeletons. The event seeks to facilitate interactions among professionals in the field, including industry end-users, academic experts, and representatives from governmental agencies. A new feature for the 4th edition was the inclusion of digital ergonomics tools and their integration with exoskeleton deployment and ergonomic workplace design.

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Oral Presentations

ACCEPTANCE, ACCEPTABILITY, AND CHANGE MANAGEMENT SUPPORT

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INTRODUCTION

Over the past two decades, musculoskeletal disorders (MSDs) have remained the most prevalent occupational diseases across Europe, affecting three out of five workers (INRS, 2024). When traditional methods for improving working conditions have been exhausted and automation is not a feasible option, physical assistance devices (PADs)—and more specifically, exoskeletons—are emerging as promising solutions to reduce workers' exposure to biomechanical risk factors associated with MSDs. In a context of rapid technological advancement, exoskeletons represent a flagship innovation in both research and industry.

However, like many evolving technologies, exoskeletons raise critical questions regarding their benefits and limitations. As INRS (2022) notes, "Understanding the risks associated with exoskeletons, including their long-term effects, is essential to ensuring their safe use." Often influenced by science fiction and dystopian imaginaries, exoskeletons must be approached with careful consideration. Originally designed to support humans in physically demanding tasks, they are now being implemented in real-world occupational settings. Their deployment cannot be reduced to biomechanical analysis alone; instead, it calls for a comprehensive examination of the psychological and organizational transformations they may trigger—at the individual, collective, and organizational levels.

This study focuses on three interconnected areas: the phenomenon of *acceptability*, the process of *acceptance* of exoskeletons, and the *change management* required for their integration into professional environments.

METHODS

This study followed a multi-method approach to examine the acceptance and integration of exoskeletons in the workplace. It combined a comprehensive literature review, ergonomic analyses of real work situations, semi-structured interviews, and the administration of a standardized questionnaire developed by INRS on exoskeleton acceptance and acceptability.

The selected version of the questionnaire focused on users and ex-users of exoskeletons. It integrates six core dimensions drawn from established models such as UTAUT and situated acceptance (Bobillier-Chaumon): facilitating conditions, usability, performance expectations (including health, safety, and physical effort), social influence, professional identity, and emotional response. The tool aimed not to produce a score but to assess the quality of interaction between users and the device at various stages of acceptance. Responses were rated on a 5-point Likert scale, and the survey duration was 15–20 minutes.

Data collection concluded on May 2025, after reaching 30 anonymized participants from sectors including logistics, construction, and agro-food. Participants had experience with exoskeletons ranging from one month to five years. Distribution formats included online (via Google Forms) and paper-based surveys conducted in person, notably with HAPO models through Ergosanté clients and a French ergonomic professional resource platform.

In addition to descriptive statistics, cross-variable analysis was conducted to interpret user experiences across the six dimensions of acceptance. Field observations and qualitative data from interviews further contextualized findings by linking them to specific work activities and sectoral realities, acknowledging the critical role of psychological and organizational factors in the adoption process.

RESULTS

The study revealed that 86% of participants were still using exoskeletons at the time of data collection. Benefits were primarily observed in the reduction of musculoskeletal strain, particularly for static trunk postures and dynamic manual handling tasks affecting the lower back and shoulders. However, several limitations were noted, including discomfort, poor task-exoskeleton fit, and psychosocial challenges such as reduced perceived autonomy and identity conflicts.

Acceptance was most strongly associated with emotional response and perceived ease of use, while social influence played a greater role during the initial stages of adoption. Over time, performance expectations—particularly regarding

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health and productivity—tended to decline without continued organizational support and adaptation. These findings underscore the importance of aligning exoskeleton solutions with real work activities and supporting users through ongoing evaluation and feedback mechanisms.

DISCUSSION AND LIMITATIONS

The adoption of exoskeletons in professional settings is a complex and evolving process that extends beyond mere technical implementation. This study reveals that while 86% of users continue to wear exoskeletons, usage tends to be moderate and intermittent, reflecting pragmatic adaptation to workplace realities. However, long-term effectiveness is challenged by limited ongoing support, as only half of users receive sustained follow-up after initial training, despite high satisfaction with prior information and formation.

Positioning exoskeletons as preventive tools rather than productivity enhancers is crucial to managing user expectations and avoiding disillusionment. Integration must be guided by ergonomic assessments and tailored to realistic, context-specific objectives. Psychosocial factors—such as perceived autonomy, professional identity, and social dynamics—play a major role in acceptance. Positive emotional responses correlate strongly with perceived social support from supervisors, colleagues, and management, highlighting the importance of workplace culture.

Exoskeletons are generally easy to use and quick to set up, but challenges remain regarding comfort (heat, perspiration), compatibility with other personal protective equipment, and fit in constrained work environments. While most users perceive improved working conditions, fewer feel safer, indicating exoskeletons are seen more as ergonomic aids than as personal protective equipment. Performance levels remain stable, aligning with the goal of reducing physical strain without increasing work pace.

The pilot implementation of a change management model within this study supports the value of structured, participatory approaches involving early user engagement and leadership endorsement to normalize use and reduce resistance.

Limitations include a small sample size, potential positive bias in responses, and predominance of one exoskeleton brand, which suggest caution in generalizing results. Nonetheless, findings emphasize the need for user-centered customization, ongoing support, and integration strategies attuned to specific work contexts to enhance long-term acceptance and effectiveness.

CONCLUSION

Exoskeletons can serve as valuable ergonomic interventions when integrated through a systemic and participatory approach. Their successful adoption depends on psychological, organizational, and technical factors that go beyond biomechanical benefits. This study underscores the critical importance of aligning implementation efforts with user expectations, workplace realities, and organizational readiness. The success of exoskeleton integration lies not only in technical design but also in the quality of human support and change management provided. Ensuring long-term adoption requires a robust framework involving early user engagement, continuous feedback, and embedded training practices. Companies must adopt a proactive strategy that considers psychosocial dimensions and tailors deployment to the specific needs of the target work environment. Finally, ongoing research is essential to explore long-term effects, identify best practices for adoption, and improve the usability and acceptance of exoskeleton technologies. Insights from interdisciplinary fields—including ergonomics, organizational psychology, and user experience design—will be key to optimizing their integration across diverse professional contexts.

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MITIGATING PHYSIOLOGICAL STRAIN DURING REPETITIVE LIFTING: INSIGHTS FROM A LAB-BASED EVALUATION OF PASSIVE BACK EXOSKELETONS

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1. INTRODUCTION

Passive back-support exoskeletons (PBEs) have increasingly been deployed in occupational settings to reduce musculoskeletal strain during manual handling tasks. While their biomechanical and perceptual effects have been extensively studied , their influence on cardiovascular load has received far less attention (1) - despite the scientifically well-established link between elevated occupational physical activity and cardiovascular risk (2).

Previous laboratory studies typically focus on single domains of strain, such as muscle activity, and often rely on heart rate as a proxy for cardiac load (1,3–5). However, this unidimensional approach fails to capture the complexity of cardiac strain, particularly myocardial oxygen demand and hemodynamic stress. A more differentiated assessment is needed to evaluate the broader physiological implications of PBE use in physically demanding occupational scenarios.

Our study addresses these gaps by using blood pressure and impedance cardiography (ICG) to quantify cardiac strain during repetitive lifting with and without PBE support, while also assessing a wide range of physiological and perceptual load domains.

2. AIM

We aim to expand current knowledge on the relieving effects of PBEs, with a particular focus on cardiac strain.

3. METHODS

3.1 Study Design

Twenty-six healthy adults (age: 25.2 ± 3.8 years, height: 175 ± 9.8 cm, weight: 71.8 ± 10.4 kg, body mass index: 23.3 ± 2.1 kg/m^2) participated in a controlled crossover study. Each subject completed a standardized lifting protocol under three conditions: no exoskeleton (FREE), with Laevo Flex V3.0 (LAEVO; Laevo BV, Netherlands), and with the SoftExo Lift V4.0 (HUNIC; Hunic GmbH, Germany). The order of conditions was randomized.

3.2 Lifting Task

The lifting task involved five minutes of repetitive one-arm lifting with a kettlebell equivalent to 15% of body weight, moving from hip to ankle height and back, paced at 6-s cycles via acoustic-visual signals. To ensure symmetric loading and enable manual blood pressure measurement, participants alternated arms every 30 s.

3.3 Outcome Parameters

Our primary outcome domain was cardiac strain, assessed via heart rate (HR), systolic blood pressure (SBP), and impedance cardiography (ICG). Stroke volume, cardiac output, and rate pressure product (RPP) were derived accordingly. Metabolic parameters ($\dot{V}O_2$, $\dot{V}CO_2$) were measured via breath-by-breath gas analysis to further calculate energy expenditure (EE). Muscle activity was recorded from seven trunk and leg muscles using surface electromyography (sEMG), normalized to maximal voluntary contractions (MVC). Perceived exertion (Borg CR10) and subjective comfort (100-mm VAS) were assessed throughout.

3.4 Statistical Analysis

Data were analyzed using repeated-measures ANOVA or nonparametric equivalents, depending on distribution. EMG data were modeled using a mixed-effects approach. Effect sizes were reported as Cohen's *f*, *d*, or Kendall's *W*, with significance set at $p < 0.05$.

4. RESULTS

Both PBEs significantly reduced physiological and perceptual load compared to the unassisted condition. Compared to FREE, RPP decreased by 8.1% with LAEVO and 6.5% with HUNIC. Similarly, EE was lower in both conditions (LAEVO: −13.9%, HUNIC: −9.4%), accompanied by decreased perceived exertion (LAEVO: −14.4%, HUNIC: −9.5%). Figure 1 shows individual responses for RPP, EE, and perceived exertion.

Regarding neuromuscular load, only LAEVO significantly reduced gluteus maximus activity (−21%, p = 0.004), while no consistent changes were observed in trunk muscle activation or under HUNIC. No significant differences emerged between the two exoskeletons in any of the physiological or perceptual outcomes.

Wearing comfort declined over time for both devices (p = 0.001), with a significant drop from pre- to post-task ratings for LAEVO (−11.6%, p = 0.033) and HUNIC (−11.2%, p = 0.036). However, no overall differences between exoskeleton types or baseline values were detected.

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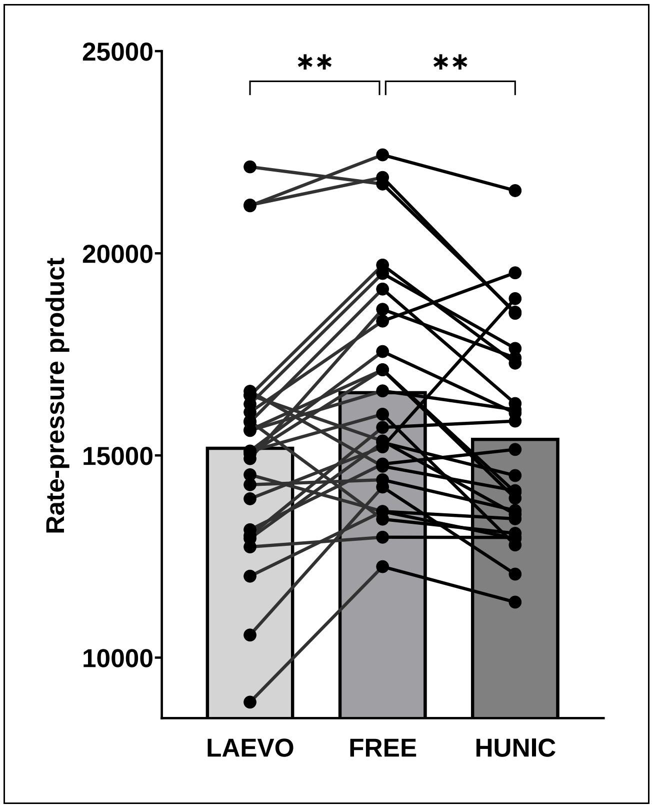

Fig. 1 Rate-pressure product during a 5-minute repetitive lifting task with two passive back-support exoskeletons (LAEVO, HUNIC) and without exoskeleton (FREE). Bars and individual data points represent mean values of the last two minutes of the lifting task. Lines indicate individual responses. p<0.05*, p<0.01**, p<0.001***, p<0.0001****.

5. DISCUSSION AND PRACTICAL IMPLICATIONS

Our study shows that both rigid and soft PBEs may acutely reduce cardiovascular, metabolic and perceived load during moderate-intensity lifting. The decrease in RPP indicates lower myocardial oxygen demand - an aspect that has rarely been addressed in prior research. The use of impedance cardiography (ICG) enabled a more nuanced analysis of cardiac strain beyond heart rate alone.

Only the rigid exoskeleton (LAEVO) reduced gluteus maximus activity, suggesting device-specific biomechanical mechanisms. Both PBEs lowered perceived exertion and energy expenditure, consistent with earlier findings (6–8). The decline in wearing comfort over time, despite high initial ratings, underscores the relevance of long-term usability.

Ultimately, our findings strengthen the evidence that PBEs may contribute to reducing physiological and perceptual strain under controlled conditions. Robust field studies are needed to determine whether these acute effects lead to lasting cardiovascular and musculoskeletal health benefits in physically demanding work environments.

6. STATEMENTS AND DECLARATIONS

This contribution is based on a manuscript currently under peer review in the European Journal of Applied Physiology. All procedures described above were performed according to the principles of the Declaration of Helsinki. The authors declare no financial or non-financial competing interests related to this work.

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EFFECTS OF TRAINING AND FAMILIARIZATION ON OCCUPATIONAL EXOSKELETON PERFORMANCE

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1. INTRODUCTION

Passive occupational back-support exoskeletons, such as the LiftSuit, can reduce strain on the back muscles during physically demanding tasks [1, 2]. Biomechanics studies with occupational exoskeletons have primarily assessed the immediate effects of support in novice users. For example, in a previous study with the LiftSuit, significant decreases of 15.7% for the Longissimus thoracis and 7.2% reduction for the Longissimus lumborum were reported during lifting with a 6 kg weight [1]. However, adapting to new assistive devices, such as exoskeletons, requires time [3]. During this process, the user needs to incorporate the forces applied by the exoskeleton on the body into existing motor pathways while on a subjective level, it comes to trust the device. It is hypothesized that, after a familiarization phase, users may therefore benefit more from the support provided by the exoskeleton. However, there is limited research with only one study to date investigating the impact of familiarization on back-exoskeleton efficacy in a parcours, including different movements [4]. Therefore, this work aims to understand the effects of back support exoskeleton familiarization on muscle activity, including a total of 1000 supported lifts.

2. METHODS

In this study 21 participants (13 female) of working age (18 to 53 years, M: 26 years) and novel to exoskeletons, were introduced to the LiftSuit 2.0 (Auxivo AG, Switzerland) passive back-support exoskeleton (Fig. 1).

Figure 1: The LiftSuit 2.0 passive back exoskeleton

This lightweight occupational exoskeleton (~1 kg) is made entirely of textiles and provides support through elastic energy storage elements (EES) aligned with the user's back. These EES stretch when the user leans forward or lifts, storing energy in the process, which is returned when coming back to upright position.

To investigate familiarization, the study consisted of four sessions, containing a total of 1000 supported squat lifts, designed to familiarize the participants with the use of the exoskeleton through training (Fig. 2). The sessions were divided into a pre-familiarization, two training, and a final post-familiarization session. A minimum break of 48 hours was given between sessions. In the pre- and post-familiarization sessions, muscle activity was measured using surface electromyography (EMG) sensors (Delsys Trigno, Delsys Europe, United Kingdom). The back muscle Longissimus, a key back stabilizer involved in back flexion and extension, was measured at thoracis and lumborum levels. Maximum voluntary contraction (MVC) measurements were conducted in the pre- and post-familiarization sessions to normalise the muscle activity signal. Participants were instructed to perform a prone spinal extension in which gravity provided resistance to the movement [6].

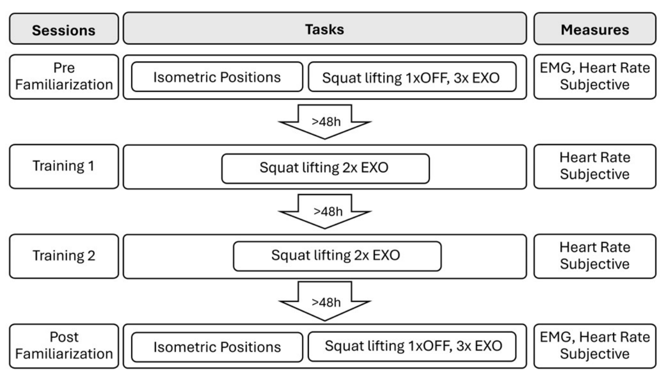

Figure 2: The study consisted of four sessions, containing a total of 1000 supported squat lifts (10x blocks of 100 lifts).

The first and last sessions contained both squat lifts and isometric positions. The effects of familiarization in the isometric positions were previously reported [7]. Here, we report the activity of the Longissimus during squat lifting.

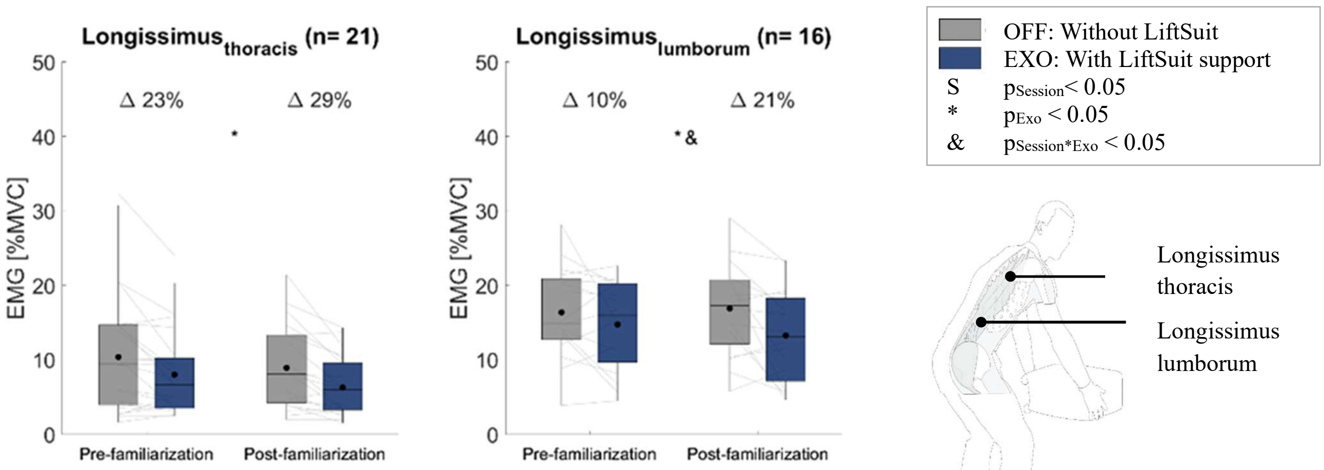

Figure 3: Change in m. Longissimus muscle activity as percent of maximal voluntary contraction (%MVC). The data are displayed as box plots, with a dot representing the mean. Two-way ANOVA: S: $p_{Session} < 0.05$, *: $p_{Exo} < 0.05$, &: $p_{Session*Exo} < 0.05$

The squat lifts were divided into blocks of 100 lifts each, with a 10-minute rest between blocks. The lifts were at a pace of 12 lifts per minute. All lifts were done with a 6 kg weight. In the pre- and post-familiarization sessions, one OFF block and three EXO blocks (300 lifts) were included, while the training sessions consisted of two EXO blocks (200 lifts). The protocol was approved by the institutional ethics committee of the ETH Zurich (EK 2024-N-66).

Data processing and statistical analysis was performed using Matlab R2022b (MathWorks, United States). Visual inspection was used to detect and remove data with artefacts. For the pre familiarization session, the difference between the OFF condition and the first block of EXO was calculated, while for the post familiarization session, the difference from the OFF block to the last EXO block was calculated. To examine the significance between the conditions and the sessions two-way ANOVA tests were used.

3. RESULTS

For the Longissimus on thoracis level, the pre-familiarization session showed a reduction of 23% between the OFF and EXO conditions (Fig. 3). In contrast, the post-familiarization session demonstrated a decrease of 29% in muscle activity when lifting with the LiftSuit. The two-way ANOVA for the condition is significant ($p_{Exo} < 0.01$).

For the Longissimus lumborum, the pre-familiarization session showed a reduction of 10% between the OFF and EXO conditions. In the post-familiarization session, a decrease of 21% when lifting with the LiftSuit can be observed. The two-way ANOVA for the condition ($p_{Exo} < 0.05$) and for the interaction between session and condition is significant ($p_{Session*Exo} < 0.01$).

4. DISCUSSION

This work investigated the effects of exoskeleton familiarization on muscle activity. In the dynamic squat lifting, muscle activity reductions when using the LiftSuit increased from pre- to post-familiarization for both the Longissimus thoracis (from 23% to 29%) and the Longissimus lumborum (from 10% to 21%). A significant interaction between session and condition was found only for the Longissimus lumborum, indicating that familiarization enhanced the effect of the LiftSuit at the lumbar level. The effect of the LiftSuit in the pre-familiarization is similar as reported in previous studies. Namely, Van Sluijs et al. reported a 15.7% reduction for the Longissimus thoracis and a 7.2% change in the Longissimus lumborum activity [1]. As reported by Favennec et al. [4], familiarization with the use of a soft back-exoskeleton did not affect Longissimus activity after 360 lifts (including 180 squats) distributed over six sessions. In contrary, our data suggests that after performing 1000 lifts over four sessions with breaks in between, a level of familiarization is reached, which allows LiftSuit users to double their support benefit. This effect is also observed in the isometric position examined in this study [7]. However, the lack of a significant familiarization effect in the upper back during lifting and in the lower back during the isometric position, may indicate that some adaptation processes are still ongoing, even after 1000 lifts. It is important to note that the intensity of the protocol led to excessive sweating in some participants, resulting in sensor detachment, particularly in the lower back area. As a result, a notable amount of data had to be excluded from analysis. Despite these limitations, the study demonstrates that extended use in one movement, such as 1000 repetitions, can improve the effectiveness of passive back-support exoskeletons. It is important to allow a familiarization period with exoskeletons before drawing conclusions based on initial performance.

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BRIDGING THE INTERACTION GAP: DEVELOPING USABLE HUMAN–MACHINE INTERFACES FOR THE XOTRUNK EXOSKELETON

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1. INTRODUCTION

Workers in industrial environments are exposed to work-related musculoskeletal disorders (WMSDs) when performing manual material handling tasks (MMH) [1]. Active exoskeletons can prevent occupational risk [2]. These are electromechanical systems with sensors and actuators that enhance human capacity and can be precisely controlled for different tasks [3]. For optimal force modulation, they require opening certain operational domains to users, ensuring safety and adaptability. User-interaction meets people's behaviour and attitudes towards the physical, technological, and interactive characteristics of robots and wearable systems [4]. How can we design intuitive control strategies that adapt to the movement patterns and intentions of individual users when using an active exoskeleton? This study presents the development and evaluation of five distinct human-machine user interfaces (HMIs) aimed at enhancing the interaction between operators and the XoTrunk exoskeleton.

1.1 Motivation

The Wearable Robots, Exoskeletons and Exosuits Laboratory (XoLab) at Istituto Italiano di Tecnologia (IIT) has developed back-support assistance exoskeletons such as XoTrunk [5] and upper-limbs exoskeletons such as Shoulder-sideWINDER [6]. The motivation behind developing user interface systems relies on the need to improve the control, adjustment, and safety of active exoskeletons by enabling direct user interaction without requiring an exoskeleton manager supervisor. Historically, our researchers adjusted our exoskeletons via a command line interface, which limited user autonomy. The research aimed to create an intuitive and simple control system that enhances usability, safety, and accessibility, especially in industrial settings, by allowing users to configure and operate exoskeletons through visual, voice, and gesture commands,.

2. METHODOLOGY

The development of the user interfaces presented in this study followed a User-Centred Design (UCD) methodology [7]. It was structured into four iterative phases: (1) user requirements gathering, (2) concept development, (3) prototyping and refinement, and (4) usability evaluation. The exoskeleton domains (functions) assessed were calibration, user information registration, and force assistance adjustment. The standardized assessment metrics used in the study were selected from the user-centered evaluation for wearable robotics devices (WRD) [8].

2.1 System description

XoTrunk is an active back-support exoskeleton designed to assist in MMH activities (see Fig. 1). Its structure consists of a rigid frame worn like a backpack on the user's body, featuring three passive joints connected from the hips to the thighs. The exoskeleton is powered by two brushless DC motors that apply forces of up to 30 Nm in the sagittal plane between the torso and thighs. The control strategy driving XoTrunk uses accelerometer data from an inertial measurement unit (IMU) placed at the sternum, which measures the specific force on the body. The assistance torque (see Eq. (1)) is calculated by combining inclination and acceleration signals, scaled by parameters such as the user's upper body mass and the distance from the hips to the center of mass ($M_{ub}L_{ub}$).

$$\tau_{acc} = K_{acc}\left(R^{nb} f^{b}\right)_x M_{ub} L_{ub}, \quad (1)$$

Therefore, XoTrunk requires the user´s weight and height information to be capture from an HMI and create an inverse rotation matrix to calibrate the exoskeleton [5].

3. RESULTS

This section presents the five user interfaces developed through the UCD process. Each interface is depicted in Fig. 1. Table 1 presents the comparative summary of XoLab's HMIs.

3.1 Monitor System Interface (MSI)

Is a visual framework implemented on a computer that allows XoTrunk users to set up and adjust the operational parameters. This interface was developed to address the limited user interaction with the exoskeleton, providing a way to perform basic actions such as calibration, activation, and modification of the exoskeleton's assistance settings [9].

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3.2 User Command Interface (UCI)

Is a wearable device attached to the exoskeleton that provides an adaptable setup system through a button-based control and a digital screen. In addition to the basic functions available in the MSI, the UCI offers security features such as fingerprint authentication, along with user database management and working profile sessions [10].

3.3 XoLab Natural Language Interface (XoNLI)

XoNLI is a voice user interface designed to facilitate human-machine interaction with XoTrunk. It comprises a portable wearable device equipped with a microphone, touch sensor, and speaker, which records user commands and communicates with a natural language processing (NLP) server hosting speech recognition, understanding, and text-to-speech modules. The system allows users to verbally modify and adjust the exoskeleton's parameters and domains, enabling a more natural and flexible way to interact with the device compared to traditional control interfaces [10].

3.4 XoNLI Multimodal User Interface (XoNLI- MUI)

This interface is designed for XoTrunk, it comprises the XoNLI elements and features a large language model (LLM) for speech context. The interface contains a round screen to visualize a minimalistic version of the UCI graphic interface.

3.5 Virtual-Reality Adaptive Force Assistance (VR-AFA)

This is an interactive interface to perform basic exoskeleton functions such as calibration, capture user information (weight and height), and modify XoTrunk´s parameters such active force assistance. The interface is displayed in a virtual-augmented environment using a virtual reality headset [11].

Figure 1: XoTrunk and XoLab's user interfaces

Table 1: XoLab's HMI comparison summary.
*Combination score of the System Usability Scale

Interface	SUS*	Strengths	Limitations
MSI	90.88	Performance	Non portable
UCI	82.35	Portable	Performance
XoNLI	89.35	Efficient	Time response
XoNLI-MUI	In progress	Size	LLM prompt
VR-AFA	In progress	Accuracy	Comfort

4. CONCLUSION

Results demonstrate that enabling direct user interaction improves autonomy and task efficiency, while reducing the reliance on external supervisors. This work presents a step toward more intuitive and accessible exoskeleton systems for occupational settings.

5. AKNOWLEDGEMENTS

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WearRAcon Europe 2025
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A NOVEL AUTONOMOUS TORQUE-BASED MECHANISM SYNTHESIS METHOD FOR EXOSKELETON ROBOT

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1. INTRODUCTION

Exoskeleton robots are designed to assist the complex, nonlinear movements of the human body, necessitating the effective conversion of simple input motions into complicated human body motions. To achieve this, a linkage mechanism comprising links and revolute joints is integrated into the exoskeleton's frame. Additionally, the growing demand for efficient actuation systems capable of executing increasingly sophisticated movements requires innovative mechanical designs. However, traditional design process for these mechanisms has heavily relied on the experience and intuition of the designer, particularly during the number synthesis [1].
Although recent advancements in design methodologies, such as optimization and AI-driven approaches, have been applied during the dimensional synthesis stage, the number synthesis stage continues to depend significantly on the designer's expertise. This reliance on traditional approaches presents limitations, as iterative dimension designs are required for each configuration until the design criteria are met. Moreover, in emerging fields like robotics, these traditional methods often fail to inspire innovative designs due to a lack of precedent and comprehensive knowledge.
To overcome these challenges, it is essential to consider both number and dimensional synthesis simultaneously. In this study, we employ the Spring connected rigid Block Model (SBM) [1], which represents both the connectivity and dimensions of mechanisms by discretizing the design space into rigid blocks to simultaneously consider the number and dimensions of mechanism. This model enables a gradient-based optimization algorithm for designing the connection relationships and shapes of these blocks, referred to as mechanism topology optimization. Despite its advancements, existing topology optimization methods primarily focus on end effector path generation mechanisms, leaving a limitation in torque and moment transmission mechanism synthesis. To address this limitation, we propose a new formulation that translate force transmission design criteria into the framework of mechanism topology optimization for synthesizing a frame of robot mechanism, facilitating the automatic design of mechanisms based on specified force or moment profiles.
In this study, we aim to apply the proposed methodology to design an upper arm assisted exoskeleton robot for shoulder movement support. By converting translational springs into compression springs within the mechanism, we intend to automate the design of an exoskeleton using proposed the mechanism topology optimization framework.

2. TORQUE-BASED MECHANISM TOPOLOGY OPTIMIZATION

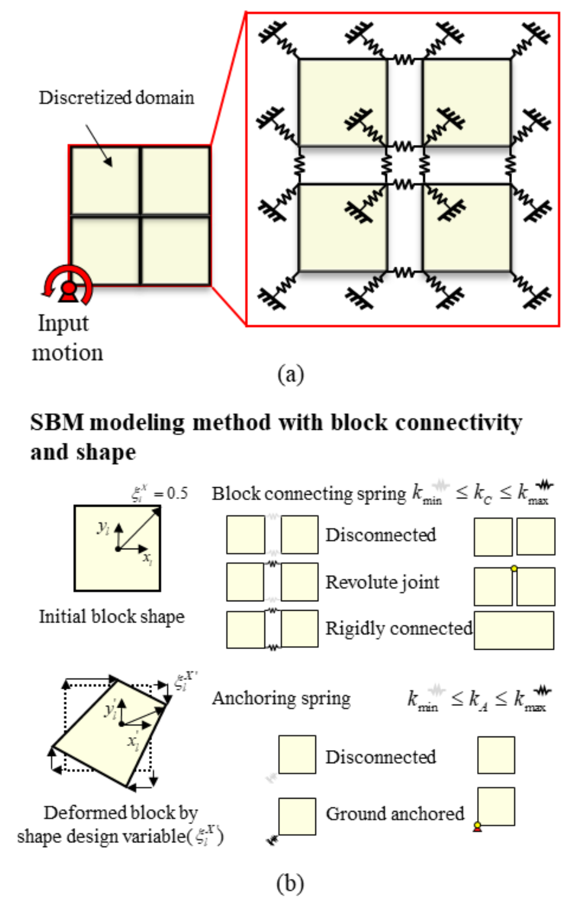

Figure 1: (a) The SBM discretizes design space into rigid blocks connected by springs. (b) By utilizing the shapes and connections of rigid blocks, mechanisms can be represented.

2.1 Modeling method

To simultaneously represent the mechanism's configuration and dimensions, we employ the Spring connected rigid Block Model (SBM). As shown in Fig. 1(a), when the design space is defined, it is discretized into rigid blocks and artificial zero

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length springs. In this context, the SBM can represent various configurations and dimensions of mechanisms through shapes of the blocks, and stiffness values of the springs connected the blocks, as illustrated in Fig. 1(b).

2.2 Mechanism topology optimization formulation

To determine the design variables corresponding to a mechanism that generates a specified torque/moment profile using the SBM, we newly propose the optimization formulation. The objective function and constraint equations of the proposed optimization formulation in this study are as follows,

$$\begin{gathered} Minimize\ 1-\bar{\eta} \\ subject\ to\ \|\hat{\boldsymbol{\tau}}-\boldsymbol{\tau}\| < \epsilon. \end{gathered} \tag{1}$$

3. SYNTHEIS OF UPPER ARM ASSISTED EXOSKELETON BY PROPOSED METHOD

The passive upper arm assistive exoskeleton robot developed by the Hyundai Motor Group Robotics Lab (Fig. 2(a)) utilizes a six-bar linkage mechanism integrated with translational tensile springs [2-3]. Although tension springs are limited by issues related to noise and durability, gas springs provide advantages in these aspects; however, they cannot be directly incorporated due to their dependence on compression for generating torque profiles. To replace the translational springs with gas compression springs, it is necessary to implement an eight-bar linkage mechanism, which involves adding two links to convert tensile motion into compression motion, thus complicating the overall system. Consequently, this study aims to design a gas spring linkage mechanism that replicates the torque profiles (Fig. 2(b)) produced by the existing tension spring-based mechanism, employing the proposed method illustrated in Fig. 2(c).

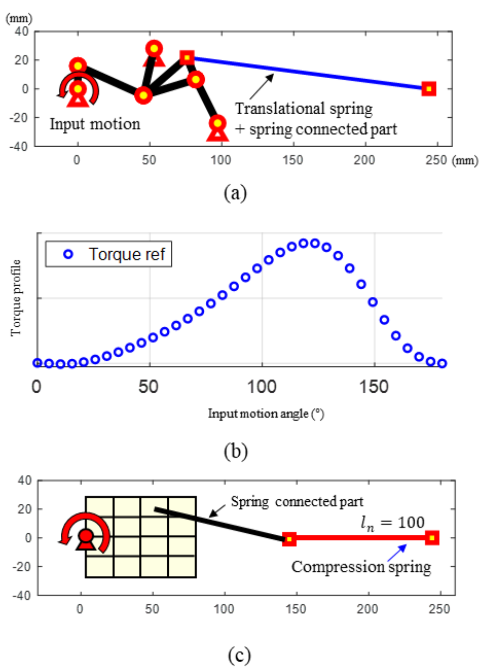

Figure 2: (a) Configuration of previous exoskeleton robot. (b) Target torque profile and (c) definition of the design problem for the compression spring assistive exoskeleton.

The optimization results demonstrated that the shapes of the blocks and their connectivity evolved throughout the iteration process, as depicted in Fig. 3. Notably, the six-bar linkage mechanism was successfully synthesized by the 313rd iteration. Analysis confirmed that while the constraint equations decreased, the objective function converged, as illustrated in Fig. 3(a). The synthesized result was then substituted to create a prototype of the upper arm assistive exoskeleton, which is composed of compression springs as shown in Fig. 3(b).

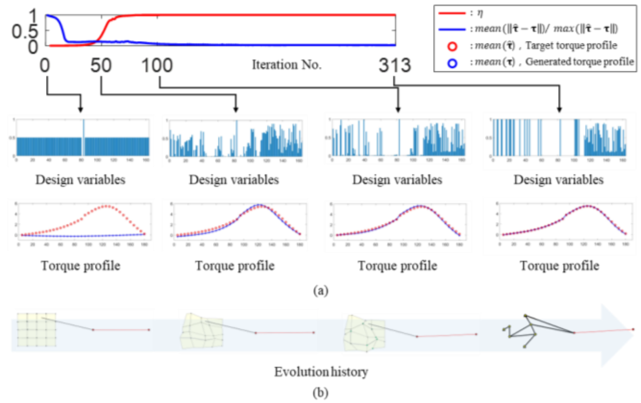

Figure 3: Optimization results of the upper arm assistive exoskeleton, (a) along with the design variables corresponding to each iteration and the target torque profile along with the generated profile values and (b) evolution history of SBM.

4. CONCLUSION

We have introduced a novel autonomous mechanism synthesis methodology that simultaneously optimizes both the configuration and dimensions of mechanisms to achieve the desired torque profile. This approach marks a significant advancement over traditional path-based mechanism topology optimization, representing a groundbreaking development in torque profile-based mechanism design. The upper arm assistive exoskeleton robot, designed using this method and equipped with gas springs, exhibits performance comparable to existing tension spring models while utilizing a six-bar linkage mechanism. This efficiency is particularly impressive as it demonstrates that equivalent results can be attained without adding links, thereby enhancing manufacturability and scalability. In the fast-evolving landscape of innovation, particularly in the field of exoskeleton robot, this autonomous synthesis methodology not only reduces design time but also encourages creative solutions to emerging design challenges.

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EXOLINK: EVENT-DRIVEN INTELLIGENCE FOR ADAPTIVE EXOSKELETONS IN COLLABORATIVE INDUSTRIAL TASK

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1. INTRODUCTION

Robotic exoskeletons are emerging as transformative technologies for safer and more ergonomic workplaces. They reduce musculoskeletal strain, enhance load handling, and improve endurance in industries such as manufacturing, logistics, and healthcare [1-2]. Conventional control approaches -based on pre-programmed routines or continuous feedback- often lack adaptability in dynamic environments, limiting efficiency and user acceptance [3].
To address this limitation, we propose an event-driven intelligence (EDI) framework for exoskeleton control that responds selectively to meaningful biomechanical or environmental events. This approach reduces computational load, enhances real-time adaptability, and leverages advances in wearable sensing, edge AI, and neuromuscular signal processing [4]. By embedding intelligence at the event level, exoskeletons can transition from passive aids to proactive collaborators, enabling context-aware, ergonomically optimized interaction with human operators.

2. EVENT-DRIVEN INTELLIGENCE (EDI)

Event-Driven Architecture (EDA) is a software design approach where system components communicate through the production, detection, and consumption of discrete events. Unlike synchronous request–response models, EDA supports asynchronous, decoupled processing, allowing systems to react in real-time to state changes or significant events. This architecture is scalable, responsive, and flexible, making it suitable for distributed and high-throughput environments [5].
Event-Driven Intelligence (EDI) as a specialized layer within EDA, monitoring, analyzing, and interpreting events to generate actionable insights, trigger automated responses, and support intelligent decision-making (Figure 1). In practice, EDI enables exoskeletons to respond selectively to significant events rather than continuously processing all sensor data. Key events such as muscle activation, joint positions, or environmental triggers, reduce computational load, improve reaction times, and ensure assistance aligns with user intent.
Key characterized of EDI include:

- Reactive but selective: Responds only to meaningful events, not continuously.
- Context-aware: Considers the user's state, task, and environments.
- Adaptive: Learns from past interactions and adjusts their behavior accordingly.
- Energy-efficient: Conserves power by activating assistance only when needed.

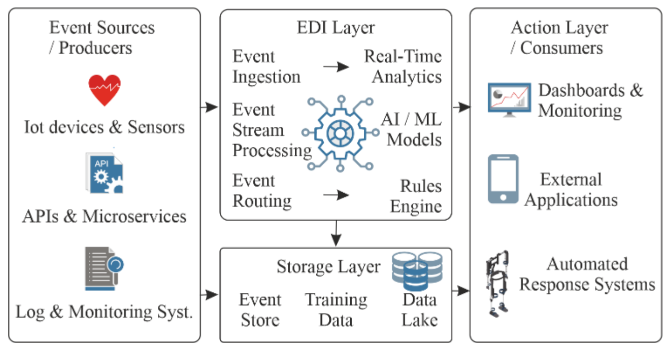

Figure 1: Event-Driven Architecture (EDA). Event sources such as IoT devices, sensors, APIs, microservices, and monitoring systems generate continuous data streams. These events are processed through the EDI layer, which performs event ingestion, stream processing, routing, and real-time analytics using AI/ML models and rules engines. Processed data is stored in the storage layer -including event stores, data lakes, and training datasets- and consumed by dashboards, external applications, and automated response systems in the action layer.

3. EDI EVALUATION – USE CASE

3.1 Collaborative beam manipulation

To evaluate the EDA, we implemented a collaborative manipulation scenario with two workers, each equipped with two robotic exoskeletons (Figure 2). When the shared wooden beam tilts, the EDI module calculates the support ratio and distributes control signals (u_l and u_r) proportionally based on the measured tilt angle. The forces (F_L and F_R) correspond to the assistive torques provided by each exoskeleton, stabilizing and lifting the object efficiently while minimizing user strain and enhancing cooperative ergonomics.
The exoskeleton used is a semi-active device providing target shoulder support for overhead tasks. It delivers up to 14 Nm per arm with smoothly adjustable, independent assistance. In the neutral position, it provides no support, and transitions

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from minimum to maximum assistance in under 0.6 s. Weighing 5.4 kg without the battery [6].

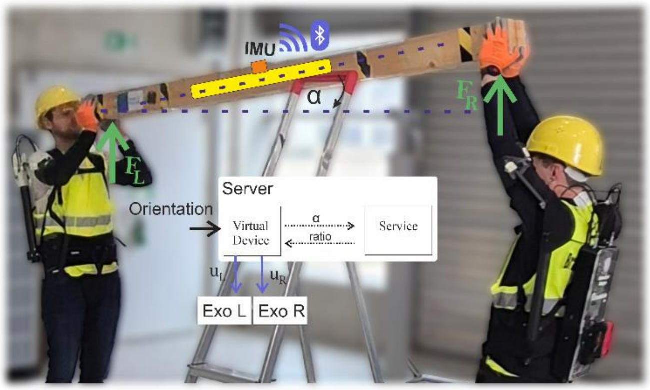

Figure 2: Two exoskeleton-assisted workers collaboratively lift and stabilize a wooden beam. An inertial sensor mounted on the beam measures tilt angle variations and transmits the data wirelessly to a server for real-time computation of support levels.

3.2 Multiple External Data Source

The EDA framework extends connectivity between exoskeletons and beam-mounted IMUs by incorporating three wearable subsystems, forming multimodal sensing and actuation architecture. This network enables continuous, wireless data exchange to improve safety, comfort, and task performance. Intelligent services -some powered by AI-predict or classify anomalies in real time, enabling proactive responses.
The three key wearable subsystems include:

- ECG (Electrocardiogram): Smartwatch-based biosensor, monitors cardiac activity to assess physical fatigue, stress, and overall cardiovascular health.
- EMG (Electromyogram): Smart garment with surface electrodes, captures muscle activation signals.
- Motion Capture System: A sensor-based system tracks posture and movement in real-time, enabling ergonomic assessments and motion optimization by predictive body postures analysis.

4. PRILIMINARY RESULTS

Exoskeleton support levels were recorded across two complete manipulation cycles, each consisting of a forward and backward motion from the start to the endpoint. During each cycle, the beam tilts twice as the workers lift it to pass over the obstacle, demonstrating the exoskeleton´s dynamic adjustment of assistance in response to user effort during these events. Figure 3 illustrates that changes in the beam tilt angle results in increased dynamic support to the exoskeleton user under load.

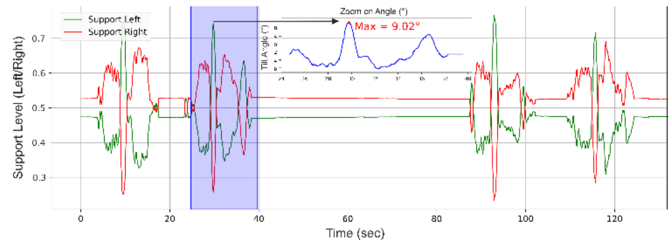

Figure 3: An inverse correlation is observed between the support levels of the two exoskeletons: periods of increased assistance from the left unit coincide with reduced output from the right. The inset graph presents the beam tilt angle over the 25-40 seconds interval, highlighting the system's real-time modulation of support in response to variations in beam inclination.

5. CONCLUSIONS

In this first use-case implementation, the EDA enables low-latency, event-based communication across distributed sensing and control modules, ensuring seamless coordination and adaptability in dynamic task environments. Building on this foundation, EDI introduces intelligent event interpretation to detect variations in the workspace and enable real-time adaptation of the exoskeleton's support level. In future work, this adaptation could be extended to predictive reasoning through AI-driven analytics. Together, these frameworks create a resilient, self-adaptive ecosystem that enhances user safety, ergonomic performance, and overall operational efficiency in human–exoskeleton collaboration.

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Poster Presentations

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ROBUST 3D ANALYSIS OF MOVEMENT IN HUMANS AND NON-RIGID EXOSKELETONS USING AN UMIMU SENSOR SWARM

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1. INTRODUCTION

Increasing optimization in lightweight construction leads to reduced rigidity in robotic arms and exoskeleton segments. Therefore, the accuracy in segment orientations and joint and/or end point positions delivered by traditional odometry suffers. Traditional end point position estimation through odometry in the joints assumes stiff segment-systems. This means that the challenge of estimating accurate and robust kinematics in such systems starts to resemble more the challenge of estimating accurate and robust kinematics in ambulatory 3D analysis of human body segments and joints, as both must deal with unknown segment flexibility and non-stiff tissues.

Typically, ambulatory movement analysis applies Magnetic Inertial Measurement Units (MIMUs) in data fusion of recorded linear accelerations, angular velocities and earth magnetic field line directions. Optimal estimators (e.g. extended Kalman filters or EKFs) estimate segment orientations, joint angles plus displacements and end point positions [1]. MIMU solutions are much more accurate and robust in estimating angular entities, like segment orientation or joint angle, than in estimating displacement or (relative) position. This is both limiting important clinical applications related to balance assessment as well as robotic applications in which accurate data on end point positions are crucial. Additional challenges arise from the limited observability of the magnetic north in the presence of ferro-magnetic materials, a performance-disturbing condition that is even harder to avoid in robotics and exoskeletons, especially close to any floor or in many workplaces [2, 3].

This paper discusses a novel sensing approach in which MIMU sensors are extended to 'UMIMU' sensors by integrating UWB nodes. This adds a second mode of tightly coupled relative position estimation intended to tame the huge integration drift errors occurring in MIMU-only estimation of displacement and position and possibly also makes observability limitations of the magnetic north less disruptive.

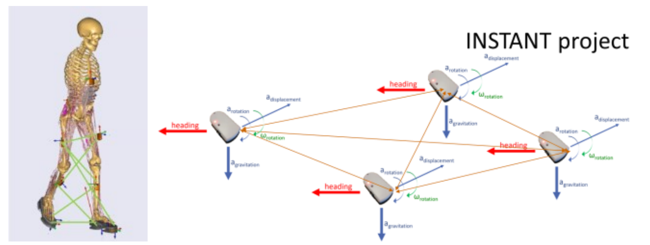

Figure 1: Schematic depiction of the data available within the UMIMU sensor swarm. For each node: distance to any of the other nodes (and derived relative position) next to traditional MIMU data of 3D orientation, acceleration, angular velocity and earth magnetic field vector (and derived relative displacements).

2. METHODS

Custom 'UMIMU sensors nodes' were developed, each comprising a fully integrated UWB/MIMU pair with a timing-optimized embedded protocol measuring all distances within an UMIMU swarm in addition to all regular MIMU data (Figure 1). All nodes took turns assuming the role of 'initiator' or 'responder' of a distance estimation as needed. Each distance was only estimated once per update. All data were centrally collected through a UMIMU node assuming the role of 'controller', connected to a laptop through USB. A custom swarm calibration method was developed to improve ranging accuracy. [5] and an EKF-based position-estimator was developed and validated that combines position updates of both UWBs and MIMUs into a robust position estimator [6,7]. A sensitivity study into characteristics and size of ranging errors in typical gait analysis conditions was performed Proposals were made for their mitigation [4].

Also, a novel segment calibration method was developed that connects UMIMU positions to joint positions as well as UMIMU orientations to (body) segment orientations [8]. This method does not need any specific poses or movements to be performed, which is a huge advantage in movement analysis in certain patients and in using movement constraining exoskeletons.

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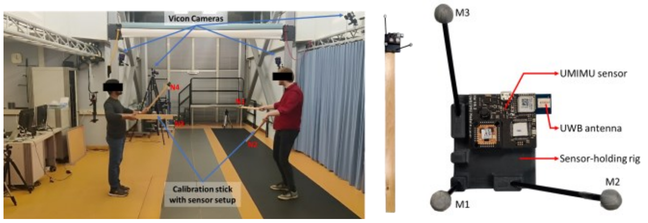

Figure 2: Experimental set-up for the pilot study, in which sensors were moved manually with speeds and ranges that are typical for analysis of human movement, while avoiding non-line-of sight situations or vicinity of human body issues (left). A special rig was developed and used for validation purposes with auto reflective markers for the reference system (Vicon) and the UMIMU mounted.

3. RESULTS

Distance estimation errors were brought down to a structural error component of about 0.5 cm plus a Gaussian distributed random error component of ±5cm with the UWB swarm calibration procedure [5]. A experimental sensitivity analysis using synthetic structural and noise errors in relevant ranges, added to position data from realistic movement measured with a Vicon system under Non-Line of Sight conditions (Figure 2), indicated that an EKF-based position estimating accuracy 6cm ± 5cm is already possible (Figure 2) [6,7]. A separate experimental study of typical distance estimation error behavior in a UMIMU swarm in physically simulated (Non-) Line of Sight conditions revealed ample opportunities to minimize their effect on position estimation accuracy [4].

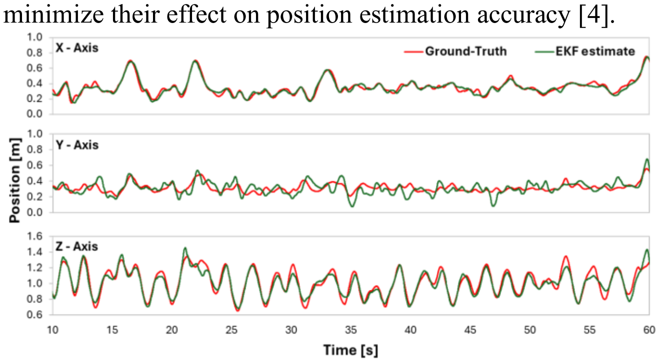

Figure 3: Results from pilot experiment x (top), y (middle) and z (bottom) position coordinates estimated with the 'gold standard' reference system (red) and with the UMIMU-based method (green).

4. DISCUSSION

It seems feasible to estimate linear/angular 3D kinematics with improved stability and accuracy using an UMIMU swarm. Residual errors achieved with the proposed approaches of a fully integrated UMIMU sensor node, a novel swarm calibration method and EKF-based data fusion show values smaller than reported before. Integration drift errors are completely eliminated. Still errors are larger than desired for analysis of human movement applications and in several current studies further optimization of these methods are researched. Future challenges are: 1. To further improve position estimating accuracy, by more optimal redundancy exploitation, 2. To maximally avoid, and/or mitigate, (Non-Line of Sight) errors in on-body application for both clinical use and in exoskeleton evaluation or control by further exploiting redundancy in the UMIMU swarm data.

5. AKNOWLEDGEMENTS

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PHYSIOLOGICAL AND PERCEPTUAL RESPONSES TO PASSIVE BACK-SUPPORT EXOSKELETONS DURING OCCUPATIONAL TASKS – A SYSTEMATIC REVIEW AND META-ANALYSIS

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1. INTRODUCTION

Occupational exoskeletons have become a topic of growing interest within the fields of ergonomics, injury prevention, and workforce-enabling technologies[1,2]. This interest is largely driven by the persistent and widespread burden of musculoskeletal disorders (MSDs), which represent the most common occupational health issue across the European Union[3]. According to recent reports, MSDs account for approximately 60% of all work-related health issues and are a leading cause of absenteeism, reduced productivity, and premature exit from the workforce[3]. These challenges are closely linked to the physical demands of many occupational environments[4-6].

Key physical risk factors contributing to the development of MSDs include awkward or static working postures, highly repetitive tasks, and manual handling of heavy loads[3]. In addition to musculoskeletal strain, high levels of occupational physical activity (OPA) have been associated with broader health concerns alike. Besides MSDs, OPA has been linked to a 35% higher risk of sustaining severe cardiac events and a 27% increased risk of cardiovascular mortality[7].

Passive back-support exoskeletons (PBEs) are proposed as an effective ergonomic tool to lower physical strain in demanding physical work settings. Current evidence is primarily based on heterogeneous laboratory studies that involve small sample sizes and a wide variety of tasks[1]. Over the past five years, there has been a notable increase in research activity focused on PBEs. Considering this growing field, systematic reviews offer a valuable opportunity to synthesize and organize the available evidence in a structured and accessible way.

However, existing, more recent reviews often concentrate on narrowly defined areas like healthcare or logistics, or they compile findings from various devices, including both passive and active exoskeletons intended for different body regions[8-10]. This heterogeneity limits the interpretability and practical use of their conclusions.

Consequently, there is a need for a comprehensive overview of the full range of physiological and perceptual effects associated with PBEs, including cardiovascular, metabolic, and neuromuscular responses, as well as outcomes like discomfort and perceived exertion.

2. AIM

This review aims to systematically evaluate the effects of PBEs on physiological and perceptual responses during occupational tasks.

3. METHODS

3.1 Search strategy

This review is conducted and documented in accordance with the Cochrane Handbook for Systematic Reviews of Interventions and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines[11]. The protocol has been prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD420251049167. A systematic literature search was performed independently by two reviewers (KC, MS) across the electronic databases PubMed, Cochrane Library, Web of Science, ScienceDirect, and Embase, from January 1, 2015 to May 2025.

3.2 Study selection

All studies are screened independently by two reviewers (KC, MS). Any disagreements will be resolved through discussion and consensus. Experimental studies are included that evaluate the use of PBEs in occupational or occupation-relevant settings that report on physiological and/or perceptual responses. Eligible physiological outcomes comprise muscle activity in the trunk, hip, or knee extensors, heart rate, energy expenditure, and blood pressure. Perceptual outcomes include perceived musculoskeletal discomfort and perceived exertion. A detailed overview of the inclusion criteria is provided in Table 1.

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Table 1: Inclusion criteria according to PICOS schema for systematic review and meta-analysis

P – Population	Healthy adults (aged > 18 years) in occupational settings
I – Intervention	Passive back-supporting exoskeleton
C – Comparison	No exoskeleton
O – Outcome	*Primary*: Muscle activity in trunk, hip, or knee extensors (i.e. %MVC), Heart rate parameters (i.e. bpm, %HRmax), Metabolic response, including: Energy expenditure (i.e. kcal/kg/min) and Oxygen uptake (VO_2, i.e. ml/min/kg or ml/min), Blood pressure (mmHg) *Secondary*: Perceived musculoskeletal discomfort (i.e. VAS, numerical rating scale), Perceived exertion (i.e. Borg RPE scale)
S - Study designs	All study designs included

3.3 Quality assessment (risk of bias and quality of evidence)

The methodological quality of each study is assessed independently by two researchers using the Cochrane risk of bias tool ROB2. The Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) approach is used to interpret and evaluate the quality of evidence. The outcome measures are reported as described in the original studies. Continuous outcomes and individual and pooled statistics are calculated as mean differences if data are on a uniform scale, and as standardized mean differences with 95% confidence intervals if the data are presented using different scales. For those that use different scales but measure the same construct, standardized mean differences (SMD) are calculated. The SMD is determined by dividing the mean difference between the groups by the standard deviation among participants. A meta-analysis is conducted on the assumption of heterogeneity using random effects models. The inconsistency index (1^2) statistic quantifies the proportion of the overall outcome attributed to variability. A 1^2 greater than 50% represents substantial heterogeneity. All data of the studies are pooled in forest plots. Statistical significance is set to $p < 0.05$, and standardized effect size magnitudes are used, with <0.2 denoting small, 0.2–0.5 moderate, and >0.5 = large effect.

4. STAGE OF THE REVIEW

At the time of this submission, the review is in the screening phase, during which search results are being assessed against the inclusion criteria. Preliminary findings are expected to be available by the time of the conference start and will be presented there.

The results of the review will be published in English. The authors declare no financial or non-financial competing interests related to this work.

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FIELD EVALUATION OF THE SHOULDER-SIDEWINDER EXOSKELETON: INSIGHTS ON METABOLIC EFFICIENCY AND WORKER EXPERIENCE

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1. INTRODUCTION

Work-related musculoskeletal disorders (MSDs) are a major concern for workers' wellbeing, often leading to limitations in daily life, reduced work capacity, and increased sick leave [1]. High-risk factors include specific work activities, such as heavy lifting, repetitive tasks, and awkward postures. Occupational exoskeletons have emerged as a promising solution to reduce physical workload by supporting workers' musculoskeletal structures during demanding activities [2]. Shoulder exoskeletons evaluated in simulated occupational tasks significantly reduce shoulder muscle activity, general and localized perceived strain, supporting their potential role in preventing MSDs [3]. However, lab-based results may not fully translate to real-world use. A study on two shoulder exoskeletons found that, while both devices positively affected isolated tasks, their support was limited in actual field conditions [4]. The lack of field studies further limits current understanding of user acceptance and long-term effects.

2. METHODS

2.1 Shoulder exoskeleton

Shoulder-sideWINDER is a bilateral active shoulder exoskeleton developed by the XoLab, Instituto Italiano di Tecnologia (IIT) in collaboration with INAIL [5]. The exoskeleton generates the assistive force through a control algorithm that consists of four control submodules [5]. These submodules estimate the load on the shoulder based on arm posture and the load on the hand, utilizing data from IMU and EMG sensors, providing optimal assistive forces for tasks involving arm elevation against gravity (e.g., overhead work or lifting tasks), which are the leading causes of MSDs.

2.2 Experimental protocol and metrics

The test was carried out in a food processing factory located in Biassono (MB, Italy), involving 5 workers (82.6 ± 8.7 kg, 175.8 ± 6.2 cm, 41 ± 9.5 years). The task required the workers to retrieve hams, weighing approximately 17-20 kg, from tubs positioned at a height of 60 cm, where they had been placed by an automated sorting system. The hams were then lifted and hung onto hooks mounted on vertical racks, with heights ranging from 50 cm to 170 cm above the ground. Each worker lifted approximately 20 hams over a 30-minute period of time, using their preferred lifting technique, typically resulting in squat or semi-squat movements. Each subject performed the task in two different conditions: without the exoskeleton (*NOE*) and with the active Shoulder-sideWINDER (*EXO*).
During the test, the subjects were equipped with the Cosmed K5 wearable metabolic system (COSMED; Rome, Italy), which consists of a mask directing respiratory flow to an analysis unit that calculates energy expenditure in Metabolic Equivalent of Task (MET) through indirect calorimetry. The MET data were compared for each subject across the two conditions (i.e., with and without the exoskeleton).
Participants filled out a questionnaire on their subjective perception of the exoskeleton assistance contains 28 questions cover five classes: Assistance, Comfort, Stability, Usability, and Acceptance. The questions were rated on a 7-point Likert scale from 1 = entirely disagree to 7 = entirely agree.

3. RESULTS

Figure 1 shows the mean values and standard deviations of MET across participants in the two conditions over time.

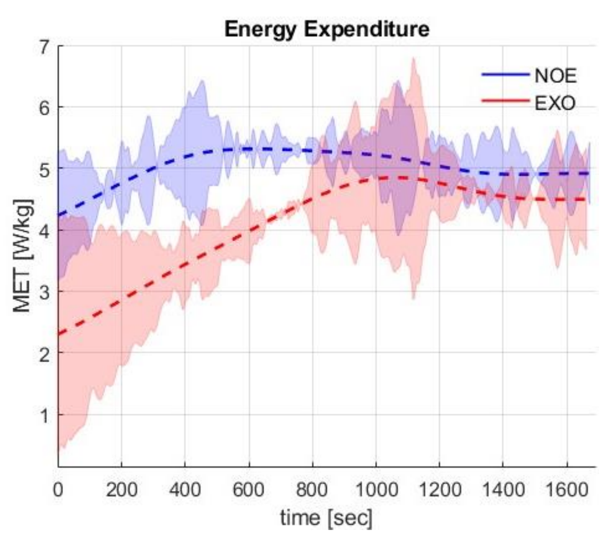

Figure 1: MET without (*NOE*) and with (*EXO*) Shoulder-sideWINDER

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A reduction in energy expenditure was observed in the *EXO* condition compared to *NOE*, with a 19.8% decrease in mean MET values and a 4.8% reduction in peak MET values.
The questions of the subjective perception questionnaire are displayed in Table 1, along with the ratings averaged across participants. Moreover, the mean ratings for the five classes are also reported. Perceived assistance, a key factor for user satisfaction with assistive devices, was positively evaluated. In particular, most workers reported that the workload of the task was reduced as well as the load on the shoulder. On the other hand, workers were less satisfied with the freedom of arm movement. Comfort was also rated positively. In particular, workers were satisfied with the breathability of the exoskeleton and the fact that they did not sweat more on the upper limbs. Moreover, the weight of the device was not considered problematic by most workers. All workers rated the stability of the exoskeleton very positively; the related questions were among the ones with the higher ratings. Usability, which strongly influences user satisfaction with a device, received positive ratings. Finally, acceptance, defined to explore the extent to which a worker is satisfied and willing to use the exoskeleton over time, obtained mixed results. In particular, the questions that scored the lowest were "I do not feel hindered by the exoskeleton during my activities" and "I feel the exoskeleton is robust and suitable for my work environment"; 4 workers entirely agreed with "I would use the exoskeleton regularly if it were available on the market" and "I think I would use it for the entire work shift", and 3 entirely agreed with "I think I would use it for all my work activities".

Table 1: Questions and ratings averaged between participants of the subjective perception questionnaire.

Assistance	**5.43**
Using the exoskeleton I struggle less	6.00
The strain on the shoulder has decreased	6.20
The exoskeleton follows my movements well	6.60
The movements of the shoulder are not hindered	4.40
The movements of the arms are not hindered	3.60
The level of assistance is adequate	5.80
Comfort	**5.58**
I think the weight of the exoskeleton is right	5.80
I think the weight distribution is adequate	6.00
I feel the harness is not too tight	3.60
I didn't feel any pressure on my chest	5.80
I didn't feel pressure on the hips	5.80
I didn't feel pressure on the arms	4.40
I think the breathability is adequate	7.00
I think I didn't sweat more on my back	5.00
I think I didn't sweat more on my shoulders	6.80
Stability	**6.47**
I feel the exoskeleton firmly anchored to my body	6.60
I feel the belt firmly anchored to my hips	6.60
I feel the arm bands firmly anchored to my arms	6.20
Usability	**5.90**
The exoskeleton is easy and intuitive to wear	6.00
It is easy to adjust the straps and take it off	7.00
I would be able to wear the exo by myself	5.00
Acceptance	**5.31**
The exoskeleton meets my expectations	6.20
I think the exo is suitable for my work activities	5.80
I do not feel hindered by it during my activities	4.00
I would use the exoskeleton regularly if it were available on the market	5.80
I feel the exoskeleton is robust and suitable for my work environment	4.20
I think I would use it for the entire work shift	5.80
I think I would use it for all my work activities	5.40

4. DISCUSSION

The reduction in energy expenditure suggests that the Shoulder-sideWINDER provides effective support during the task and reduces fatigue, consistent with previous lab-based findings showing a reduction in shoulder muscle activity [5].
The main issue emerged by the questionnaire was partial restriction of upper body mobility; in fact, the questions with the lowest agreement were "The movements of the shoulder are not hindered", "The movements of the arms are not hindered", "I feel the harness is not too tight", "I didn't feel pressure on the arms" and "I do not feel hindered during my activities". Future development should prioritize improving freedom of movement to better fit tasks that require a wider range of upper-limb mobility. Notably, the participants in this study were considerably taller and heavier than those in prior lab trials, which may have affected the fit of the device.
A second aspect underlined by the workers was concern about the exoskeleton robustness and suitability for the workplace. Since the task involved food handling, hygienic requirements such as washable garments and protective covers emerged as critical needs, which the current design does not fully address. Finally, despite some usability concerns, several participants expressed strong willingness to adopt the exoskeleton, indicating its potential for real-world implementation.

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ELSA LOGICARE - A 12-WEEK RANDOMIZED CONTROLLED FIELD TRIAL ON PASSIVE BACK-SUPPORT EXOSKELETONS IN LOGISTICS AND CARE

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1. INTRODUCTION

Musculoskeletal disorders (MSDs) are among the most prevalent work-related health problems across Europe (1), particularly affecting workers in physically demanding sectors such as nursing and logistics. Activities involving frequent lifting, manual patient handling, prolonged forward-bent postures, and dynamic load transport contribute to sustained biomechanical strain, leading to chronic pain, reduced work ability, and early retirement (2–5). In light of growing workforce shortages and demographic shifts, there is an urgent need for effective, evidence-based solutions to mitigate these physical demands.

Passive back-support exoskeletons (PBEs) have gained increasing attention as a potentially scalable ergonomic intervention (6). While laboratory studies suggest positive biomechanical, physiological, and perceptual effects (7,8), real-world implementation remains challenging due to organizational, cultural, and individual barriers. To date, only few studies have systematically explored the use of passive back-support exoskeletons in everyday work contexts(9). There remains a critical need for robust field-based randomized trials to generate transferable, real-world evidence on their practical value.

The ELSA LogiCare trial addresses this need with a large-scale, field-based evaluation of PBEs in real-world logistics and care settings. Using a multidisciplinary and participatory research framework, the project captures physiological and perceptual outcomes alongside implementation dynamics, user acceptance, and sector-specific factors.

2. AIM

We aim to generate robust evidence to guide exoskeleton investment and funding decisions, supporting their sustainable use in demanding workplaces.

3. METHODS

3.1 Study Design

This multi-center randomized controlled field trial follows a mixed-methods design. Participants are randomized (1:1) to an intervention or waiting-control group, stratified by sector (logistics vs. healthcare) to enable sector-specific comparisons. The intervention group uses the passive exoskeleton during regular work tasks for a period of 12 weeks, while the control group continues standard work practices and receives the exoskeleton after final data collection. Assessments are conducted at four time points: baseline, 4 weeks, 8 weeks, and 12 weeks, allowing for the evaluation of trajectories in usage, effectiveness, and user experience over time under real-world working conditions. The trial is registered in the German Clinical Trials Register (DRKS-ID: DRKS00036072).

3.2 Participants

Eligible participants are employees in logistics or healthcare settings who perform regular physical work involving lifting, carrying, or forward-bending tasks. Inclusion criteria are age between 18 and 65 years, current employment in the respective sector, and the ability to provide written informed consent.

Exclusion criteria include acute or chronic medical conditions that could be exacerbated by exoskeleton use (e.g., unstable spinal conditions, recent surgeries), cardiovascular contraindications to moderate physical activity, pregnancy, known intolerance to wearable devices, and participation in other intervention studies that could interfere with outcomes.

3.3 Primary and Secondary Outcomes

Primary endpoints include:

a) Applicability: measured via exoskeleton usage frequency and duration using wearable sensors (Garmin Vivoactive 4) and weekly self-reports.
b) Effectiveness: reduction in musculoskeletal complaints assessed with the German Cornell Musculoskeletal Discomfort Questionnaire (D-CMDQ).

Secondary outcomes include physical and mental workload (NASA-RTLX), fatigue (Fatigue Scale), psychosocial stress (COPSOQ), job satisfaction, cognitive performance (Vienna Test System), ergonomic load (Exo-LiFFT tool), and work-related sick days. Contextual differences in implementation and adherence across sectors are explored through structured workplace comparisons. Process evaluation includes brief interviews and validated tools on user acceptance (Technology Commitment Scale), satisfaction (QUEST 2.0), and perceived barriers.

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3.4 Statistical Analysis

Data are analyzed using an intention-to-treat approach with mixed-effects regression models, accounting for clustering and drop-out.

4. IMPLEMENTATION STATUS

At the time of abstract submission, initial recruitment and onboarding activities have commenced at selected hospitals and logistics partners. Site-specific preparatory measures included workplace walkthroughs, hygiene concept development, and information sessions with operational stakeholders. The first wave of baseline assessments is underway, with sector-specific implementation pathways being piloted in both logistics and care sector. Participating institutions have shown a high level of interest, yet early feedback underscores practical considerations such as storage logistics, donning and doffing procedures, and sector-specific workload variability.

5. CONTRIBUTION TO THE FIELD

Our trial is designed to generate actionable insights into both the mid-term effectiveness and long-term applicability of PBEs in complex occupational settings. Beyond quantitative endpoints such as musculoskeletal discomfort and workload perception, the study explores real-life implementation dynamics - barriers, facilitators, and user perceptions - through qualitative and mixed-method approaches. Our project aims to provide a nuanced understanding of how PBEs can be integrated into existing workflows.

Ultimately, ELSA LogiCare seeks to inform the development of sector-specific implementation guidelines and to support decision-makers in occupational health, procurement, and workplace design. Findings are intended to contribute to the growing evidence base on the real-world value of PBEs and may serve as a basis for follow-up studies, manufacturer feedback loops, and policy-level recommendations. At the time of the planned presentation in November 2025, preliminary findings from the first measurement wave are expected to be available. Our results may provide early indications regarding effectiveness, user adherence, feasibility, and sector-specific implementation experiences.

6. STATEMENTS AND DECLARATIONS

This research project is funded within the framework of the "European Regional Development Fund (EFRE)" through resources from the European Union and the state of Saxony-Anhalt, represented by the Investment Bank of Saxony-Anhalt. The funding period runs from 2024 to 2027.

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Understanding the Implementation of a Lumbar Support Exoskeleton (HAL) in UK Adult Social Care: A Survey informed by the NoMAD Instrument

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1. INTRODUCTION

Local authorities (LAs) across the UK face challenges delivering high-quality adult social care amidst chronic workforce shortages, musculoskeletal injury risks, and rising service demands. In 2021, as part of its digital transformation strategy, an English LA, Hampshire County Council (HCC) implemented the Hybrid Assistive Limb (HAL) for Care Support, a wearable back-support exoskeleton (Cyberdyne Inc., Japan), locally referred to as a 'Cobot'. The aim was to enhance carer independence in physically demanding tasks, reduce reliance on double-up care packages, and support long-term workforce sustainability (Snowdon et al., 2021). While occupational exoskeletons have been widely studied in industry and, increasingly, in healthcare internationally, there is almost no evidence of their real-world implementation in UK adult social care. The regulatory, workforce, and operational conditions of social care differ significantly from industrial or healthcare contexts, creating unique challenges for adoption and implementation.

This paper presents findings from Phase 2 of a mixed-methods doctoral study, exploring Cobot implementation within HCC's adult social care services. The research is informed by Normalisation Process Theory (NPT) (May et al., 2009), which explains how innovations become embedded (or not) into everyday practice. This phase involved adapting and testing the Normalisation MeAsure Development (NoMAD) survey (Finch, 2015), for use in social care. The objectives were to explore how staff perceived, engaged with, enacted, and appraised the HAL Cobot, and to identify priorities for qualitative inquiry in Phase 3.

To our knowledge, this is the first application of the NoMAD survey to occupational exoskeleton implementation in UK social care, an area largely absent from implementation science literature. This work offers new insights into staff perceptions, sociotechnical readiness, and barriers to normalisation, and demonstrates the value of group-based cognitive interviewing for adapting implementation measures to complex care environments.

2. METHOD

Phase 2 followed a sequential two-stage design. Methods included (i) group-based cognitive interviews (September 2024) to pretest the adapted survey questions (Phase 2.1), and (ii) a cross-sectional online survey (January - March 2025) to assess staff perceptions and implementation constructs (Phase 2.2). Ethical approval was obtained from the University of Southampton (ERGO ID: 91895). Phase 2.1 involved cognitive interviewing with frontline care staff (n=5; 1 male, 4 female) from HCC's reablement centre. All had direct experience using the HAL device and were asked to comment on the wording, flow, and contextual relevance of selected NoMAD items, including six new items derived from a prior scoping review (under review). Interviews were audio-recorded and transcribed. Using Knafl et al.'s (2007) intent-matching approach, randomly selected responses were reviewed by the lead researcher (SB) and supervisor (MM) and categorised as "Match," "Partial mismatch," or "Significant mismatch" to inform item refinement.

Phase 2.2 was a cross-sectional online survey (Qualtrics, University of Southampton license) of HCC staff with direct or indirect exposure to Cobot implementation (n=21; 15 female, 6 male). A purposive sampling approach ensured representation of frontline care workers and supervisory/leadership staff, supplemented by snowball recruitment via internal communications. Participants from Phase 2.1 were excluded. The survey instrument included three parts:

[1] Part A (Demographics): Age, gender, job role, care setting, and Cobot exposure.

[2] Part B: Three original NoMAD "general normalisation" items ((Finch, 2015) ; 0-10 scale) and six additional context items developed from the scoping review (comfort, safety, task suitability, mobility, compatibility, and physical strain reduction; 0-10 scale).

[3] Part C (Implementation constructs): Twenty NoMAD items mapped to the four NPT domains- Coherence (sense-making work), Cognitive Participation (engagement), Collective Action (operational work), and Reflexive Monitoring (appraisal work), rated on a 4-point Likert scale with two "Not applicable" options.

Descriptive statistics (medians, interquartile ranges) were calculated for ordinal data. Frequency distributions, including 'Not applicable' responses, were reported to capture role relevance. Role-based comparisons (care workers vs supervisors/managers) used Mann-Whitney U tests, interpreted cautiously due to small and unequal groups. Internal consistency for each construct was assessed with Cronbach's α, reported cautiously given the modest sample size (n=21). Items and constructs with low scores, wide variability, or frequent 'Not applicable' responses were flagged for qualitative follow-up. Analyses were conducted in IBM SPSS Statistics (v21; University of Southampton licence) , and reporting followed the CROSS checklist (Sharma *et al.*, 2021) for survey research.

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3. RESULTS

3.1. Phase 2.1 (group-based cognitive interviews)

Group-based cognitive interviews with five care workers confirmed the clarity and contextual relevance of the adapted NoMAD survey. Most items were interpreted as intended. For “working relationships,” “legitimacy,” “skills”, and “awareness of reports,” explanatory prompts (bracketed clarification or examples) were added to enhance interpretability, based on participant feedback. Overall, participants found the survey straightforward and of acceptable length. They welcomed the inclusion of ‘Not applicable’ options and endorsed removing the neutral midpoint for Part C, improving clarity and role-relevance.

3.2. Phase 2.2 (Survey)

A total of 21 participants completed the survey: 12 care workers and 9 managers/supervisors. Most respondents (62%, 13/21) reported having received training on the HAL device, while only 10% (2/21) indicated regular or frequent use.

Responses to the nine Part B items, comprising three original NoMAD ‘general normalisation’ items and six additional context-specific items (comfort, safety, task suitability, mobility, compatibility, and physical strain reduction), were heterogeneous. Median scores suggested potential benefits for reducing strain (median ≈ 5), while ratings for compatibility and safety were more variable. Comfort was polarised, and task suitability remained consistently low (median ≈ 2). Supervisors were more optimistic about familiarity, perceived normalisation, and environmental compatibility, whereas care workers reported higher scores for comfort, mobility, and physical strain reduction. These divergences, though not statistically significant (Mann-Whitney U, all $p > 0.05$), highlight differences in perceived relevance and value across roles. A radar chart (Figure 1) visualises these role-based differences in median scores across the nine Part B items.

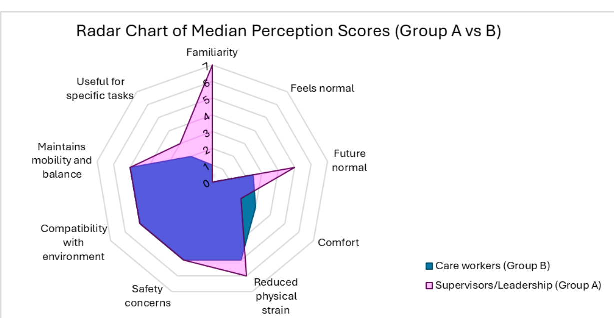

Figure 1. Radar chart comparing median perception scores across nine items from part B of the survey instrument, between care workers (Group B) and leadership/supervisors (Group A).

Analysis of the NoMAD Part C (20 NPT construct items):

- Coherence (sense-making): Most staff agreed the understood the purpose and potential value of Cobots (median = 3), with few NA responses.
- Cognitive Participation (engagement/legitimacy): Strongest domain; staff generally felt participation was a legitimate part of their role (median = 3; α = 0.85).
- Collective Action (operational work): Most contested. While medians sat at 3, up to one-third disagreed on training/resources, and up to 25% selected NA on integration or skills, signalling role/stage misalignment.
- Reflexive Monitoring (appraisal): Weakest domain (medians = 2-3; α = 0.65), with mixed agreement on value and feedback processes and up to 20% NA for report awareness.

Overall, survey findings indicate that Cobots were not perceived as routine practice. Staff understood the purpose (Coherence) and accepted legitimacy (Cognitive Participation), but practical integration (Collective Action) and appraisal/feedback mechanisms (Reflexive Monitoring) were weak or unclear. High NA responses further highlighted limited role relevance for some staff. These patterns informed Phase 3 by prioritising qualitative exploration of contested domains.

4. CONCLUSION

This study demonstrates the feasibility and value of adapting the NoMAD survey for adult social care, strengthened by cognitive interviewing. The results reveal divergent staff perspectives and limited normalisation of HAL Cobots, with particular barriers around comfort, task suitability, integration, resources, and feedback. While engagement and legitimacy were relatively strong, operationalisation and evaluation remained weak. These findings directly shaped the Phase 3 qualitative study and highlight the need to tailor implementation strategies to specific workforce roles and organisational context. Although the small sample size and case study design limit generalisability, the findings provide a valuable foundation for advancing technology-enabled care innovation and underscore the importance of role- and context-sensitive approaches when scaling new technologies in adult social care.

5. ACKNOWLEDGEMENTS

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IMPACT OF LOWER BACK EFFORT AND FATIGUE WHILE WEARING MATE–XB DURING LIFTING TASKS

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1. INTRODUCTION

Work-related musculoskeletal disorders (MSDs), particularly low back pain (LBP), are widespread and associated with significant burden for the sociosanitary systems; globally, the lifetime prevalence of LBP is estimated to increase to 80–84% [1]. MSDs are often attributed to physical strains in the workplace, such as the lifting techniques, load weights, and adopted postures strongly affect forces on the lumbar spine.

In the last decade, passive back-support exoskeletons have emerged as promising ergonomic interventions to reduce spinal loading and muscular effort during lifting. Several studies have shown that passive exoskeletons can effectively reduce muscle activity in the lumbar erector spinae by approximately 10–40% [2], both in symmetric and asymmetric conditions, potentially decreasing fatigue and long-term injury risk.

However, despite their biomechanical advantages, evidence on how these devices affect muscle fatigue and perceived effort remains scarce, especially in realistic, task-oriented scenarios. Most existing assessments focus on average muscle activation or peak electromyography (EMG) values, without examining time-based indicators of fatigue or cumulative muscle effort during the execution of the task [3].

In this study, we aimed to investigate whether a passive back-support exoskeleton (MATE-XB, Comau, Italy) can reduce muscular effort and fatigue during simulated real-world lifting scenario.

Here, we studied whether the exoskeleton reduced low-back effort and fatigue during lifting using surface electromyography (sEMG) data. The root mean square (RMS) values of EMG signals, area under the curve (AUC) of EMG activity over time, were measured as these metrics are complementary: RMS reflects muscle activation and fatigue trends, while AUC captures the total muscular effort across the task duration [4].

2. MATERIAL AND METHODS

2.1 Protocol

Simulated lifting tasks were performed by three healthy subjects (1.85±0.10 m; 75.33±12.66 kg; 29±2.65 years). Participants were asked to mimic an industrial workflow by lifting and handling a 10 kg load for 30 minutes (Fig. 1). Specifically, the subject was asked to lift the load from a 25cm height shelf (A), place it on another shelf at 45cm height (B), turn around a cone (C), come back to B shelf, pick up the box and then, return it to its initial position leaving the box in A. Each trial contained 10 repetitions of this task, which was 6 minutes long. Five consecutive repetitions of this were performed. The experiment was performed with (“Exo”) and without the exoskeleton (“NoExo”), in randomised order.

The MATE-XB uses a spring-based mechanism that stores energy during trunk flexion and releases it to assist during extension, aiming to reduce mechanical stress at the L5–S1 level. The exoskeleton has 5 levels of support; in the experiment, the third one was used, in which the total assistive torque went from 0 to 60 Nm.

A 12-camera optoelectronic system (Qualisys, Sweden) with 82 passive optical markers, to use the lifting full body model [5], and wireless surface EMG probes (Cometa, Italy), placed on trunk muscles (longissimus thoracis, longissimus lumborum, and iliocostalis, on both sides), recorded, respectively, kinematics and muscle activations.

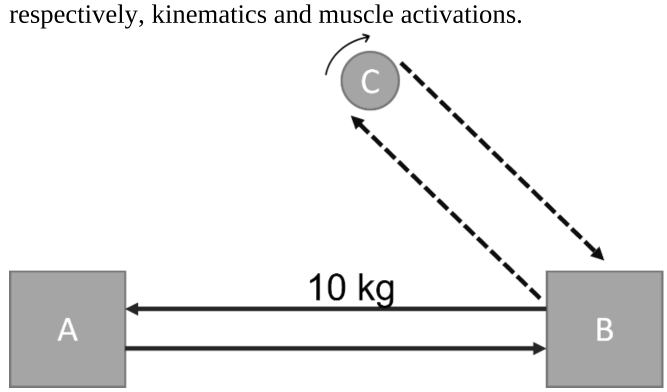

Figure 1: Scheme of the circuit performed by the subjects.

2.2 EMG data processing

The raw EMGs were first bandpass filtered between 30 and 300 Hz. Then, the signal was rectified and low-pass-filtered (cutoff frequency of 6 Hz) to find the linear envelope. The EMG amplitude was normalised to the maximum voluntary contraction (MVC) of the specific muscles. MVC targeting each muscle group was obtained during a trial in which the

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participants maximally activated the respective muscle against resistance provided by the researcher. All filters used were fourth-order zero-lag Butterworth filters.

The RMS and the AUC of the normalized EMG amplitude were computed. Since the tasks involved the trunk muscles symmetrically, values from the right and left sides were averaged, both for RMS and AUC parameters.

The RMS was calculated for each of the 5 trials. Moreover, from RMS values, the polynomial fitting and its mean slopes were evaluated, as shown in Eq. (1):

$$slope = \frac{1}{n}\left(\frac{dRMS}{dtime}\right), \quad (1)$$

where n is the number of trials in each condition, in the study $n = 5$, and $time$ is the overall duration of the task.

The AUC was computed over the signal obtained from all 5 repetitions, for all the muscles, resulting in one value for the NoExo and one for the Exo condition, for each subject.

3. RESULTS

The analysis performed on the EMG data was reported. Figure 2 shows the mean RMS values of trunk muscles for each trial, for each subject, and the standard deviation for the NoExo condition (first five bars) with the Exo condition (last five bars). For each subject, the second-degree polynomial fit of the RMS values is shown (Fig.2).

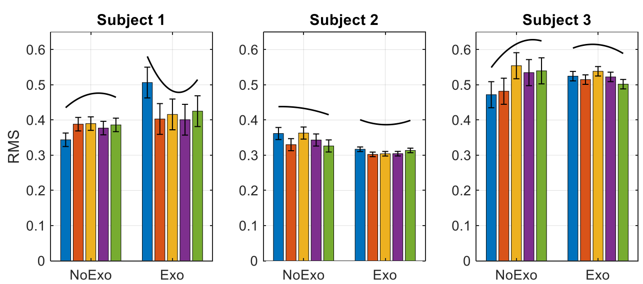

Figure 2: RMS value for trunk muscles. In each panel, bars are divided into five groups, corresponding to the five trials. Second-degree polynomial fit of the RMS values are reported above each group.

Table 1 collects the data on the change of the slope of the polynomial fit of the RMS values for each subject in the two conditions.

Table 1: Mean slope of the polynomial fit of the RMS value for subjects

	NoExo	Exo
SBJ001	0.0106	-0.0203
SBJ002	-0.0088	-0.0008
SBJ003	0.0170	-0.0057

Figure 3 shows the mean of the AUC value calculated across all five trials of the NoExo and Exo conditions. The value reported on the graphs, for each subject, is the percentage of the change between the two conditions.

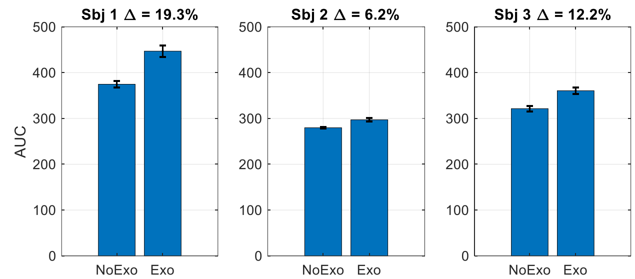

Figure 3: AUC mean value and standard deviation across all the trials in both conditions, for each subject.

4. DISCUSSION

The analysis of RMS values suggests a reduction in muscle fatigue (in particular, for subjects 2 and 3) when using the exoskeleton, indicating a possible decrease in muscle strain due to the support of the device. This trend is further confirmed by slope analysis, which shows negative values in the exoskeleton condition, reflecting a slower rate of fatigue development over time. In contrast, the effort, evaluated as AUC, reveals no differences between conditions, suggesting that total muscle activation over time may remain comparable. From this preliminary analysis, we showed that for a handful of participants, the MATE-XB reduces the fatigue accumulation but does not impact the effort. The sample size needs to be increased to strengthen these results and clarify the relationship between muscle demand and subjective exertion. Overall, this study supports the growing evidence that passive exoskeletons can help reduce the load on back muscles and relieve pressure on the spine, two key factors associated with work-related LBP. In contexts where traditional safety measures are difficult to implement, devices such as the MATE-XB can offer a practical solution to improve lifting strategies and reduce the risk of injury.

5. AKNOWLEDGEMENTS

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WIRELESS CONTROL OF 3D-PRINTED PROSTHETIC HAND USING FAT-INTRABODY COMMUNICATION

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1. INTRODUCTION

In recent years, prosthetic technology has seen remarkable advancements, driven by increasing demands for customized and affordable prosthetic solutions to restore functions in amputees, mainly focused on upper limb amputations[1]. In the present scenario, myoelectric prostheses a well-established technology, which relies on electromyography signals to actuate and control the prostheses movements. Still, this technology has limitations in performing nuanced actions and is not intuitive[2]. Our research investigates the novel application of Fat-IBC for wireless control of 3D printed hand prosthetics, offering a potentially more secure, efficient, and intuitive alternative to existing methods. The concept of novel Fat-IBC technology was developed by our Microwaves in Medical Engineering Group (MMG), Department of Electrical Engineering at Uppsala University, Sweden. The present work introduces a proof-of-concept system that utilizes human fat tissue as the communicative channel to transmit and control signals from a sensor unit to a 3D printed prosthetic hand. The motivation for this work stems from the implicit limitation of conventional myoelectric prosthetics and wireless technologies. Widely recognized and used myoelectric prostheses require extensive training and cognitive effort from the user to perform coordinated daily activities precisely. The technology maps multiple muscle signals from various hand gestures, which is challenging for an amputee with limited muscle control or altered limb morphology. So, in cases like these, depending on the quality of training data, the complexity increases in assigning or labelling certain gestures or actions[3]. So, we have proposed a transmission system to address the limitations of the existing prosthetic control technology by utilizing the unique properties of Fat-IBC. Here, the fat is used as the communication channel, eliminating the need for external radio frequencies, enhancing security, and reducing power consumption. By integrating Fat-IBC to control the Inmoov prosthetic hand, we aim to validate the potential of this method, which could transform prosthetic control technology.

2. MATERIALS AND METHODS

Artificial Tissue Emulating (ATE) phantoms or Phantom tissue were used and fabricated for research because they possessed human tissue properties, eliminating the need for real human tissues. It is fabricated to replicate the tissue's mechanical and electromagnetic properties. The main advantage of ATEs over real or animal tissues is that they are easy to handle and highly available, as they are produced in-house in MMG. The thickness of the fat layer is based on previous research in the group. The fat channel's performance depends on the fat layer's thickness, which results in less attenuation at 2.45 GHz. The phantom model will be a triple-layered model, with muscle and fat tissue being the exact dimensions per previous research, forming the first and second layers, and the skin forming the third layer. The dimensions being 20cm(L) * 5cm(W) * 2.5cm(H). We have used two in-house developed waveguides for data transmission through fat, and the width of the phantom is similar to the waveguide for proper data transmission[4,5]. The Inmoov hand design, an open-source 3D printable prosthetic hand, is a platform for our proof of concept. This design uses tendons to actuate the prosthetic hand, offering a balance of functionality, affordability, and accessibility, making it ideal for prototyping and experimentation[6]. We 3D printed the hand, which was then assembled with a tendon mechanism. The servo push-pull mechanism connects two threads from the fingertip, operating via the interior of the hand, and then to opposing sides of a wheel steered by a servo. When the servo spins to contract, the palm-side thread is drawn, pointing the finger to agreement. Pulling the thread on the rear-of-the-hand side pulls the servo as it turns in the opposite direction, causing the finger to stretch back out. With this tool's aid, the servo's rotational force can be transformed into the capacity to flex the fingers. We used two Arduino boards(Uno Rev3) to process commands to the prosthetic system. An Arduino Wireless SD shield, mounted with an XBee RF module, was used to transmit data via UART (Universal Asynchronous Receiver Transmitter). One module was named the transmitter, while the other was named the receiver. The transmitter side is powered via USB and connects to a custom-built glove with resistive flex sensors as an input to the prosthetic system. The receiver side, powered by a battery pack, is mobile and connects to the five servo motors in the prosthetic, receiving commands and actuating the fingers.

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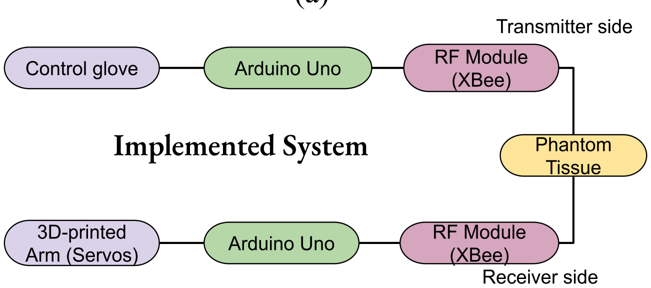
3. RESULTS AND DISCUSSION

In this project, we successfully fabricated the phantoms. We also characterized them using Agilent Keysight instruments to verify the similar dielectric properties of human muscle, fat, and skin. The muscle phantom was very close to the actual value of human tissues in both permittivity and loss tangent. At the same time, the fat and skin had slight deviations from the exact values, likely due to fabrication or characterization mistakes. We performed a signal loss test across 20 cm of fat tissue, which showed a transmission loss of -67.1 dB at 2.45 GHz. This confirmed a higher attenuation than previously reported studies, which showed -32 dB, leading to higher permittivity and loss tangents. The system was validated using a custom-built flexion sensor glove acting as an intuitive input interface, and the prosthetic responded accordingly. The signals were successfully transmitted through the ZigBee modules operating at one mW power, achieving reliable prosthesis control over a 10 cm phantom fat channel and intermittent control across 20cm. Despite minor limitations in signal stability over long distances, the proposed transmission system demonstrated the viability of Fat-IBC communication for prosthetic control, laying a foundation for further development and refinement.

(a)



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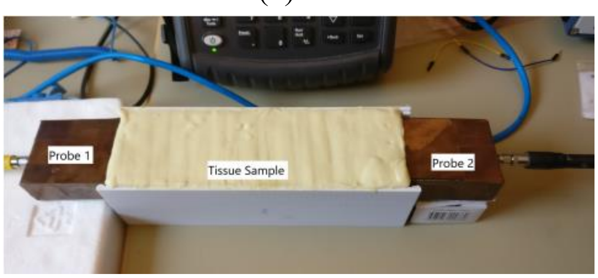

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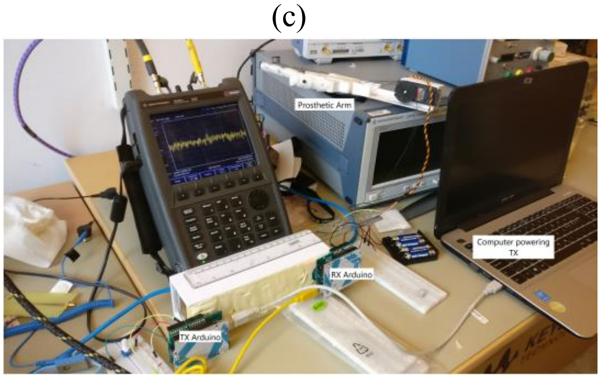

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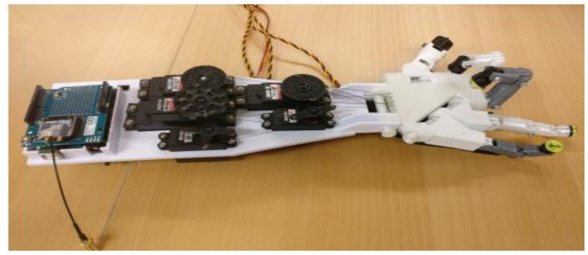

Figure 1: (a). Chart showing the implemented fat-IBC bionic arm system in this project. **(b).** The test setup for measuring signal transmission losses. **(c).** Communication test setup. The antennas and RF Modules were pushed into the skin of the fat channel to confine the signal as much as possible inside of the tissue. The antennas penetrated the skin into the fat tissue. **(d).** Finished Arm construction, with strings attached, showing full flexion on the index and middle fingers.

4. CONCLUSION AND FUTURE WORK

The next step in this avenue would be to conduct a comprehensive test using the custom-built waveguide probes to gather knowledge and insight on the signal behaviour of the phantom tissue. The XBee modules can be replaced by more realistic alternatives, such as implantable antennas, to better suit clinical and wearable applications. Additionally, the shape and design of the phantoms could be enhanced by fabricating them in a circular or more anatomically shaped model to reflect human geometry better, potentially improving measurement accuracy. The scope of this application can also be extended beyond the upper limbs, such as the leg, which could offer valuable insights, particularly for rehabilitation in lower limb amputees.

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SYSTEMATIC TRIAL OF EXOSKELETONS IN AN INDUSTRIAL WORKPLACE

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1. INTRODUCTION

Demographic change, skilled labor shortages, and extended working lives pose major challenges for companies [1]. As a result, employees in physically demanding jobs are increasingly exposed to musculoskeletal disorders, which are among the most prevalent work-related health problems in Europe [1] and make effective prevention a critical necessity. Exoskeletons, wearable support systems, offer the potential to reduce physical strain in industrial workplaces [2], [3]. Despite their potential, exoskeletons are not yet widely adopted in European industries [4]. Laboratory findings on biomechanical benefits often fail to translate into heterogeneous workplace settings [5]. Additional barriers include limited acceptance due to donning/doffing times, varying task profiles, and unrealistic expectations [6], as well as conflicting interests among manufacturers, users, and occupational safety stakeholders [4], [5]. To address these challenges, structured approaches for the selection, evaluation, and implementation of exoskeletons have been proposed (e.g., [5], [7], [8]).
This article reports a case study in which a structured approach was applied for the systematic trial of exoskeletons in an industrial workplace. By combining workplace, system, and user analyses, the study seeks to address the persistent challenge of translating exoskeleton use into real-world contexts. The findings of the user study are presented together with a discussion of their implications for companies that evaluate the introduction of exoskeletons in the industry.

2. STRUCTURED APPROACH

Effective exoskeleton use requires alignment with the support context, i.e., the user, task, and system characteristics [9], [10]. All requirements from the support context must therefore be clearly defined and systematically evaluated. Building on the 7-phase model [8] and guidelines [5], [7], a three-stage procedure was applied that begins with workplace analysis, continues with exoskeleton testing under controlled conditions, and ends with field trials focusing on user acceptance (see Figure 1). Progression to the next stage occurs only if results do not contradict exoskeleton suitability.
The first phase identifies whether the tasks are suitable for exoskeleton support. Established ergonomic tools and motion-capture assess physical strain on body regions and movements. Worker surveys capture subjective load experience, while safety experts and occupational physicians contribute with their expertise. Task variability, shift patterns, and secondary activities are also considered.

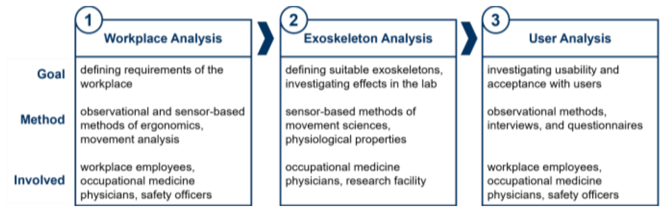

Figure 1: Multi-stage process for the structured selection and testing of exoskeletons in real working environments.

If tasks appear suitable, potential exoskeletons are analyzed in laboratory environments that simulate workplace conditions [8]. Pre-selected exoskeletons must target the relevant body regions and fit task profiles [10]. Several systems and settings from different manufacturers are compared to ensure objectivity. Tests involve multiple users performing simulated tasks, monitored by biomechanical analyses of kinematics, movement patterns, and muscle activity.
Finally, user acceptance and effectiveness are evaluated in a six-week workplace study (see Figure 2). Participation is voluntary and coordinated with health and safety experts and occupational physicians. After system introductions and individual adjustments, participants complete a one-week familiarization phase, using the exoskeletons for a few hours daily with on-site support. This is followed by a test period of four weeks minimum, during which workers may freely use the system of their choice while documenting usage and perceived effects. If the systems are rated as effective and practical, companies may consider their permanent integration into work processes.
The method was implemented at an industrial site involving metal processing tasks. Workplace analysis identified physically demanding activities, particularly static overhead work, for which shoulder exoskeletons appeared suitable. Following laboratory evaluation and approval from safety officers and occupational physicians, two passive shoulder exoskeletons were selected for user testing. The study was conducted with five participating workers.

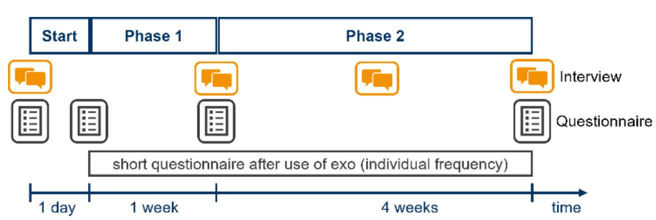

Figure 2: User study protocol including interviews and questionnaires at different phases.

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3. RESULTS

During the first week, the duration of exoskeleton use steadily increased. The peak of exoskeleton use was reached in the second week of the study, when the devices were tested across all permitted tasks, and participants even slightly adjusted their workflows to maximize use. However, these adjustments proved impractical due to longer distances and additional effort. Thus, in the subsequent weeks, usage declined progressively, and exoskeletons were only used selectively for suitable tasks. By the final week, no participant continued to use the exoskeleton. However, two participants expressed willingness to continue, though limited task applicability reduced perceived value. Others acknowledged the support but did not view their job profiles as suitable. Preferences for one of the two tested models correlated with participants' body height and proportions.

Throughout the study, participants consistently agreed with the statement "I quickly got used to the exoskeleton". This indicates that the process of familiarization was not a barrier to use. Subjective satisfaction varied over the course of the study. During the first days, ratings increased steadily. From week three onwards, however, a decline was observed. Some participants no longer considered the exoskeleton "useful" or "comfortable". By the end of the study, a further decrease was noted, and some participants were also negating "supportive". The statement "The exoskeleton was supportive for me" showed a slight drop in agreement after week three. In contrast, the question regarding perceived work facilitation gradually increased in agreement across the study. Questions addressing usability ("easy to use", "adapted well to movement", "comfortable to wear") showed an initial increase in agreement, but declined slightly after week three. Finally, the question on long-term use ("I have no concerns about using the exoskeleton over a long period") showed a slight drop between day three and week three, showing remaining concerns of using the system over a longer time.

Interviews with participants revealed several reasons for discontinued use, such as the diversity of tasks with frequent, short-term changes, restrictions such as the prohibition of occupational health professionals from using heavy tools while wearing exoskeletons, and the irregular occurrence of relevant activities.

4. FINDINGS AND IMPLICATIONS

Initial evaluation narrowed the selection to two shoulder exoskeletons suitable for workplace evaluation, highlighting the importance of early involvement of health and safety experts. Field trials demonstrated that anthropometric fit and ergonomics are decisive for acceptance and usability, as systems that could not be adjusted to individual body dimensions were rejected early. Workflow adaptations could partly lead to prolonged and more effective use, but these proved impractical over time.

Although participants generally perceived the exoskeletons as supportive, usage declined toward the end of the study. However, reports of users indicated that the exoskeleton did not always match the requirements of the task profile, limiting their usability during the work processes. High variability in secondary tasks and restrictions on tool use further constrained the application.

The findings underline the need for structured evaluation procedures, combining quantitative measurements with user feedback on comfort, mobility, and strain. Access to multiple systems and prolonged trials are essential to identify potential, limitations, and realistic long-term applicability. While broadly transferable, exoskeleton implementation must always be context-specific, accounting for task characteristics, workflows, and organizational conditions.

5. CONCLUSION

Exoskeletons can support industrial workers effectively when their selection, testing, and introduction are reflective, context-specific, and continuously monitored. The structured procedure and insights from practice provide companies with guidance for decision-making. For sustainable use, integration into occupational safety strategies, clear responsibilities, regular evaluations, and active involvement of all stakeholders, especially employees, are decisive.

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SYSTEMATIC DEVELOPMENT OF A STANDARDISED TEST ENVIRONMENT FOR THE EVALUATION OF EXOSKELETONS IN HEALTHCARE

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1. INTRODUCTION

Demographic shifts and the rise in life expectancy are expected to result in an increased need for healthcare assistance [1]. Contributing factors to the shortage of skilled workers in nursing are the physical exertion demanded and musculoskeletal disorders [2]. Current research is evaluating exoskeletons as potential ergonomic measure [3, 4]. However, most laboratory studies are designed very specifically, making it difficult to generalize results for real workplaces [5]. Standardised Exoworkathlon® Parcours are designed to evaluate exoskeletons in realistic work activities [6]. This article presents a general process for setting up such Parcours and applies it, in collaboration with field experts and digital ergonomic tools, to establish a healthcare Parcour.

2. Methods

2.1 Exoworkathlon® - Parcours Developement

The Exoworkathlon® was developed to evaluate exoskeletons in standardised test Parcours that include relevant and realistic work tasks, while collecting prospective data [6]. Professional workers or apprentices complete a Parcour randomly one hour with and without exoskeleton. The methodology and existing Parcours are part of the American Society for Testing and Materials (ASTM-International) [7, 8] (further details: www.exoworkathlon.de). This article introduces a general Parcour development process and applies it to the health care sector (see Fig. 1). First, a work sector is identified as potentially exoskeleton-relevant (exhausted technical and organizational measures). Second, a set of work tasks is identified with field experts where exoskeletons could be used regularly or over long time periods. An interdisciplinary team reviews and transfers the selected tasks to the Exoworkathlon® standard. Tasks must be defined to be repetitively performable for one hour. In this context, digital models can provide early process and ergonomic insights [9] to facilitate expert discussions. Finally, the course is tested for feasibility and iteratively adjusted in several test runs with professionals. The optional ASTM standard certification may be granted after consultation with the ASTM committee.

2.2 Development of the Health Care Parcour

In discussions with healthcare professionals, the potential of exoskeletons for nursing staff was acknowledged. In an on-site workshop, frequently performed strenuous activities were identified with specialists from a clinic, a nursing training centre and an elderly nursing home. In iterative consultation, the nursing activities, procedures, and test environment were selected and standardised. In pilot measurements with eight subjects, the execution times, challenges, and feasibility of the Parcour were tested. The low patient transfer (bed to wheelchair) was exemplarily simulated with the ema Work Designer (emaWD). Hereby, individual task durations were selected manually instead of MTM-UAS standard time, as it was considered too fast for caring interpersonal contact. The model's task durations and upper body rotation and flexion angles are compared with measured movement data (one subject, seven trials, no exoskeleton). A critical posture

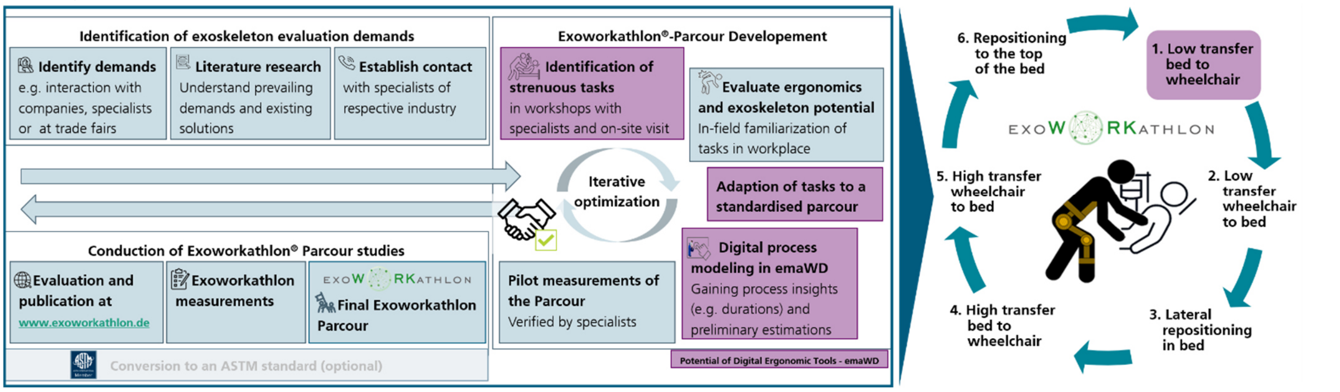

Figure 1: General Exoworkathlon® Parcour development process with optional ASTM standard and digital ergonomic tool applications exemplary applied to set up a health care Parcour that includes six realistic and strenuous nursing tasks.

identification is considered successful if it yields similar posture classifications within DGUV thresholds [10].

3. Exoworkathlon® Health Care Parcour

The on-site conditions imposed prior adjustments for the pilot measurements, i.e., opposite wheelchair positioning and adding a urinary catheter. Nevertheless, Figure 2 shows promising visual similarities between predicted and real patient transfer (low bed to wheelchair). The estimated duration of 75.4 s is comparable with the measured average of 77.3 s (±25.3 s). Without demanded time restriction, a high standard deviation was expected. The posture comparison shows that critical upper body flexion and rotation thresholds [10] reached in the simulation are often confirmed by the measured data (see Fig. 2). The rotation in (B) is mirrored due to the opposite wheelchair position. Post-pilot study decisions were to increase the mannequin's weight (16 kg to 30 kg) and fill the urinary catheter with water to improve realistic patient handling. Finally, six tasks were selected for one round: transfer of a mannequin from bed (low and high) to wheelchair and reverse, as well as two methods of patient repositioning in bed (see Fig. 1). A mannequin is used to eliminate variable patient weight and support. Assessments (e.g. usability, stress perception) must be carried out in accordance with the official Exoworkathlon® format [6].

4. Discussion

The tasks selected occur frequently in everyday nursing care, are considered particularly stressful by experts, and classified by literature [11] as "definitely hazardous". However, this set does not cover the entire spectrum of nursing activities. The task selection process, primarily based on expert feedback that provides valuable insights into practical applications, can be further improved by digital tools. The preliminary results of the task simulated with emaWD are promising to aid future selection through objective analysis and visual support (see Fig. 2) in expert discussions. Therefore, the overall Parcour must be simulated and compared to additional subjects to confirm the preliminary results. More detailed analysis is possible with ergonomic assessment methods (e.g., EAWS) or

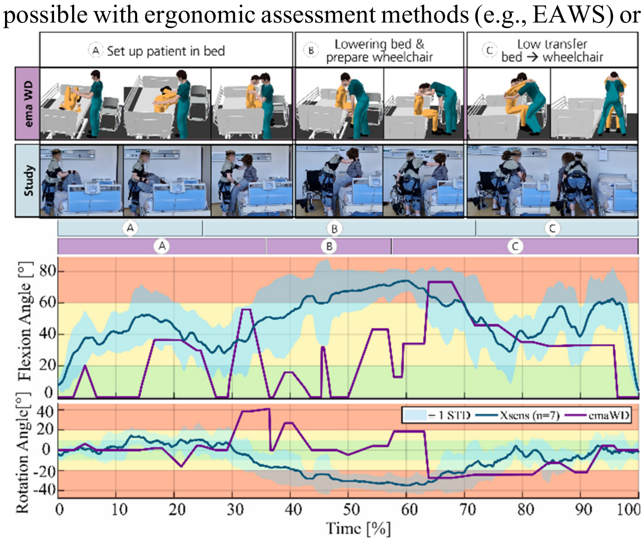

Figure 2: Upper body joint angles and visual comparison.

musculoskeletal models [12]. Real measurements with professionals, feasibility, and subjective feedback, however, cannot be replaced. This healthcare Parcour sets the foundation to generate comparable results bridging the gap between lab and field studies in real workplaces [5].

5. Conclusion & Outline

A standardised healthcare Parcour for the evaluation of exoskeletons was developed and implemented. Hereby, digital ergonomic tools can not only support planning and documentation but also serve in objective task selection. Future Exoworkathlon® Parcour development could further utilize digital tools like emaWD [9] or AnyBody [12] to increase ergonomic and biomechanical insights.

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BIOMECHANICAL EVALUATION OF SHOULDER EXOSKELETONS: EFFECTS ON THE SHOULDER GIRDLE USING A TEST RIG

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1. INTRODUCTION

Musculoskeletal disorders and diseases are a common cause of incapacity for work and early retirement [1, 2]. Shoulder problems are the second most common impairment of the musculoskeletal system [2]. The shoulder girdle complex, consisting of several joints, muscles, tendons and ligaments, enables a large range of motion through its complex dynamic interaction [3, 4]. If problems occur in one or more of these structures, the interaction is impaired, which increases the risk of pain, injury and disease in the shoulder region [4]. The shoulder is mainly stabilized by muscles, although the rotator cuff muscles ensure that the humeral joint head is centered in the joint cavity [3]. Repetitive strain on the shoulder, especially during activities above shoulder height or above head height, leads to an increased risk of enthesis-related disorders [1]. An option for reducing strain during overhead activities is the use of shoulder exoskeletons [5, 6]. Exoskeletons are externally wearable mechanical structures that support humans by applying an external force [5]. The maximum torques for passive shoulder exoskeletons range between 2.5 Nm and 13 Nm, depending on the setting, and are achieved at a shoulder angle between 80° and 120° [7].

2. METHODS

The aim of this study is to replicate and investigate the supportive effect of a shoulder exoskeleton in a standardized setting. For this purpose, twelve participants perform an abduction movement with six different support levels in the scapula plane using a test rig. At each support level, five trials are done, and the mean value is used for further data processing. 3D motion capture (Qualisys Track Manager) is used to measure the movements of the right arm, upper body and shoulder girdle. The scapular kinematics are recorded using an acromion marker cluster. This data is compared to the data of a marker cluster on the sternum to eliminate thoracic movements. Electromyography (EMG) of the deltoideus medialis, infraspinatus, latissimus dorsi, serratus anterior and trapezius muscles (pars descendens and pars ascendens) are recorded and normalized to the maximum voluntary contractions (MVC). Additionally, the motion caputure data and EMG data are related to the trial with 0 Nm torque support in order to exclude individual movement patterns from the results.

3. RESULTS

The muscle activity of the two agonists, deltoideus medialis and trapezius descendens, decreases with increasing support (Fig. 1, Fig. 2). This is significant at angles of 60°, 90° and 120° in both muscles during concentric and eccentric arm abduction movements.

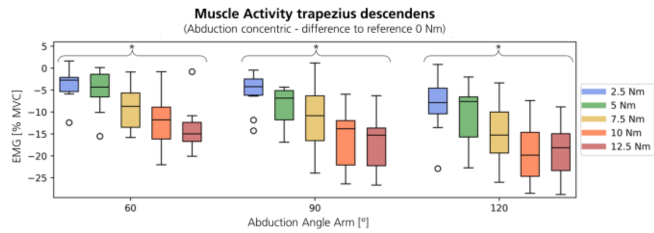

*Figure 1 | Muscle activity of the trapezius descendens during concentric abduction. Shown with box plots for each torque during abduction of 60°, 90° and 120°. Significant differences determined by ANOVA/Friedman test and marked with * (p<0.05).*

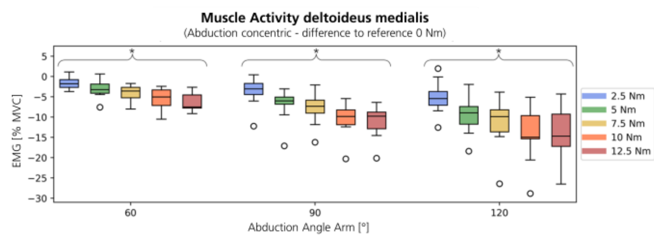

*Figure 2 | Muscle activity of the deltoideus medialis during concentric abduction. Shown with box plots for each torque during abduction of 60°, 90° and 120°. Significant differences determined by ANOVA/Friedman test and marked with * (p<0.05).*

In correlation with that also the activity of the serratus anterior muscle decreases. On the other side the muscle activity of the latissimus dorsi and trapezius ascendens muscles increase at the higher support levels during the eccentric movement. With the concentric movement the activity of the infraspinatus muscle shows a decrease with low support and an increase with stronger support. Accordingly, the total muscle activity decreases by increasing support up to the highest support level, where a slight increase occurs again, especially during eccentric movement (Fig. 3). This is accompanied by a shift in the percentage distribution of muscle activities. Whereas the agonists show reduced activity, the percentage activity in the antagonists (infraspinatus, latissimus dorsi and trapezius ascending) increases.

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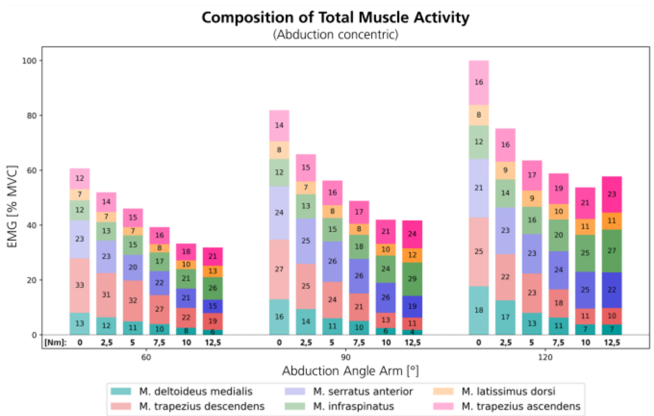

Figure 3 | Respective muscle activity and percentage of total activity during concentric abduction of 60°, 90° and 120° abduction of the measured muscles.

The scapula kinematics show increased vertical movement of the scapula and also an increased lateral rotation with greater support during concentric and eccentric movement (Fig. 4). This is associated with a negative correlation between these scapular movements and the EMG of the trapezius descendens and serratus anterior.

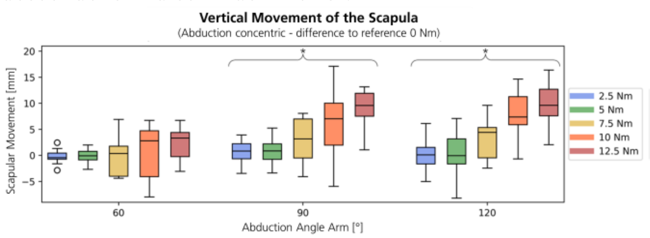

*Figure 4 | Vertical movement of the scapula during concentric abduction. Shown with box plots for each torque during abduction of 60°, 90° and 120°. Significant differences determined by ANOVA/Friedman test and marked with * (p<0.05).*

4. DISCUSSION

In accordance with previous studies, this study demonstrates that the muscle activity of both agonists (deltoideus medials, trapezius descendens) can be reduced by the effect of a shoulder exoskeleton [6]. It also shows that the level of support also has an influence, and even small amounts of support can lead to significant changes. Since less motor units are generally required for eccentric movements [8], which is also evident from the lower EMG compared to concentric movements, the effect of the test rig is also lower in this case. The arm abduction angle also has an effect on the results, especially since the test rig produces the highest torque at 90°, but this is often the case with conventional exoskeletons [7]. This effect has less impact on the trapezius descendens, as this muscle starts to be involved in the abduction movement at an angle of 60° [3]. The infraspinatus, representing the rotator cuff here, secures the shoulder joint and normally works synergistically with the deltoid muscle [3]. The increase in muscle activity of the infraspinatus and simultaneous decrease in activity of the deltoid at higher support levels suggests that the rotator cuff must additionally secure the humeral head against the external force of the test rig. Without the test rig or a shoulder exoskeleton, the agonists would usually work eccentrically to return the arm back down. But in this case, at higher torques, the antagonistic muscles have worked more intensively to enable the arm to be returned. The increase in scapular movement with a decrease in the corresponding muscle activity indicates a change in the physiological kinematics of the shoulder girdle. These changes are also again caused by the influence of the external forces.

Overall, the decrease in agonist muscle activity with increasing support is demonstrated, but this affects the intermuscular interaction in the shoulder region. However, these effects are dependent on numerous other factors – which is the reason why the impact of shoulder exoskeletons on the biomechanics of the shoulder girdle complex cannot be interpreted immediately and unequivocally. These results underscore the importance of further research in this area. This is especially relevant because the strain on the agonist muscles is reduced even at low torques, while the kinematic effects only become more pronounced at higher torques. In future, it will be interesting to investigate which mechanics and support levels enable muscle relief while minimizing impairment of kinematics and intermuscular interaction. Such a balance could allow physiological movement to be maintained as far as possible while reducing the strain on the agonist muscles. In this context, the impact of these biomechanical effects on the risk of injury or musculoskeletal disorders must also be considered. In this context, it is interesting to differentiate precisely between the individual components of the scapulohumeral rhythm and its effects on the complex interaction within the shoulder girdle.

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