International Journal of Industrial Ergonomics 97 (2023) 103494

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Insights into evaluating and using industrial exoskeletons: Summary report, guideline, and lessons learned from the interdisciplinary project "Exo@Work"

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ARTICLE INFO

Keywords:
Industrial exoskeleton
Support system
Musculoskeletal disorders
Acceptance
Usability
Workplace ergonomics

ABSTRACT

Industrial exoskeletons represent a future-oriented technology for physically supporting humans during work. Especially in industrial workplaces, exoskeletons offer the potential for preventing musculoskeletal disorders and, thus, improving ergonomics since many workplaces and processes continually require a high proportion of demanding manual activities. Despite the number of available systems and the demand for personal support, exoskeletons have still not reached widespread adoption and regular application in occupational workplaces. In addition to the modest acceptance and usability, experts especially criticize the rare evidence of effective benefits of exoskeletons. The project "Exo@Work" examined evaluation approaches for exoskeletons in the industrial working world pursuing a mixed-methods strategy and three heterogeneous strands: (A) semi-structured interviews with experts ($n = 18$), (B) study-based workplace investigations with students and industrial workers ($n = 78$) using fourteen qualitative and quantitative evaluation methods as well as 17 exoskeletons, and (C) a questionnaire study on acceptance and usability with industrial workers ($n = 33$). The results reveal various support effects of different active and passive exoskeletons as well as several influencing factors for acceptance and usability. The findings flowed into a guideline with recommendations for practitioners as a prospective basis for evaluating and using exoskeletons in a targeted manner and promoting their widespread use in the industry.

1. Introduction

1.1. Background and motivation

Human-centered technical support becomes increasingly vital in work systems characterized by high physical and psychological stress (Weidner et al., 2015). As one possible approach, exoskeletons are an emerging technology (Gartner, 2018) offering beneficial potential by easing physical strain and, thus, reducing the risk of suffering from musculoskeletal disorders (MSD) (Bogue, 2018; de Looze et al., 2016). They consist of structures that are external to the body (Fox et al., 2020) and aim to, for example, stabilize static or facilitate dynamic movements (Weidner and Karafillidis, 2018). Exoskeletons can be divided into active and passive systems and address different body regions (Crea et al., 2021; de Looze et al., 2016; Fox et al., 2020). After exoskeletons were predominantly related to medical and military contexts, there has also been a noticeable upsurge in available systems over the past few years (Hold et al., 2020; Weidner et al., 2020a) based on the rising interest in using exoskeletons in the industry (Bogue, 2018), gaining relevance since manual work will remain essential for value chains despite the ongoing automation in factories (May et al., 2015; Wang, 2018; Weidner et al., 2017). Especially where flexibility, sensorimotor ability, and cognition are relevant, human workers with their skills and abilities (Diebold, 1953) cannot be substituted by automated solutions (Ott et al., 2022) and will continue to play a crucial role in the human-centered factory of the future (Casla et al., 2019; May et al., 2015).

Performing manual tasks often accompanies strenuous postures

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https://doi.org/10.1016/j.ergon.2023.103494
Received 14 April 2023; Received in revised form 26 July 2023; Accepted 30 July 2023

(Barthelme et al., 2021) and physically demanding working conditions, for example, the repeated execution of hand and arm movements during assembly tasks or moving and lifting heavy objects in logistics (Eurofound, 2017; Eurostat, 2010). Work with these characteristics carries the risk of MSD, which has emerged as the most common health problem in European workplaces, affecting around 60 percent of the industrial workforce (European Agency for Safety and Health at Work et al., 2020; Eurostat, 2010; Roquelaure, 2018). Thus, prevention becomes increasingly relevant due to exacerbating factors like later retirement age or demographic change (Barthelme et al., 2021; European Agency for Safety and Health at Work et al., 2020).

Previously, workplace treatments to prevent MSD commonly focused on reducing biomechanical loads on employees or introducing technological or organizational measures to minimize their exposure to severe or repeated loads (Roquelaure, 2018). Exoskeletons can intervene as a preventive personal-related measure following occupational safety principles and contribute to improving work ergonomics (Schick, 2018). Accordingly, they represent a promising approach to physical relief and have, thus, already been piloted and tested in many industrial sectors and field applications (de Bock et al., 2022). In the literature, various studies investigate support effects of exoskeletons in the industrial workplace, most frequently for typical scenarios with exoskeletons addressing the back (Kermavnar et al., 2021) and shoulder region (de Vries and de Looze, 2019). Concerning back-support exoskeletons, the focus was mainly on the work processes of order picking (Motmans et al., 2019), stocking components (Siedl and Mara, 2021), or order distribution (Yandell et al., 2022) as well as preparatory activities within the framework of assembly (Graham et al., 2009; Hensel and Keil, 2019). Publications on shoulder-support exoskeletons most frequently consider the automotive sector. For instance, studies examine the cab and hydraulic assembly, the painting and hanging of parts as well as the welding of the frame (Gillette and Stephenson, 2019), lifting and screwing tasks overhead during exhaust installation (Hefferle et al., 2021), mounting clips, sealing underbody (both overhead), and mounting seal (in front of the body) (Spada et al., 2018), or the transfer of windscreens between storage racks and trailer (de Bock et al., 2021). Other studies examine common overhead assembly scenarios in the automotive industry (Ferreira et al., 2020; Iranzo et al., 2020; Smets, 2019). In addition, there are many studies carried out with exoskeletons in a controlled laboratory environment, following different focal points and study designs concerning, for example, body regions addressed, functional principles applied, or support scenarios considered (Crea et al., 2021; de Bock et al., 2022; Hoffmann et al., 2022). In these settings, test courses have demonstrated their suitability for assessing exoskeletons according to a clearly defined scheme (e.g., (Bostelman et al., 2019; Hefferle et al., 2020; Kopp et al., 2022; Kozinc et al., 2020; Nabeshima et al., 2018; Ralfs et al., 2021)).

However, the frequency of exoskeletons used in European industrial workplaces does not satisfy the high expectations raised, e.g., due to lacking biomechanical and medical evidence of their mitigating effects, especially in the long term (Crea et al., 2021; de Bock et al., 2021; de Looze et al., 2016; Steinhilber and Jäger, 2020). Despite the excessive analysis of the biomechanical effects of exoskeletons, knowledge on the side effects and adverse effects during system usage is scarce (Kranenborg et al., 2023). Accordingly, it is often difficult to compare exoskeletons with one another, and decisive system effects are sometimes not considered in the evaluations. Even if studies indicate effects by exoskeletons on users for the examined scenarios, they only allow a limited general conclusion of practical evidence (Hoffmann et al., 2019), especially against a missing product standard for exoskeletons and varying protection goals of exoskeletons in Europe (Crea et al., 2021; Schick, 2018). The regulatory boundary conditions have not kept pace with the rapid technical development of system technology. As a result, different directives apply to exoskeletons depending on their intended use: Directives 2006/42/EC for machines, EU 2016/425 for personal protective equipment, 93/42/EWG for medical products, or EN ISO 13482 in general for personal assistant robots. Following a missing product standard, there has also been a lack of a uniform test standard for exoskeletons.

As a result, implementing exoskeletons in industrial operations remains challenging (Delgado-Llamas et al., 2023), especially against the background of heterogeneous work activities (Baldassarre et al., 2022). Factors like donning and doffing times or mixed task profiles still limit the widespread adoption of exoskeletons in the industry (Schwerha et al., 2021). Additionally, side effects (e.g., discomfort or limited usability), which are primarily caused by an incorrect fit or reduced degree of freedom, were found to prevent users from using exoskeletons (Kranenborg et al., 2023).

1.2. *Aim and contribution of the project “Exo@Work”*

At the start of “Exo@Work” in 2018, only few studies were available on the support effects of exoskeletons in industrial application environments. Most of them considered selected workplaces with a limited number of exoskeletons, evaluation approaches (i.e., methods and criteria), and job tasks. As a result, a lack of knowledge was identified regarding comprehensive evaluations of the support effects of exoskeletons. This motivated the initiation of the “Exo@Work” research project (duration 2018 to 2021), which pursued a broad-based study on evaluating exoskeletons in the industrial working world in the DACH region.

Following a mixed-methods strategy, “Exo@Work” aimed to develop a comprehensive methodology for evaluating exoskeletons. This approach was intended to serve as a basis for facilitating and catalyzing the widespread adoption of exoskeletons in the industry. Therefore, a multi-criteria evaluation was conducted to identify and assess the suitability of heterogeneous qualitative and quantitative methods for investigating the support effects of exoskeletons. Hence, exemplary applications at workplaces in industrial production, logistics, industrial crafts, and trade comprised physically demanding tasks. Contrary to most comparable studies, the focus was not only on examining the extent to which exoskeletons support main tasks but also on how they restrict the performance of secondary activities. In this way, “Exo@Work” provides a broader basis for evaluating exoskeletons by also considering use cases the systems are not specially designed for but are part of daily work processes. The analyses also consider the acceptance and usability of exoskeletons as relevant drivers for their adoption in operational practice. To assure decent dissemination, deriving and developing a guideline with recommendations has added value in terms of helping companies use and evaluate exoskeletons in a targeted manner in industrial workplaces.

Therefore, the focus of this article is to provide a summary as well as the results and insights derived about the use and evaluation of exoskeletons. Accordingly, it addresses the following key questions (KQ):

(KQ1) How can exoskeletons be evaluated sufficiently and in a structured manner?

(KQ2) What recommendations can be derived for using exoskeletons in industrial workplaces?

The article takes up exemplary study results at a higher level to present general findings and provide recommendations for future adoption of exoskeletons in the industry. To stick to the main purpose of the article, the results are not described in every detail. In case of interest, project-related publications dealing with specific topics are referenced at relevant points in the manuscript.

2. Materials and methods

Since there is not a single method enabling a comprehensive evaluation of exoskeletons (Hoffmann et al., 2022), using heterogeneous and complementary analysis methods is essential. Accordingly, a mixed-methods strategy was pursued within the project, considering different focuses and objectives of investigations, test groups, and evaluation methods (Fig. 1). Generally, three overarching strands can be classified: (A) expert talks, (B) workplace investigations, and (C) questionnaire studies:

(A) The first strand contains expert talks with stakeholders (n = 18). In the form of semi-structured interviews, the experts provided insights about relevant topics regarding the evaluation of exoskeletons to determine relevant factors and focal points for the further course of the project. All interviewees had a technical or professional connection to exoskeletons.
(B) Regarding the use of exoskeletons, initiatives investigated the support effects of exoskeletons in both laboratory and field scenarios (n = 78). The test persons were young workers, students, or assembly and logistics workers. In addition, workshops with potential future users of exoskeletons took place on-site. The focus was on enabling interested companies to test exoskeletons as well as to exchange views and experiences with managers and employees.
(C) Besides, an accompanying questionnaire study on the acceptance and usability of exoskeletons was used to ask employees (n = 33) of a logistics service provider about the (unexperienced) use of an active and a passive exoskeleton. The aim was to determine influencing factors that are central motivations and challenges to the continuous use of exoskeletons.

Thereby, the expert talks (strand A) were held in the first year of the project before the study-based investigations focusing on the effects of usage (strand B) as well as acceptance and usability (strand C) of exoskeletons were conducted in the further course of the project concurrently (Fig. 1).

The multi-layered approach ultimately allowed considering different perspectives and a multi-criteria evaluation of exoskeletons. The evaluation method(s) used in each scenario decisively depended on the respective object of investigation. The studies included a cross-section of people regarding age, professional experience, hierarchical levels, and experience with exoskeletons.

2.1. Expert talks (Strand A)

The expert talks used personal semi-structured interviews to consult various stakeholders (n = 18) like manufacturers, accident insurers, end users, ergonomists, biomechanists, engineers, and occupational physicians (Weidner et al., 2020b). The interviews dealt with different cross-cutting topics and challenges towards exoskeletons and personally targeted the respective interviewee's backgrounds, interests, and roles. The considered issues were general questions, hopes and expectations, use and acceptance, areas of application, responsibilities, and expected future trends regarding exoskeletons (Fig. 2). The conception, structure, and analysis of the interviews followed (Kaiser, 2014). All interviews were automatically transcribed and manually edited. Central statements were extracted and assigned to the appropriate cross-sectional topic.

2.2. Workplace investigations (Strand B)

2.2.1. Used exoskeletons

The workplace investigations focused on shoulder and back-support systems and an evaluation of their support effects. All in all, 17 exoskeletons, including 15 commercial systems and two prototypes ("Lucy" (Otten et al., 2018) and "Power Suit" (Yao et al., 2019)), were considered (Table 1). They all differed in terms of addressed body region (e.g., shoulder or back), shape (e.g., tight-fitting or expansive kinematic structure), construction (e.g., rigid or soft materials), as well as mechanical (e.g., tensile or compressive force) and biomechanical (e.g., physical relief on the body) function.

2.2.2. Applied evaluation methods

Applied methods differed according to whether they enable a qualitative or quantitative analysis. Accordingly, the application and combination of fourteen methods helped account for and examine different investigation focuses like modeling and simulation (methods: system characteristics determination, biomechanical modeling), muscular activity (electromyography), motion analysis (3D motion capture, gait analysis), cardiovascular load (heart rate measurement, spiroergometry), dynamometry (pressure and force measurements, posturography), tissue analysis (near-infrared spectroscopy), fine motor skills (nine-hole-peg test), as well as subjective perception and attitude (survey, observation) (Table 1). For specific descriptions of the evaluation methods, reference is made to both the appendix of the guideline attached as supplementary material and to the specialist literature.

2.2.3. Study designs

Within the laboratory and field studies (n = 78), various support effects of exoskeletons were investigated, most predominantly from a biomechanical and physiological viewpoint. The results of the workplace investigations considered a total of n = 78 test persons but smaller sample sizes in the specific studies. Usually, 6 to 15 test persons participated in the studies, depending on the measurement method and test scenario. A wide range of methods evaluated heterogeneous outcome variables. However, not every evaluation method was used in every application setting. First, studies were performed in the laboratory

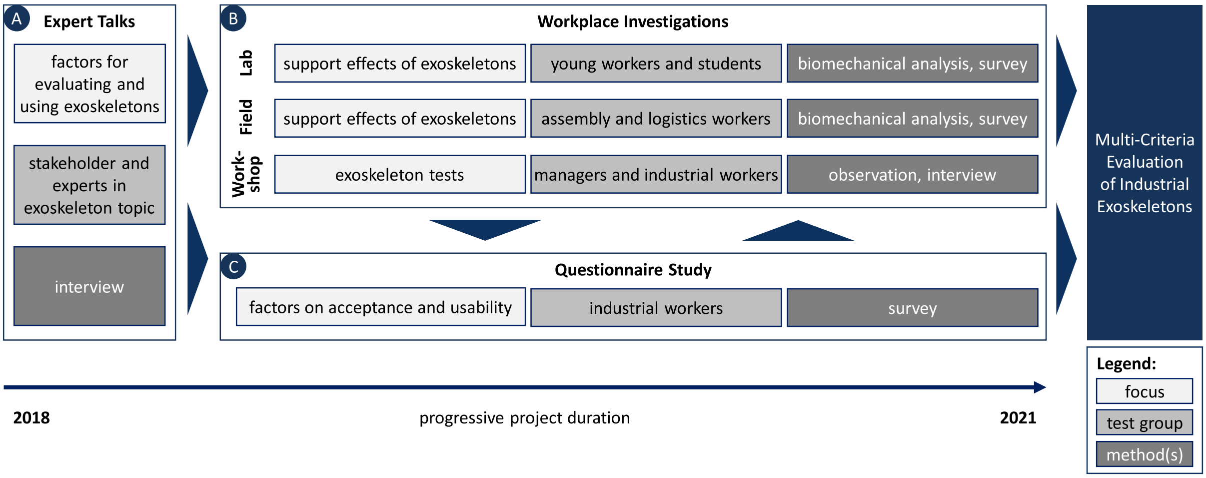

Fig. 1. Overview of the pursued multi-layered approach of evaluating exoskeletons with project strands and timeline.

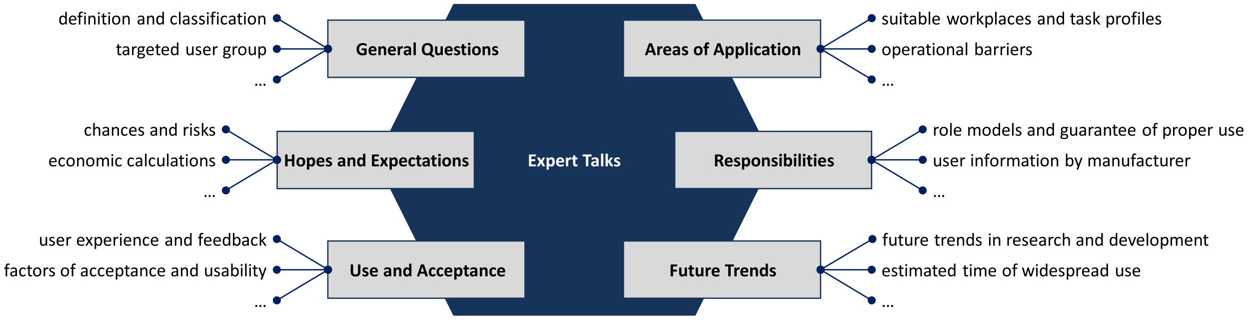

Fig. 2. Exemplary topics from the expert talks (strand A).

Table 1
Used exoskeletons (sorted in descending order by addressed body region and alphabetic exoskeleton name) and applied evaluation methods (sorted in right-going order of meaningfulness regarding results) in workplace investigations (strand B).

Exoskeleton				Evaluation Type							
Name (Manufacturer)	Property		Use-Case Setting	Quantitative							Qualitative
	Supported Body Region	Actuation Type		Modelling and Simulation	Muscular Activity	Motion Analysis	Cardiovascular Load	Dynamometry	Tissue Analysis	Fine Motor Skills	Perception and Attitude
Apex (HeroWear)	B	P	L					X			X
BackX (SuitX)	B	P	L, F	X	X	X		X			X
Bionic.Back (hTRIUS)	B	P	L		X	X	X			X	X
Chairless Chair (Noonee)	B	P	L								X
CrayX (German Bionic)	B	A	L, F	X	X	X	X			X	X
Power Suit (HSU)	B	A	L		X	X		X			X
Japet.W (Japet)	B	A	L		X	X				X	X
Laevo v2 (Laevo)	B	P	L, F, W	X	X	X		X			X
LiftSuit (Auxivo)	B	P	L								X
Rakunie (N-Ippin)	B	P	L, W		X	X	X			X	X
SoftExo (Hunic)	B	P	L, W		X	X	X			X	X
Airframe (Levitate)	S	P	L, F, W			X	X	X			X
Lucy (HSU)	S	A	L, F, W	X	X	X	X	X	X	X	X
Mate (Comau)	S	P	L		X	X			X		X
Paexo Shoulder (Ottobock)	S	P	L, F, W		X	X	X	X	X		X
ShoulderX (SuitX)	S	P	L, F		X	X		X			X
SkelEx 360 (SkelEX)	S	P	L, F, W		X	X		X	X		X
Sum:	B = 11 S = 6	P = 13 A = 5	L = 18 F = 8 W = 7	4	13	14	7	9	4	6	17

Legend.
Body Region: B = Back; S = Shoulder.
Actuation Type: P = Passive Exoskeleton; A = Active Exoskeleton.
Application Setting: L = Laboratory Study; F = Field Study; W = Workshop.
X: Scenario studied within the “Exo@Work”.

under controlled conditions and with larger sample sizes. On this basis of knowledge, tailored field tests targeted the validation with a smaller number of participating workers. All studies followed an intervention design with the intra-individual comparison of the scenarios with and without exoskeleton use. Therefore, they required randomization of the different test levels (e.g., order of exoskeletons and tasks) while at the same time limiting the test scope (e.g., duration of study, complexity of test task) to consider the physical condition of the test persons and, thus, avoid uncontrolled and blurring interaction effects.

2.2.4. *Evaluated tasks*

First, the studies were carried out in the biomechanics laboratory within a standardized modular and configurable test course environment (Ralfs et al., 2021). It enabled investigations regarding the system's usability in industry-related activities and the proof of practicability and applicability of the exoskeletons concerning functional criteria (Fig. 3). A multi-stage evaluation at nine different stations examined simple isolated activity sequences (e.g., grasping and screwing objects, lifting, holding, and carrying boxes) with variations (e.g., in

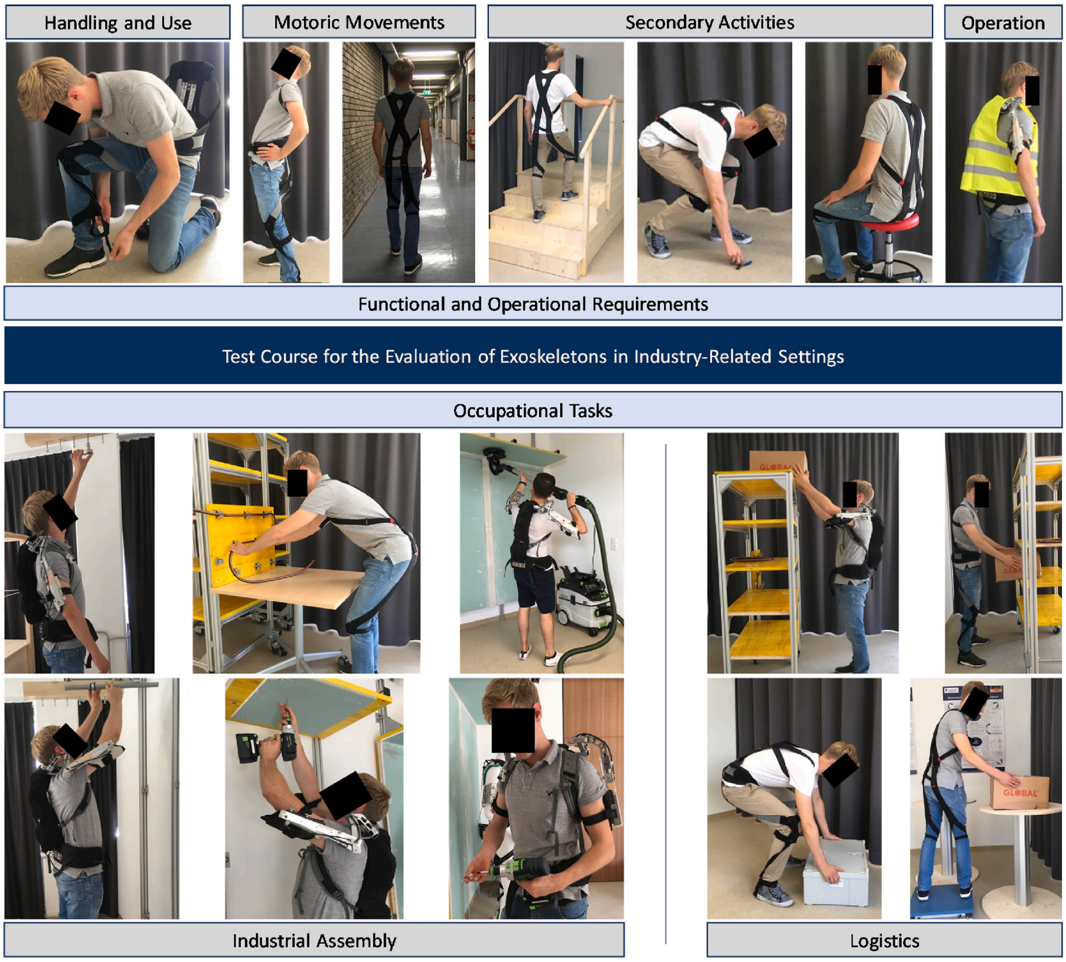

Fig. 3. Exemplary laboratory test settings for evaluating exoskeletons (strand B).

terms of work height, load weights, orientation) or even realistic simulations of entire work processes. Besides, an assessment of the general usability and handling (e.g., donning and doffing the exoskeleton, elementary working tasks, motoric movements), safety aspects, and secondary activities (e.g., walking, sitting) became possible for 20 different operational requirements.

Apart from that, studies investigated effects of exoskeletons during regular operation (i.e., incidental activity profiles and working conditions) on-site. Studies with back-support exoskeletons focused on workplaces in the mobility service and furniture industry, where packages were picked up, transported over a short distance, and stored in a pallet cage. Elsewhere, logistics activities included lifting and sorting parts of various weights into racks and boxes at different heights. Investigations with shoulder-support exoskeletons primarily happened in the automotive and aircraft industries, where exoskeletons helped during cable and underbody assembly.

2.2.5. *User workshops*

In addition to the immediate study-based analyses, workshops in companies facilitated qualitatively evaluating exoskeletons and exchanging experiences about exoskeleton usage. The seminars took place in various application settings and routine processes of logistics, order picking, the automotive industry, and container handling. The central goals of the initiative were to enable employees to gain (initial) experience with exoskeletons at selected workplaces and to explain their potential use for more ergonomic work design. Building on this, the aim was to provide knowledge how to assess general application suitability based on the tested scenario and how to specify application-related system requirements.

2.3. *Questionnaire study (Strand C)*

Primarily qualitative methods (esp. surveys) helped evaluate the acceptance and usability of exoskeletons, considering the subjective impressions. A questionnaire study over four to six weeks at eight different locations of a logistics service provider included several employees ($n = 33$, including 31 male and two female, age: 20–55 years, no prior experience of using exoskeletons). Depending on whether an active or passive system was used, the participants were assigned to two different groups.

The questionnaire study was divided into three parts and targeted the relevant issues for evaluating exoskeletons at each stage (Fig. 4). For anonymous assignments between test persons and questionnaire in different stages, an individual code word was used. The structure and questions of the study followed established documents regarding user experience (Laugwitz et al., 2008; Schrepp, 2015), affinity with technology (Franke et al., 2019), stress characteristics (Hart and Staveland, 1988), physical symptoms (Liebers et al., 2022), and perceived discomfort per body region (Corlett and Bishop, 1976). The division of the questionnaire study into three parts allowed to gain experience and consider learning effects. Before coming into touch with or even using exoskeletons, the first part collected an unbiased database, including questions about personal affinity for technology, physical symptoms, and perceived stress in everyday working life. The second part was completed after the first day of using an exoskeleton. It helped assess the first impression of the exoskeleton and possibly changed symptoms. The

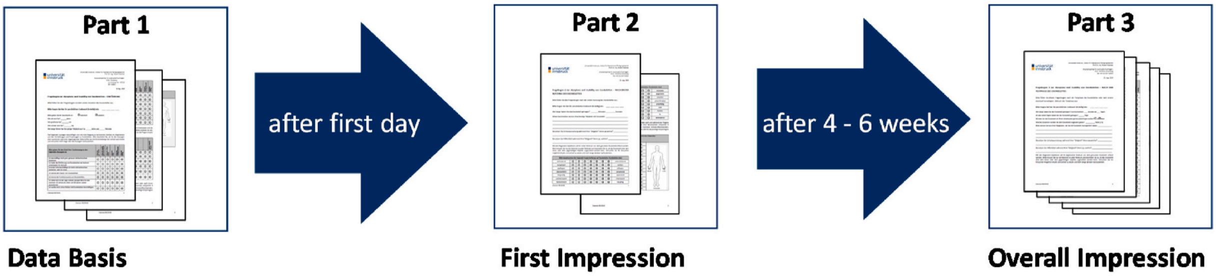

Fig. 4. Structure of questionnaire study with three separated survey parts (strand C).

third and last part at the end of the test phase asked about the handling, overall impressions, bodily symptoms, and feeling of stress on the job. The third questionnaire was the most extensive and aimed in particular at determining user experience. The three distributed questionnaire parts are listed in the supplementary material. They are cited in English but also existing in different languages to face possible language barriers.

3. Results

3.1. Evaluation findings

3.1.1. Findings from expert talks (Strand A)

As a result of the expert talks (Weidner et al., 2020b), it became obvious that experts' statements and opinions partly agree and disagree concerning different aspects and cross-sections (Fig. 5). For example, manufacturers and engineers mentioned that the technical design and realization of the exoskeletons often do not meet general expectations (e.g., enabling human superpowers, wearing the system as a second skin, universal system applicability) but show potential for future use, e.g., regarding reducing sick days or increasing work accuracy. Concerning the general attitude towards exoskeletons, the experts pointed out that another benefit of using industrial exoskeletons can lie in the possibility of (re)integration of (temporarily) performance-impaired employees into everyday work and health prevention and ergonomic design of versatile, flexible, or temporary workplaces that are difficult to access. In addition, the lack of evidence from long-term studies on the exoskeleton's positive and negative effects was underlined. Against this background, the experts initially recommended only temporary and voluntary use of exoskeletons in pilot and test applications before using them in daily (regular) operation. For all experts, the exoskeleton needed to be compatible with the work context (e.g., availability of space, climatic conditions) and neither impede secondary activities (e.g., picking up objects, sitting down) nor induce an increased risk of accidents. It was stated beneficial to always accompany operational use by medical surveillance. Among other things, the interviewees partly criticized insufficient support by the exoskeletons and improvable wearing comfort. Some experts noted that manufacturers bring immature systems to the market and thus do not meet user expectations. Besides, they stated the relevance of necessary organizational and legal regulations and operating instructions for exoskeletons (e.g., on the maximum wearing time or on inspection and maintenance intervals). Even though controversially debating their suitability, experts used similar methods repeatedly throughout the evaluation.

3.1.2. Findings from workplace investigations (Strand B)

Since no universal assessment methodology for evaluating exoskeletons exists (Hoffmann et al., 2022), the evaluation covered multiple heterogeneous aspects with different methods (Table 1). Within the project duration, several studies and its results have already been published in preliminary publications (e.g., on system characteristics determination and biomechanical modelling (Johns et al., 2021; Villotti et al., 2023), on electromyographic analysis (Ralfs et al., 2023; Reimeir et al., 2023), on motion analysis (Glitsch et al., 2020; Reimeir et al., 2023), or tissue analysis (Linnenberg and Weidner, 2022)).

Throughout the analyses, the three investigation focuses "Modeling and Simulation", "Muscular Activity", and "Motion Analysis" have proven to be the three most relevant and meaningful of the quantitative evaluation methods used. They are also common in scientific studies of exoskeletons with industrial application, enabling the analysis of various research objects (Hoffmann et al., 2022). Thus, the following results summarize the aggregated findings for these major investigation focuses. Concrete and quantifiable results are presented in more detail using an exemplary study on each of the three evaluation methods. Due to the large number and complexity of the conducted investigations and non-disclosure agreements with project-involved companies, the results are not presented in detail but summarized into core findings and recommendations. By presenting objective and impartial findings, this approach also supports the intention to avoid possible distortion of competition between exoskeleton manufacturers. In case of displaying detailed measurement and analysis data, the authors anonymized the investigated exoskeleton(s).

3.1.2.1. Modelling and simulation. The analysis of torque-angle curves of exoskeletons was necessary to gain deeper knowledge of mechanical effect provided in movement sequences. Comparisons with real human joint moments allowed conclusions regarding the support offered and required. In combination with biomechanical modeling and simulation, it was possible to determine internal musculoskeletal loads, gain knowledge about the system behavior, and derive statements about the level and proportion of support.

Across different studies in this project, the support function of passive back-support exoskeletons was analyzed. The flexion angle dependent support torque for two exemplary exoskeletons (combined support for both joints) for a flexion-extension cycle were investigated (Fig. 6). Passive exoskeletons differ typically in terms of their level of maximum support torque, but also in the shape of their angular-torque curve. Due to friction in the systems, a loss of energy throughout the movement (hysteresis) is inevitable in passive systems (Fig. 6).

Regardless of the presented example, the generalized main findings of the modelling and simulation are as follows:

- The design and construction influence the characteristics of an exoskeleton. According to their functional principle, exoskeletons cause different biomechanical effects on the human body concerning their level of support and the angle-dependent curve shape. For example, actuators differ in achievable forces and cause varying dynamic properties, which is reflected in characteristic support curves and possible speed dependencies (e.g., in terms of course and gradient).
- The support curve describing the resulting angle-dependent torque of an exoskeleton determines its application range (concerning the Range of Motion and breadth of conceivable tasks). It significantly affects the working range of the system. Accordingly, the highest effect of an exoskeleton is achieved when the system is in the optimal

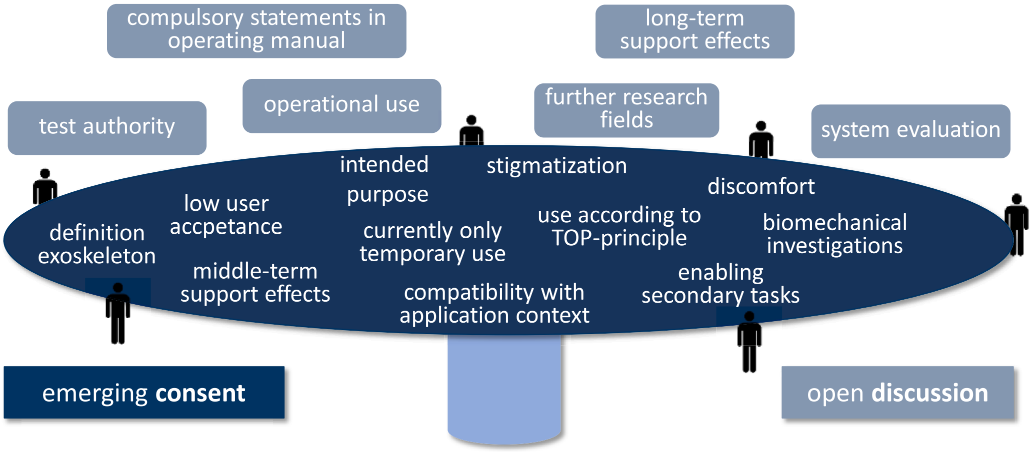

Fig. 5. Considerations to different cross-section topics of exoskeletons with emerging consent or open discussion from expert talks (illustration in reference to (Weidner et al., 2020b)).

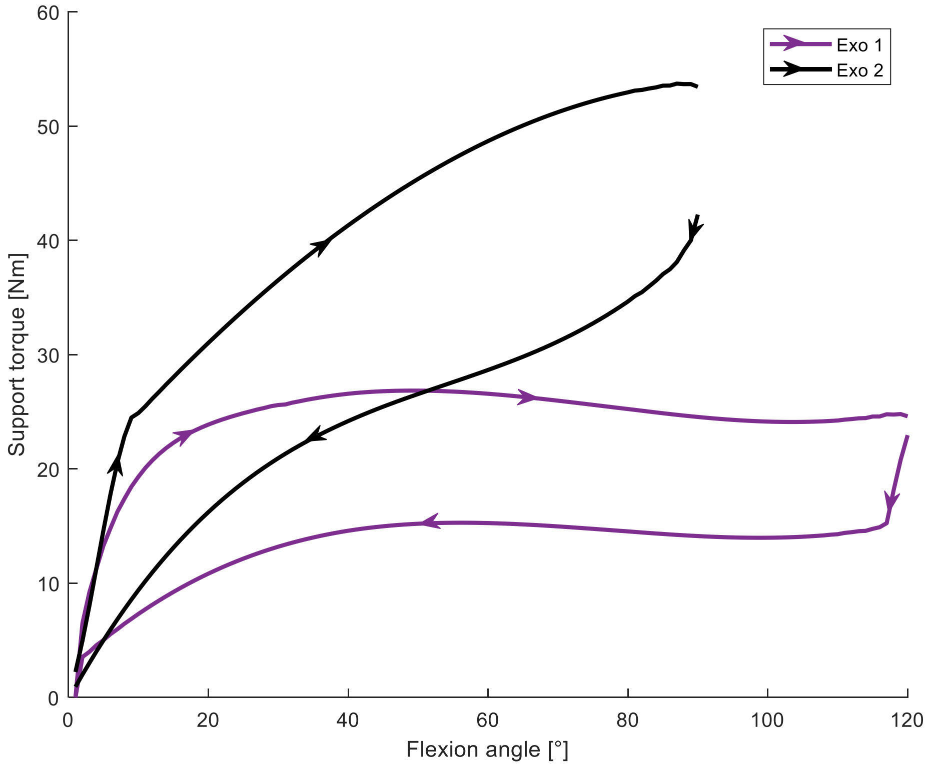

Fig. 6. Angle-dependent support characteristics for two different passive back-support exoskeletons (illustration in reference to (Johns et al., 2021)).

working range for the movement to be supported. As a result, exoskeletons can only provide partial support.

- In the best case, the support curves of exoskeletons correspond to and follow the torque curves of the human joints. The course of support by exoskeletons can be adapted to the situation, for example, by realizing directional dependencies with task-related body loads (e.g., tools, packages, materials). Depending on the task, a direction-dependent characteristic is advantageous, e.g., for support when raising the arm and omitting a counterforce when lowering the arm.

3.1.2.2. Muscular activity. Results for measuring muscular activity were based on surface electromyography (EMG), comparing scenarios with and without using an exoskeleton. With this approach, it became possible to analyze the loading and unloading effect of exoskeletons in the addressed and other body regions.

An exemplary study[1] using EMG investigated the support effect of exoskeletons on the user's muscular activity during a logistics-related

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[1] **Sample**: n = 12 (three female, nine male, 27.2 ± 1.8 years, 179.4 ± 9.2 cm, 75.3 ± 11.3 kg); **Task**: lifting, carrying, and lowering a box; **Task characteristics**: object weight: 13 kg, table height: 105 cm, walking distance: 3 m; **Scenarios**: without support (baseline), with support of passive exoskeleton (three systems), and with support of active exoskeleton (two systems); **Instrumentation**: eight-channel wireless surface EMG (Myon, Aktos, 2000 Hz); **Statistics**: paired t-tests for identification of pairwise differences between scenarios, significance level at $p < .05$.

task. Passive and active exoskeletons led to significantly reduced muscle activations in certain movement phases compared to the baseline scenario (exemplarily shown for one active and passive system in Fig. 7), whereby the strength of the relief effect on muscular activity between the distinct task phases differed. The highest measurable deviation in reduced mean and peak activity between the support scenarios appeared for deep lifting and lowering the box (phases 1 and 6) that required a forward flexion of the upper body. In these phases, the effect of the exoskeleton proved to be significant. Relative reductions in mean muscle activity for two active and two passive exoskeletons compared to baseline during lifting the box (phase 1) ranged from 18.5% to 23.5%. During lowering the box (phase 6), one active and one passive exoskeleton each achieved a relative reduction of 17.3% and 23.8%, respectively. While carrying the box (phases 2 and 5), using the exoskeleton appeared to be mostly insignificant. In addition to the mean values, however, the standard deviation indicates that reduced muscle activities did not occur in all movement phases for all test persons. Overall, the respective values also differed for every applied exoskeleton.

Regardless of the presented exemplary results of a specific study, the generalized main findings of the electromyographic evaluations are as follows:

- When used appropriately, exoskeletons can cause a reduction in muscular activity in the addressed muscle, both at peak and on average. The magnitude of the effect varies with the situations in which the exoskeleton is used, its suitability for the given task, and the exoskeleton itself. Reduced muscular activations by 20–30 % MVC (maximum voluntary contraction) in selected situations are achievable. The standard deviations differ depending on the activity profile, movement phase, user, and exoskeleton. It should always be considered during result interpretation.
- Exoskeletons do not provide support throughout the full range of tasks. For example, passive and active back-support exoskeletons can reduce muscular activity during deep lifting and lowering body movements. During assembly activities, the highest effects of shoulder-support exoskeletons on reducing muscular activity occur during movements at and above shoulder height, which, depending on the exoskeleton and configuration, starts at an elevation angle of the shoulder of 50°–70°.
- The use of exoskeletons can reduce or slow down muscular fatigue effects. The effect is particularly evident in the case of strenuous movements performed in forced postures.
- Although exoskeletons can cause the desired muscular relief in the targeted body region, they can also lead to additional stress in other body parts. An example is the added strain on the lower extremities when using a back-support exoskeleton, which can result in desired reduced activity in the lower back but can, in case of a high system weight, additionally burden the leg muscles during performing secondary activities (e.g., climbing stairs, covering distances).

3.1.2.3. Motion analysis. Fixed-mounted cameras or mobile inertial sensor systems captured movements to enable statements about changes in movement patterns or behavior during using exoskeletons. Conclusions were based on determining the accelerations in the joints and the subsequent analysis of the course of the joint angles.

An exemplary study[2] using motion capture investigated the course of the joint angles of knees and hips during a logistics-related task. Over the entire movement, a change in hip range of motion (RoM) when using an exoskeleton compared to baseline was detectable (Fig. 8). During the first half of the movement, which comprised lowering the body and lifting the box from the floor, an absolute mean deviation of 2°–5° for the two passive exoskeletons compared to the baseline scenario occurred. With an active exoskeleton, an absolute mean deviation in the hip angle of around 10° appeared. In the second half of the movement, this deviation was between 1° and 10° in the passive exoskeletons and of 15° in the active exoskeletons. One of the active exoskeletons did not lead to any major hip angle deviation in either the first or second half of the activity. Besides, the data showed higher standard deviations around the mean angle for the knee than for the hip angle RoM. With regard to the change in knee angle, the decisive factor proved to be whether the exoskeleton was attached below or above the knee. For exoskeletons with an interface at the lower leg, the absolute average mean deviations were between 8° and 12°, while for systems with interfaces above the knee, they were mostly between 1° and 4°. At this point, the relevance of considering the standard deviations also becomes apparent since the values between the test persons varied greatly. In this exemplary study, absolute deviations between the test persons of almost 20° occurred.

Regardless of the presented exemplary results of a specific study, the generalized main findings of the motion analysis are as follows:

- Passive and active exoskeletons usually alter the human range of motion and movement behavior. In the example of back-support exoskeletons, this is due to the fact that systems provoke a more upright trunk posture or lower hip flexion angles when lifting heavy loads. The strength of the effect depends on the mechanical functionality and morphology of the exoskeleton.
- In the case of exoskeletons for back support, the joint angles deviate more when lowering a load in front of the body than when lifting it. Accordingly, there is a directional influence on whether the exoskeleton acts to support humans in or against the direction of gravity.
- Due to their high level of movement fidelity, exoskeletons using soft materials tend to show lower joint angle deviations than rigid systems. One reason is that since they do not have any joints that act parallel to the body, they can support movements in other ways (usually through tensile forces) and restrict human motion to a lesser extent.
- Non-congruent rotation axes of an exoskeleton with the anatomical joints, the position of the interface for connecting the exoskeleton to the user's body, and unexpected or unsuited levels of support can lead to higher deviating joint angles.

3.1.2.4. Qualitative evaluation. Besides, surveys and observations complemented the quantitative evaluation methods. Qualitative evaluations proved to be a useful supplement to investigate subjective perceptions and attitudes. They were easily adaptable and enabled the assessment of multiple aspects in a compact way. Partly, the results corresponded to quantitative evaluation results or helped with their interpretation. The generalized main findings are:

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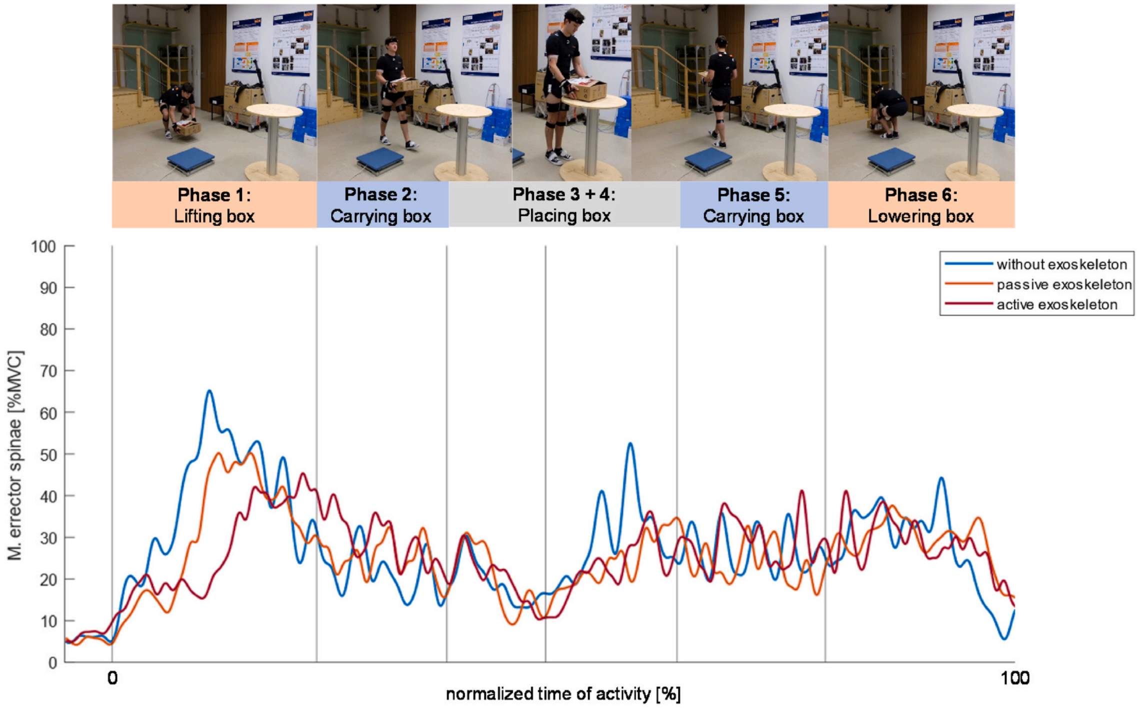
[2] **Sample**: n = 12 (three female, nine male, 27.2 ± 1.8 years, 179.4 ± 9.2 cm, 75.3 ± 11.3 kg); **Task**: Lifting and lowering a box from the floor; **Task characteristics**: object weight: 6 kg; **Scenarios**: without support (baseline), with support of passive exoskeleton (three systems), and with support of active exoskeleton (two systems); **Instrumentation**: inertial sensor tracking (Xsens MVC Awinda, 60 Hz) using 17 IMU sensors; **Statistics**: paired t-tests for identification of pairwise differences between scenarios, significance level at $p < .05$.



	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Scenario
M	-18.5%	-6.5%	-3.8%	-16.9%	-8.6%	-17.3%	passive exoskeleton
SD	12.8%	4.8%	21.5%	21.4%	10.7%	22.6%	
M	-23.5%	-14.5%	-20.1%	-6.7%	-2.6%	-23.8%	active exoskeleton
SD	20.1%	17.0%	20.4%	25.7%	15.3%	26.5%	

Fig. 7. Curve progressions in %MVC (diagram) and relative deviation of %MVC (table) in activity for M. erector spinae shown for an exemplary passive and active exoskeleton compared to the baseline scenario (n = 12; MVC = maximum voluntary contraction; M = mean value; SD = standard deviation).

- Exoskeletons usually support only in one motion direction (moving against gravity). In the gravitational direction, an additional force by the users is required, causing a feeling for users to work against the system. The effect is higher for passive exoskeletons since the mechanical springs needed to be stored.
- Using exoskeletons can improve the subjectively perceived level of physical exertion and lead to a feeling of relief. The strength of the effect depends, among other things, on the level of support of the exoskeleton. However, the perceived level of support does not always correlate with the measured effect shown by quantitative methods, e.g., in terms of muscular activity. The subjective feeling of relief initially correlated with higher discernible support. However, this started to change after a while, especially with passive systems, since working against the functional mechanism of the exoskeleton is often perceived as stressful in the long run.
- Detectable deviations in motion when using an exoskeleton do not necessarily result in a movement behavior perceived as more unpleasant.

3.1.3. *Findings from questionnaire study (strand C)*

The results of the questionnaire study[3] revealed the impact of factors on acceptance and usability. Due to the selected study design with separated questionnaires in defined time lags, changes in the overall impression of test persons about exoskeletons became apparent in terms of, e.g., personal system assessment (based on clustered items) and perceived physical complaints (Fig. 9). With regard to the assessment before the test phase, the predictability of passive exoskeletons received a higher level of approval after the test use. It was shown that the passive exoskeleton is more predictable over time regarding its mechanical system control but forfeited the user's first interest, enthusiasm, and motivation for further system use. In the case of active exoskeletons, originality and simplicity were assessed more positively after the test use. They showed a positive development in the personal assessment of comprehensibility, familiarization, and inventiveness. With a view to body complaints, the passive system caused physical relief shortly but increased after prolonged usage, e.g., on the upper and lower back. Complaints on the chest and thigh also increased since the exoskeleton featured contact points where exoskeletal interfaces transfer forces on the human body. Concerning the active system, changes in perceived complaints were principally less distinct. For example, slight increases were detected for the shoulder and thigh as well. Overall, a more negative assessment of the factors after the test use of the exoskeletons was evident. All test persons rejected to use the passive exoskeleton after final test use, whereas five test persons intended to further use the active exoskeleton.

Generally, the study shows that the properties of the exoskeletons, the procedure of the operational introduction, and the integration and use within the working environment decisively influence the acceptance and usability of exoskeletons. Additionally, exoskeletal properties (e.g., morphological structure, mechanical and biomechanical functionality, appearance) play a role. For the operational introduction, an explanation of the benefits and functionality, a positive attitude and high level of

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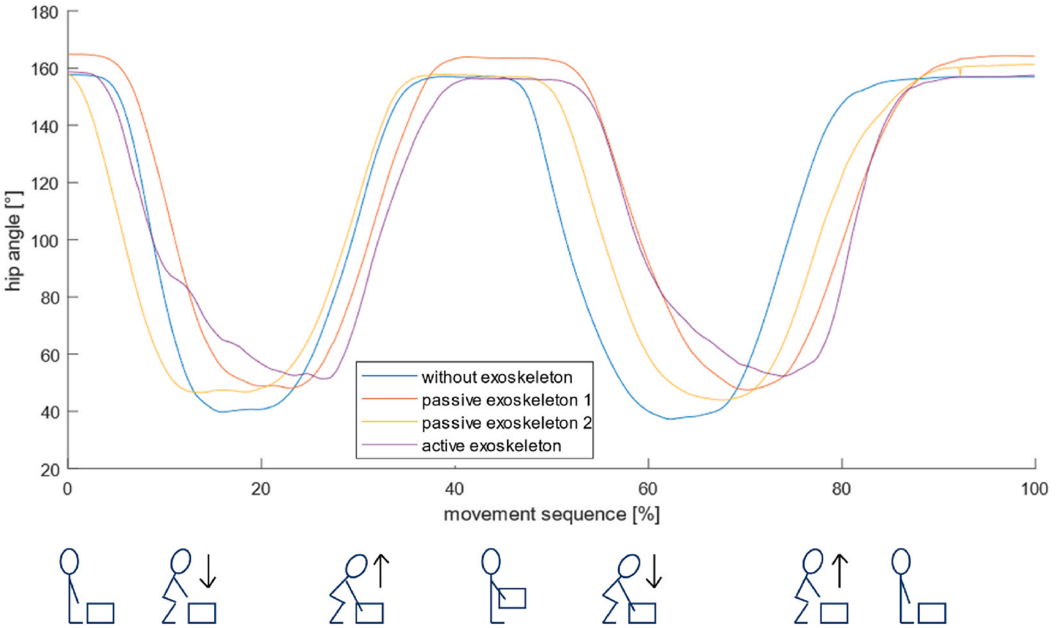
[3] **Test Group "Active Exoskeleton"**: n = 26 with 24 male and two female participants, finished by 20 employees, survey in eight locations; **Test Group "Passive Exoskeleton"**: n = 7 (male) participants, finished by five employees; survey in three locations.



	Lifting box	Lowering box	Scenario
M	-4.6°	-10.2°	**passive exoskeleton 1**
SD	6.4°	17.1°	
M	2.3°	1.3°	**passive exoskeleton 2**
SD	9.4°	8.3°	
M	-10.4°	-15.0°	**active exoskeleton**
SD	11.1°	8.6°	

Fig. 8. Angular curve progressions (diagram) and angle deviations (table) for hip range of motion shown for two exemplary passive and one active exoskeleton compared to the baseline scenario (n = 12; M = mean value, SD = standard deviation).

commitment, encouragement for voluntary use, and an open and innovative corporate culture are important. Concerning the integration into the working environment, considering spatial and climatic conditions, the functionality, reliability, and durability of the exoskeleton, as well as the combinability with tools or (mandatory) personal protective equipment, is relevant. Stigmatization, misconception, and the resulting misjudgment are additional aspects.

Due to different survey times, feedback from participants was implemented in the design and content of the questionnaires for later surveys. For example, one concern was to improve the general understandability and usability, which led to adaptions like less differentiation in wording and options as well as a shortening of every questionnaire part. The iterated and final versions of the questionnaires have emerged as another concrete result of the project.

3.2. *Recommendations for action*

The overarching and higher-level findings flowed into general recommendations to help promote the broader applicability of exoskeletons in the industry. Three categories thematically classify the results. Under "Application Context", results are assigned that relate to general aspects of the application of exoskeletons, their suitability and system fit to the user, and the collected user and usage experiences. "Support Effects" include aspects and tendencies concerning measurement-related results from studies with evaluation methods or the general procedure during an evaluation. The superordinate evaluation findings do not only consider the study results described above as examples for the main research areas of modeling and simulation, muscular activity, and motion analysis but also findings from other analysis approaches like cardiovascular load, dynamometry, tissue analysis, or fine motor skills. Findings on socially-related factors like the influence of leadership and information are assigned to “Communication”. In addition, an indication displays the connection of the finding to the three evaluation strands (strand A) expert talks, (strand B) workplace investigations, and (strand C) questionnaire study (Fig. 10). In general, the evaluation of the results shows the relevance of the mixed-methods strategy and the necessity for considering different strands for the deriving findings. Any knowledge of support effects and the suitability of methods for evaluating exoskeletons is based on workplace investigations (B). The application of quantitative and qualitative evaluations in laboratory and field environments for insights related to the user are essential. In addition to the workplace investigations (B), the assessments of the experts (A) and the findings from the survey on acceptance and usability (C) also proved to be relevant for findings relating to the application context and long-term use. Findings regarding the relevance of communication are primarily based on the user workshops (B) and the study on acceptance and usability (C).

On the basis of the gathered superordinate evaluation findings, a total of 22 derived recommendations address the use, evaluation, acceptance, and usability of exoskeletons (Fig. 10). The strength of the connecting lines between findings and recommendations is a qualitative indication of how strongly the findings interrelate with the categorized recommendations. The illustration shows that the findings on the application context primarily flew into recommendations for using exoskeletons. For example, statements about the relevance to considering occupational safety principles or manufacturer information on the

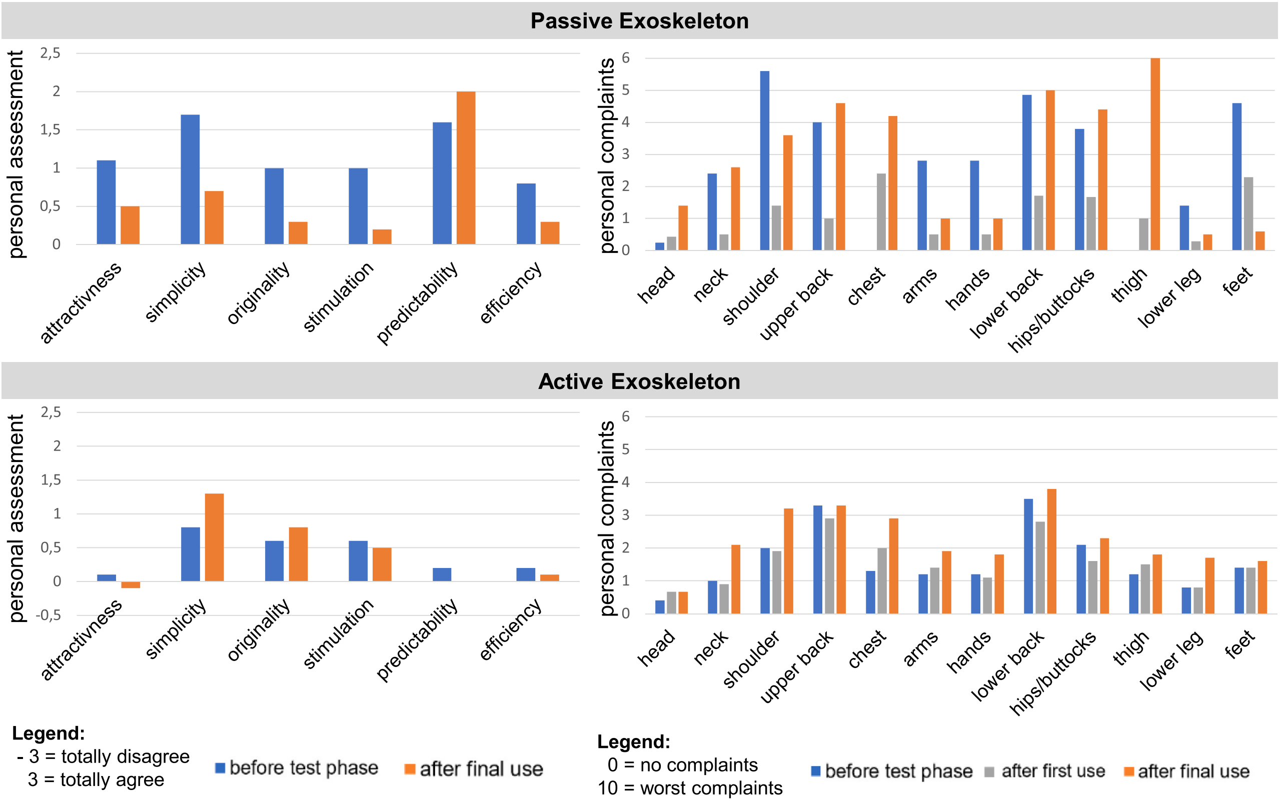


Fig. 9. Changes in personal impression towards exoskeletons and personal complaints over time (mean values) for an exemplary passive (n = 5) and active exoskeleton (n = 20).

respective exoskeleton models were derived. It was also shown for the use of exoskeletons that the systems are designed to support a primary body region and can only provide support for certain task areas and movements. This reinforces the approach from project-related publications (e.g., (Hoffmann et al., 2021; Ralfs et al., 2021, 2022)) to always consider the respective application context (e.g., activity variation, dynamics, work height) and user (e.g., physical constitution) in the assessment of the support situation, which at the same time means that secondary activities are included. The recommendations for carrying out the evaluation primarily result from the application of the measurement methods. This resulted in an increased informative value in the evaluation if, for example, several methods with different research focuses were used and quantitative and qualitative methods were sensibly combined. The aspects to be considered for acceptance and usability primarily result from the corresponding study. These address, for example, the fit and wearing comfort of the exoskeleton, the role of transparent communication, and the careful planning of test and introductory phases during ongoing operations. The supplementary material delivers a more concrete formulation and explanation of the aspects.

3.3. *Guideline for evaluating and using exoskeletons*

In addition to the recommendations for practical use, a procedure containing seven phases was developed for evaluating exoskeletons sufficiently and in a structured manner, referred to as the seven-phase model (Ralfs et al., 2021). It is a circular approach guiding the user through a controlled self-evaluation. The phases for characterizing the support situation (phase 1) and preparing for the evaluation (phase 2) are assigned to the setup stage, including the consideration of work activities and exoskeletons and the selection of suitable evaluation methods and test scenarios. The implementation is divided into pre-, core- and post-evaluation (phases 3–5). The focus is on the first tests of the suitability of test scenarios, the application of quantitative and qualitative methods in evaluating the exoskeletons, or the investigation of learning effects. At this point, considering the recommendations for conducting the evaluation can provide added value. The final step of implication includes deeper analysis (phase 6) and critical reflection (phase 7). The focus is on the interpretation of the generated data and the derivation of findings (phase 6), as well as the derivation of improvement measures and actions for the (further) use of exoskeletons (phase 7). Recommendations aimed at using exoskeletons and the acceptance and usability of systems can provide further guidance. Accordingly, the seven-phase model can be seen as an overarching result of the project and takes up some of the derived and referenced recommendations for action (Fig. 10) at an overarching level.

The results of the "Exo@Work" project are summarized in a comprehensive guideline document that aims to support evaluators by providing structural specifications for a suitable sequence and additional content-related aids like instructions, procedures, overviews, checklists, core questions, or questionnaires (e.g., on acceptance and usability). The document enables operating practitioners in industrial companies to implement, test, or evaluate exoskeletons according to a standardized and comprehensive approach. To do this, it takes up the general structure of the seven-phase model and recommendations for action (Fig. 10) to specify them for the respective evaluators through detailed descriptions and more specific information. The original version of the guideline has been published by the German Social Accident Insurance (DGUV) for its member companies, which already use, share, and apply it. The supplementary material contains the translated full version of the guideline for addressing international researchers and experts from academia and the industry.

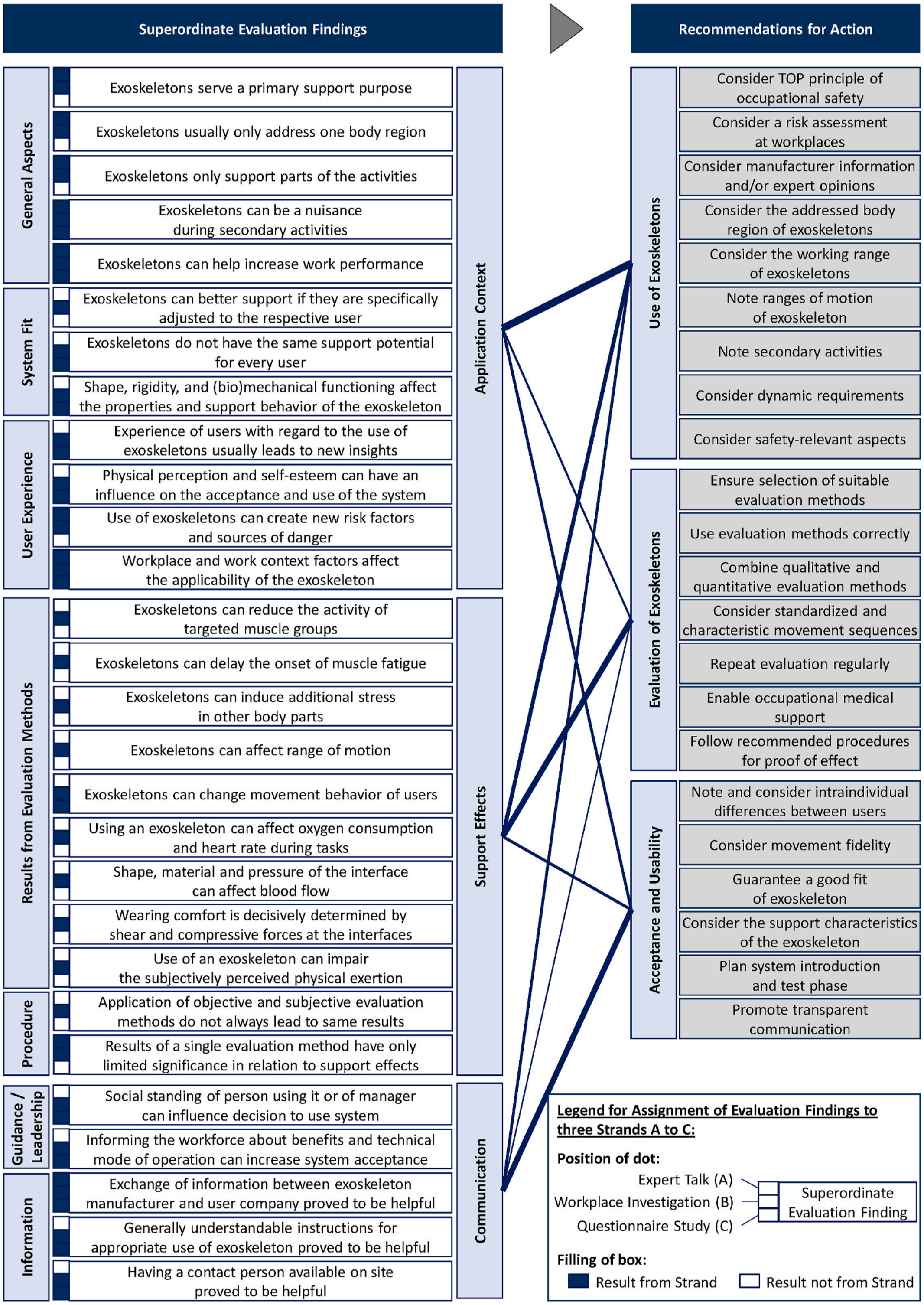


Fig. 10. Summary overview over superordinate evaluation findings and derived recommendations regarding the use and evaluation as well as acceptance and usability of exoskeletons (thickness of lines indicates the strength of the connection between findings and derived recommendations).

4. Discussion

"Exo@Work" pursued a mixed-methods strategy for evaluating exoskeletons and, thus, took up the spirit of a broad evaluation approach, which is also considered relevant by other scientists (e.g., (Crea et al., 2021)). Nevertheless, the presented results and the evaluation approach are not considered all-encompassing due to the number and diversity of existing evaluation methods. Therefore, this section discusses limitations and critically reflects the research results at first before directly referencing the key questions at the end of the paragraphs. The findings are compared to results from other scientific publications.

4.1. (KQ1) How can exoskeletons be evaluated sufficiently and in a structured manner?

First, it is crucial to emphasize that the described study results focused on biomechanical and work-physiological aspects so that an assessment of other effects, especially from a medical perspective, has not been pursued.

Even though field studies in industrial application settings have been conducted, the presented results mainly refer to evaluations in laboratory sites. Here, the simulation of working conditions and surrounding influences in laboratory settings remains a good approximation but cannot identically map realistic scenarios. Changing working conditions make it hard to compare results with and without exoskeleton support and between groups of people and work scenarios. Considerations over a longer time (e.g., several hours or complete shifts) allow for reducing the effect of random variables. However, the test arrangement must not be overloaded and, thus, undesirably affect the test person and their activities. Attempts to counteract these aspects were the focus on isolated activities and decreasing work complexity and endurance while at the same time not prescribing standardized movement sequences for the execution of tasks.

Compared to laboratory studies, field studies under realistic working conditions offer more potential to identify obstacles and success drivers and to be able to address them in the subsequent step when using exoskeletons. In general, studies combining laboratory and field tests appear advantageous since they offer the potential to consider synergy effects that favor the required effort and the quality of the results. Based on this knowledge, field tests can be targeted and meaningful as a validation study. With a view to the results, the field investigations fundamentally confirm the collected findings from the laboratory studies.

Due to the diversity of used methods and the high effort in conducting and analyzing the quantitative measurements, the studies included changing groups of test persons and varying sample sizes. Recruiting industrial workers with the desired job experience for studies in a particular laboratory course appeared difficult. Thus, students or young people without specific education in assembly or logistics operations were partly recruited as test persons. These showed different experience levels and movement patterns when performing the tasks. However, despite the predominant use of convenient samples, care was taken to ensure that the ratio between male and female test persons was based on realistic employment shares in the industry. Test persons falling within a suitable anthropometry range helped attain a resemblance to the intended working population.

Likewise, a possible bias of the evaluation of the exoskeletons cannot be ruled out, possibly resulting from the fact that not all exoskeletons were evaluated using all methods. Besides, systems differ according to their degrees of maturity and suitability for fields of application, which in turn led to varying results for the exoskeletons. In this respect, it turned out to be crucial that, for example, the maximum support torque alone is not sufficient for evaluating exoskeletons but rather the support characteristics of the system in the specific situation. The support curves in the modeling corroborate this, which, like other studies, show a hysteresis effect for exoskeletons (e.g., (Delgado-Llamas et al., 2023; Koopman et al., 2019)). Hitting the same notch, even though the investigations primarily aimed at the body regions that were to be supported by the exoskeleton, global effects can also occur, which are detectable to varying degrees, depending on the evaluation method. For example, it is not advised to solely investigate the muscular activity in the addressed body region in electromyographic investigations. Other scientists followed a similar approach in their studies (e.g., (Delgado-Llamas et al., 2023)). By doing so, the analysis is not limited to desired relief effects in the addressed body region but also allows an investigation of a possible additional burden in other body regions.

As a result, the mixed-methods strategy has underpinned there is no universally suitable method for evaluating exoskeletons. Reviews confirm this statement (Del Ferraro et al., 2020; Hoffmann et al., 2022; Kermavnar et al., 2021). However, even investigations using one method generally show useable results despite only considering quantitatively or qualitatively measurable criteria in the evaluation. Comparable studies confirm and complain about a one-dimensional research focus regarding parameters and targeted body regions during measurements (Bär et al., 2021). Accordingly, the consultation of several complementary methods is advisable for evaluating exoskeletons, which enables both a qualitative and quantitative assessment. They should always target the respective evaluation variables that can differ between stakeholders (Crea et al., 2021; Feldmann et al., 2020).

Based on the findings, a criteria-methods matrix was derived. It indicates the general suitability of evaluation methods for investigating the support effects of exoskeletons (Table 2). The categories "Loads and Support Effects" (e.g., muscular unloading, joint strain), "Technical Criteria" (e.g., support torque, addressed body regions), "Physical Demands and Limitations" (e.g., the feeling of relief, movement restriction), "Wearing Comfort" (e.g., adaptability options, system fit), and "Acceptance and Usability" (e.g., general and specific usability) each include several subjective or objective evaluation criteria (extended version of criteria-methods matrix in the appendix of the guideline in supplementary material). The methods are graded concerning their meaningfulness and relevance for evaluating exoskeletons, resulting in the following prioritization of investigation focuses (also see appendix of the guide (supplementary material) with the list of methods): modeling and simulation, muscular activity, motion analysis, cardiovascular load, dynamometry, tissue analysis, fine motor skills, and subjective perception and attitude. Overall, the seven-phase model developed during the project has shown its suitability as a procedure, which successively includes the setup (characterization and preparation), the conduct (pre-, core-, and post-evaluation), and the implication (analysis and reflection) for evaluation (Ralfs et al., 2021).

4.2. (KQ2) What recommendations can be derived for using exoskeletons in industrial workplaces?

The investigations revealed the support effects of exoskeletons for user support when used appropriately and purposefully while performing work tasks. Other scientific studies have also shown that the suitability for using active and passive exoskeletons differs depending on the actuation principle chosen for an exoskeleton (Toxiri et al., 2019). Nevertheless, successfully adopting exoskeletons in operational processes is challenging due to varying job tasks and associated work profiles (Baldassarre et al., 2022; Delgado-Llamas et al., 2023). Against this background, the adoption and use of exoskeletons in regular operations vary for different company sizes (Schwerha et al., 2021).

In the surveys, the acceptance of exoskeletons proved to be a decisive factor for the future long-term use and, thus, the success of exoskeletons in industrial workplaces. Information to the workforce on the benefits and technical mode of operation, the physical perception and self-esteem, and the social standing of the wearing person or the endorsing manager are central drivers of system acceptance. The findings mirror the results from studies of other authors, which confirmed the role of users and managers and self-efficacy during use to be most important (Baltrusch et al., 2021). They also substantiate that the self-efficacy of using exoskeletons heavily depends on whether the exoskeleton addresses a targeted purpose (e.g., lifting or working in repeated or static forward bending) or performing secondary activities (e.g., sitting) (Baltrusch et al., 2021). Other studies identified dimensions like social acceptance, appearance, a fit of technology, and health and well-being effects (Siedl and Mara, 2022) or found an influence of physiological, work-related, policy-related, implementation-related, and psycho-social factors on the acceptance of systems (Elprama et al., 2022). However, if the pertinent user has not been studied, conclusions from acceptability studies are hard to translate into actual practice.

Concerning usability, there were noticeable differences between the

Table 2
Criteria-methods matrix for indicating the general suitability of methods for investigating the support effects of exoskeletons.

Categories of Evaluation Criteria	Evaluation Type								
	Quantitative							Qualitative	Sum:
	Modelling and Simulation	Muscular Activity	Motion Analysis	Cardiovascular Load	Dynamometry	Tissue Analysis	Fine Motor Skills	Perception and Attitude	
Loads and Support Effects	X	X	X	X	X	X	X	X	8
Technical Criteria	X	X	X		X			X	5
Physical Demands and Limitations		X	X	X	X	X	X	X	7
Wearing Comfort					X	X		X	3
Acceptance and Usability	X							X	2
Sum:	3	3	3	2	4	3	2	5	

Legend.
X: Suitability of Method for Evaluating Category of Evaluation Criteria.

assessments from surveys in the controlled laboratory environment and the field environment. The investigation results show that in addition to the actuation principle mentioned in another study (Toxiri et al., 2019) the morphological shape of an exoskeleton also affects the usability of exoskeletons in different contexts. Exoskeletons made of soft materials tend to support static postures, while exoskeletons with rigid and stiff kinematics have a higher support capacity for dynamic activity profiles. In the case of back-support exoskeletons, for example, the sluggish following of the movements by the exoskeleton, the restriction during the performance of secondary activities (esp. walking), the slipping of interfaces during the performance of tasks, the connection between the degree of support and restricted movement as well as overriding specifications by the exoskeleton are proven as challenges. Shoulder-support exoskeletons often require counteracting the support torque when lowering the arm from elevated angles, which requires working against the system with additional effort. Related topics like discomfort and limited usability have also been shown to be relevant in other scientific studies (Kranenborg et al., 2023). Investigating the long-term effects of exoskeletons and broader user experience remains an open need for research in longitudinal studies on the way to more evidence of the exoskeleton's support effect, preferably with occupational medical support. Other studies also underline the need for further studies in real application situations (Crea et al., 2021; Del Ferraro et al., 2020; Kermavnar et al., 2021; Spada et al., 2017).

Since lacking evidence complicates recommendations on selecting and using suitable exoskeletons for the application context, supporting aids and guidelines for practitioners have been developed: a decision-support matrix to help characterize support situations by matching properties of tasks, work profiles, and system characteristics (Ralfs et al., 2022), and a procedure for implementing exoskeletons based on key indicators (Hoffmann et al., 2021). Consequently, the successful implementation requires an initial and iterative analysis of the use case, the selection of a suitable system (in case the suitability of an exoskeleton as a sensible technology is given), an evaluation based on a test use, and the decision for long-term use. If the usability evaluation is positive and the workforce approves acceptance, the further use of exoskeletons can be beneficial. All the findings have been incorporated into the guideline attached as supplementary material, specifying the approaches and recommendations for action for using exoskeletons.

5. Conclusion

"Exo@Work" pursued a mixed-methods strategy for gaining insights into and deriving recommendations for evaluating and using exoskeletons in industrial workplaces. For this purpose, interviews with exoskeleton experts, study-based workplace investigations, and an acceptance and usability survey were conducted, reflecting the key questions (KQ1) how to sufficiently evaluate exoskeletons in a structured manner and (KQ2) what recommendations for exoskeleton use can be derived. Qualitative and quantitative methods examined heterogeneous exoskeletons with different morphological structures and actuation principles in exemplary production, logistics, trade, and commerce scenarios. Despite the critical reflection of the approach and its results, the multi-layered investigations have led to several findings, which underpin and broaden the results of other scientific research. In short, it has been shown that exoskeletons can physically support employees in activity sequences and specific body regions when used in a targeted and appropriate manner. Besides, the studies have highlighted the relevance of acceptance and usability. The findings have flowed into recommendations regarding evaluating and using exoskeletons. Overall, the article has given insights into three years of exoskeleton research. It offers practitioners a generic guideline that can be individually tailored for using and evaluating exoskeletons in their companies. By doing so, the article promotes their future adoption in the industry.

Remark

For further information on the results of the "Exo@Work" research project, reference is made to the download links of the published final report (LINK_Report) available in German language as well as the publications on the project mentioned in the manuscript. The guideline document is attached as supplementary material.

Funding

The research was funded by the German Employer's Liability Insurance Association for Trade and Logistics (BGHW) (project no. IFA 4235: "Exo@Work - Evaluation of exoskeletons for the working world").

Author contributions

Conceptualization: L.R., N.H., U.G., R.W.; Methodology: L.R., N.H., U.G., R.W.; Software: N/A; Validation: L.R., N.H., U.G., K.H., J.J., R.W.; Formal Analysis: L.R., N.H., U.G., K.H., J.J.; Investigation: L.R., N.H., U.G., K.H., J.J; Resources: U.G., R.W.; Data Curation: N/A; Writing – Original Draft: L.R.; Writing – Review & Editing: L.R., N.H., U.G., K.H., J.J., R.W.; Visualization: L.R., N.H., J.J.; Supervision: R.W.; Project Administration: L.R., U.G., R.W.; Funding Acquisition: R.W.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2023.103494.

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