Zurich University
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Benefits and limitations of exoskeletons for the prevention of musculoskeletal disorders in occupational settings

A Scoping Review

Final report on behalf of the State Secretariat for Economic Affairs (SECO)

Winterthur, 04.07.2024

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Abbreviations and acronyms

CMSDQ	Cornell Musculoskeletal System Discomfort Questionnaire
CR	Category-Ratio
DGAUM	German Society for Occupational and Environmental Medicine/ Deutsche Gesellschaft für Arbeitsmedizin und Umweltmedizin
EMG	Electromyography
JBI	Joanna Briggs Institute
L Ex	Lower extremity
NASA-TLX	NASA Task Load Index
PCT	Pragmatic Clinical Trial
PRISMA-ScR	Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews
QUEAD	Questionnaire for the Evaluation of Physical Assistive Devices
RCT	Randomized Clinical Trial
RPE	Rating of Perceived Exertion
SECO	State Secretariat for Economic Affairs/ Staatssekretariat für Wirtschaft
SUS	System Usability Scale
VAS	Visual Analogue Scale
U Ex	Upper extremity
ZHAW	Zurich University of Applied Sciences/ Zürcher Hochschule für Angewandte Wissenschaften

Summary

The prevention of musculoskeletal disorders in industrial work environments is of central importance for the long-term health and performance of employees. In this context, exoskeletons are often discussed as a promising technological solution, as they can support certain movements and reduce the strain on muscles and joints. However, there are also indications on potential negative effects, for example due to discomfort or limited acceptance of such technology. To understand the current evidence on the benefits and limitations of such devices in the workplace setting, a scoping review was conducted to identify the types of exoskeletons typically used. Further, the objective and subjective effects when wearing an exoskeleton were defined.

Different databases were systematically searched for articles assessing exoskeletons in workplace settings for their effects on objective (e.g. body posture, energy expenditure) as well as subjective metrics (e.g. perceived exertion, discomfort, usability). The results were discussed in a workshop with experts from organization psychology, ergonomics, and wearable mechatronic systems.

Of the initial 1462 articles, 37 fulfilled all inclusion criteria after full-text screening. They covered a total of 28 exoskeletons, both passive and active products and prototypes for the back, upper extremities, and lower extremities. For most outcome variables, studies indicating a positive as well as a negative effect were found. Due to the limited number of studies for a specific exoskeleton and the large variability on variables that were reported, it was difficult to draw specific conclusions. Overall, there is a strong need for future research evaluation the long-term effects of exoskeletons systematically. Usability aspects, such as the ease of donning and doffing, and observations on the use of exoskeletons in the workplace must be included in future studies. When implementing an exoskeleton in a workplace setting, the exoskeleton must facilitate the work while supporting the worker’s competence. Exoskeletons must be fitted to the worker and should not improve productivity without improving the physical strain, specifically in settings with high risk of musculoskeletal injuries.

There are broader guidelines that may support the implementation and collection of data on use and effect of exoskeletons. It is important to collect such standardized data to determine the effectiveness of exoskeletons in the workplace.

1 Introduction

Musculoskeletal health problems are among the most common health impairments caused by work in the Swiss labour force [1]. Mechanical overload due to excessive repetition, awkward postures, and heavy lifting are risk factors for work-related musculoskeletal disorders [2]. The prevention of musculoskeletal disorders in industrial work environments is of central importance for the long-term health and performance of employees. In this context, exoskeletons are often discussed as a promising technological solution. Exoskeletons are wearable robotic technologies that can support certain movements and thus reduce the loads exerted on muscles and joints. Various scientific laboratory studies have shown a reduction in the biomechanical strain on a muscle when supported by an exoskeleton [3,4].

However, other studies also show various negative effects when using exoskeletons, such as discomfort when wearing them [5], increased demands on antagonistic muscles, increased cardiac strain and kinematic changes [6].

The current state of the literature places an emphasis on lab-based studies in comparison to field studies [7], but job dynamics in actual work environments are more complex than lab settings [8]. It is therefore essential to understand the benefits, but also the limitations of implementing this technology in work environments. A systematic literature review was conducted to clarify which types of exoskeletons are currently used in industry, construction and healthcare and what health effects the integration of these technologies has.

2 Research Questions

The specific aims of the literature review are as follows:

- Define the main types of exoskeletons used in organisations
- Identify the objective and subjective effects associated with wearing and using exoskeletons at the workplace
- Clarify the evidence base regarding the effectiveness of exoskeletons in preventing musculoskeletal disorders in organisations
- Identify factors that have a positive or negative impact on workers' health associated with the use of exoskeletons
- Identify examples of the implementation of exoskeletons in companies and, if possible, derive best practice principles
- Identify existing knowledge gaps

3 Material and methods

3.1 Scoping Review

A scoping review was conducted on the basis of the Joanna Briggs Institute (JBI) manual on evidence synthesis (Chapter 11) [9] and the report follows the reporting recommendations provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) [10].

3.1.1 Search strategy and systematic search

A systematic electronic search was conducted in December 2023 in the following databases: MEDLINE/PubMed, EMBASE (Ovid), CINAHL (EBSCO), Cochrane Library, ClincialTrials.gov, Web of Science and Scopus. The bibliographies and references of the included articles were also reviewed. Additionally, we tried to identify scientific articles published by manufacturers using standard search engines and the key words exoskeleton, work, occupational use.

A combination of database-specific terms and subheadings, e.g. MeSH terms, and keywords were used. The full search histories are presented in the Appendix 8.3.

3.1.2 Screening and eligibility

After the search was conducted, all duplicates were removed and the retrieved publications were screened for suitability based on title and abstract, followed by a full-text screening. The screening process and study selection was conducted by two independent reviewers, based on the inclusion and exclusion criteria (Table 1). Discrepancies in decisions to include or exclude studies were resolved by discussion and finding consensus between the researchers. The literature and screening process was managed using the software Covidence (Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org). For a flowchart of the study selection process, please refer to Figure 1.

Table 1. In- and exclusion criteria

	Inclusion criteria	Exclusion criteria
Technology	– Active or passive exoskeleton technology for upper extremity, lower extremity, back, and neck	–

Setting	– Exoskeletons intended for occupational use (industrial manufacturing, health care, logistics, military)	– Exoskeletons for patient rehabilitation
Outcomes	– Objective metrics, e.g. energy expenditure etc. – Subjective metrics: perceived exertion, discomfort, usability, acceptability, etc. – Economic (e.g., cost-efficacy, complication rate)	– Data collection lab-based only
Study design	– Clinical trials (RCT, PCT, cohort studies, cross-sectional, case–control case series) – Qualitative studies – Case Reports	– Opinion literature/author replies – Literature reviews – Study protocols
Context	– Publications within the last 20 years (2003-2023) – Language English or German	– No full text available

3.1.3 Data charting

A data charting form was developed by the ZHAW research team, in agreement with the SECO (Table 2). The form was pretested by all reviewers and refined before implementation into the software Covidence. The final data charting form allowed for reporting on specific details about study, exoskeleton technology and participant characteristics, outcome measurements, study procedures, and key findings with relevance to the review. Data charting was performed independently.

Table 2. Data charting form

Item	Description
User characteristics	– Demographics: age, sex, weight, height – Occupation – Eligibility criteria (inclusion and exclusion)
Study characteristics	– Title, authors, country of origin – Publication date, type of publication

	– Study design, purpose – Setting: industrial manufacturing, healthcare, logistics, military etc., occupational tasks
Technology characteristics	– Exoskeleton types – Companies – Purposes
Types of outcome metrics	– Objective metrics, e.g. energy expenditure, electromyography, electrocardiogram, motion capture – Subjective metrics, e.g. perceived exertion, discomfort, usability, acceptability – Economic, e.g., productivity, cost-efficacy, complication rate – Other
Key findings	– Subjective and objective effects on user – Implementation (e.g. tasks, safety) – User feedback (e.g. acceptability, usability)

3.1.4 Analysis and synthesis

After the extraction process, the data were summarized, analysed, and clustered to report the implications of the study findings. The analysis is presented in figures, charts and tables in a manner that aligns with the objective of this scoping review and in narrative descriptions of the data.

3.2 Expert workshop

In May 2024, a 1,5 h workshop with three experts was conducted to discuss the preliminary results of the scoping review and to explore aspects that affect successful implementation and evaluation of exoskeletons at the workplace. The experts were scientists specialising in organization psychology, ergonomics, and wearable mechatronic systems. Key points of the discussion were noted in a protocol and later summarized for this report. The key recommendations from experts were synthesized with the main results from the literature review in the discussion.

4 Results

The initial search yielded 2413 publications, thereof 2363 from the scientific databases, 11 from the clinical trial register and 39 from the desktop search. After removing the duplicates, 1460 studies remained for the title and abstract screening, whereof 1076 studies were excluded. In the following full-text review, 296 studies were excluded with the wrong study design (reviews, lab-based only, opinion pieces). A final number of 37 studies were included in this scoping review (Figure 1).

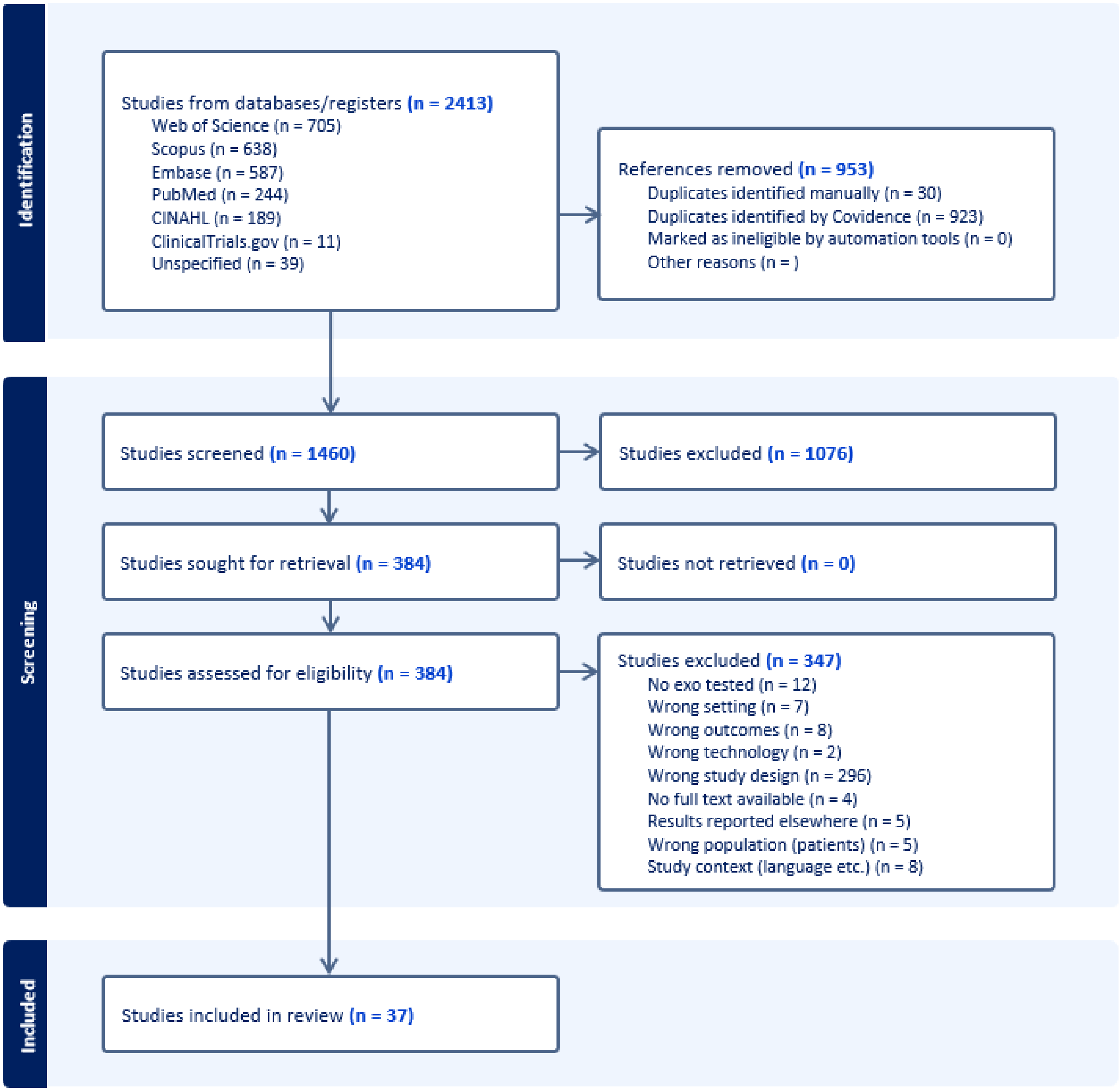

Figure 1. Prisma flow chart

4.1 Characteristics of included studies

Appendix 8.1 provides an overview over all included studies and their characteristics (year, study design, sample size and characteristics, occupational settings, exoskeletons and aim of each study).

The majority of studies were published within the last 4 years, between 2021-2023 (n=26). A high number of the includes studies were conducted in the United States (n=12), followed by Germany (n=4), the Netherlands (n=3) and France (n=3). Studies evaluated exoskeletons in a variety of occupational settings, ranging from manufacturing (n=9), logistics (n=8), automotive (n=7), construction (n=6), healthcare (n=6), agriculture (n=4), waste collection, slaughterhouse, cleaning, and forestry (n=1 each). Several studies reported on more than one setting, for example both manufacturing and logistics.

There was large heterogeneity in the applied study designs (Figure 2) and unclear terminology. The distinction between lab-based studies and field studies are not always clear, as some studies evaluated applied tasks in a lab setting or standardized tasks in the field. We categorized studies that undertook an in-field evaluation, or a combination of standardized tasks followed by an in-field evaluation as “field studies” (n=19). If exclusively standardized tasks were evaluated in the field, we categorized them as “experimental study” (n=4).

A total of 821 participants were included in the studies, thereof 578 men (70%) and 59 women (7%). For the other participants, no gender information was available (23%). The mean age ranged from 29 to 47 years.

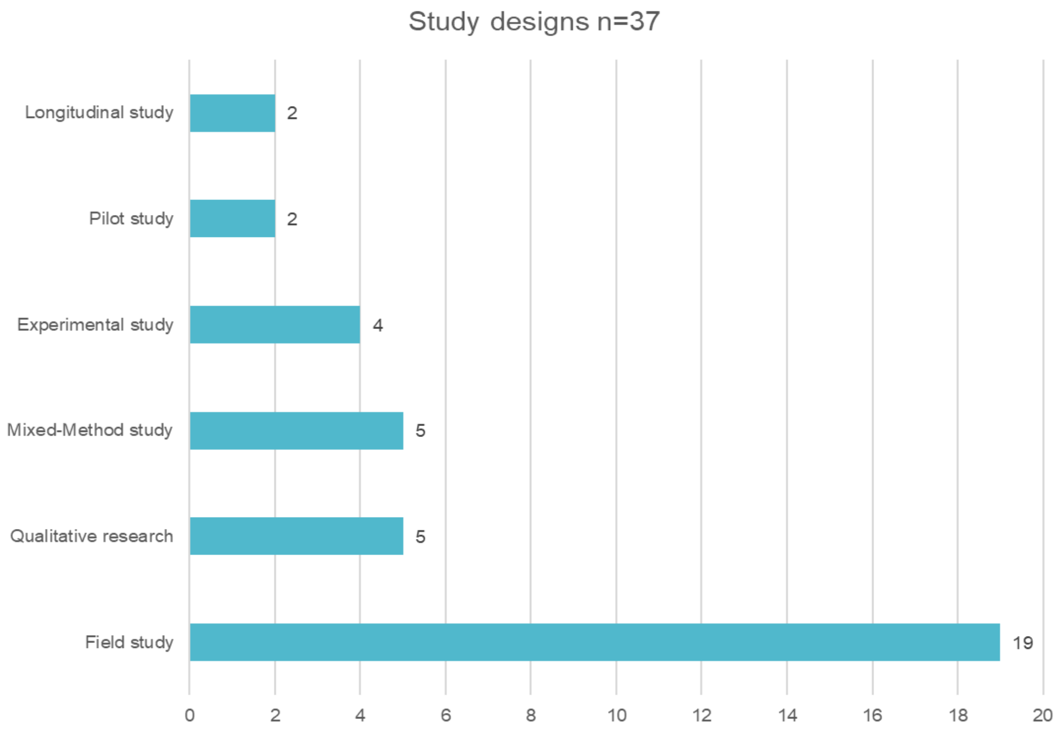

Figure 2. Study designs

4.2 Types of exoskeletons

Over all studies, 28 different exoskeletons were evaluated. The exoskeletons can be categorized by either supported body area or mode of function (active vs. passive). Active exoskeletons use actuators to generate forces or torques acting on the body. Passive exoskeletons use passive elements such as springs or elastic straps to support the body. The distribution of exoskeletons according to those categories in the studies is displayed in Figure 3. In the reviewed field studies, predominantly commercially available exoskeletons were used and only three studies reported on non-commercial devices. Some studies also investigated former versions of exoskeletons, that have since been updated.

The most frequently evaluated exoskeletons were the Laevo (n=11) and BackX (n=7) for the back, and Airframe (n=8) and ShoulderX (n=5) for the upper extremity. Depending on the product, different versions were used in different studies. A table with detailed information on each exoskeleton, including pictures, can be found in the Appendix 8.2.

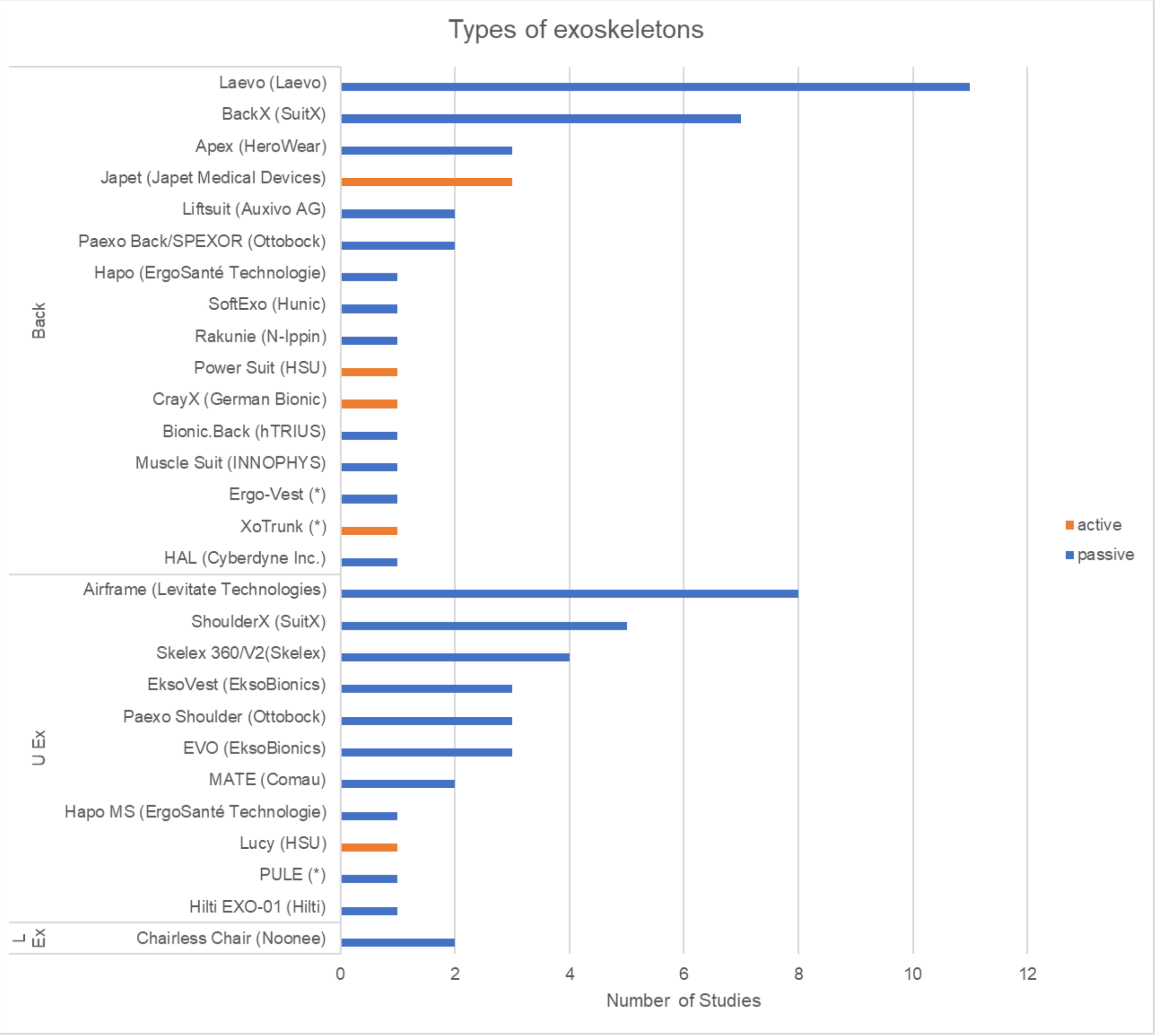

*Figure 3: Types of exoskeletons (blue = passive exoskeletons, orange = active exoskeletons) reported in studies with number of studies that utilized a specific product, sorted according to supported body area (U Ex = Upper Extremities, L Ex = Lower Extremities). *non-commercial*

4.3 Types of outcome metrics

The following Table 3 lists the outcome measures reported in the studies regarding physical, self-reported, use, and other variables and details on how they were recorded.

Table 3. Types of outcomes and measures used in studies. N = number and % = percentage of studies that reported on an outcome.

Outcomes		**N**	**%**	**How was it measured?**
Physical	Muscle activation	12	32%	electromyography
	Physical activity	4	11%	heart rate, steps, energy expenditure and metabolic rate
	Body postures	9	24%	inertial or optical motion capture, accelerometery
Self-reported	Perceived body discomfort	10	27%	Body part discomfort Scale, Cornell Musculoskeletal Discomfort Questionnaire (CMDQ), Borg CR-10 Scale
	Self-Efficacy	2	5%	Task-specific self-efficacy (TSSE), Modified Spinal Function Sort (M-SFS)
	Musculoskeletal complaints	4	11%	Visual analogue scale (VAS), pain inventory, No. of and reason for medical visits
	Perceived workload or task effort	5	14%	NASA Task Load Index (TLX), self-developed questionnaires
	Perceived exertion	5	14%	Rate of Perceived Exertion (RPE)-20 Borg scale, Borg CR-10 scale
	Fatigue	3	8%	pain inventory, self-developed questionnaires
Use	Usage (patterns)	4	11%	observations, self-developed questionnaires
	Usability	19	51%	System Usability Scale (SUS), Usability Metric for User Experience (UMUX)-Lite, self-developed questionnaires
	Acceptance/Satisfaction	4	11%	self-developed questionnaires
	Intention to use	11	30%	Technology acceptance model (TAM), self-developed questionnaires
Other	Productivity	3	8%	open-end survey questions, qualitative interviews or focus groups
	Factors affecting implementation	7	19%	open-end survey questions, qualitative interviews or focus groups

4.4 Physical effects of exoskeletons

4.4.1 Muscle activation

Muscle activation is quantified with electromyography. While this does not allow to measure the force generated by the muscle, it indicates the activity and consequently is a measure of the exertion of the muscle. Thirteen studies analysed the effect of exoskeletons on muscle activation. It needs to be considered that these studies used a variety of variables to quantify muscle activation and performed non-standardized tasks which limits the comparability of the results. Nevertheless, overall there appears to be a reduction in muscle activation during occupational tasks for the M. anterior deltoideus, M. trapezius pars descendens, and M. biceps brachii. Ten out of the 12 studies that analysed muscle activation are reporting a decrease of activation of one or all of these muscles [11–20]. On the other hand, there appears to be little effect of the exoskeleton on the activation of M. erector spinae, M. pectoralis major, and M. latissimus dorsi. Seven studies measured the activity of these muscles and did not find a change with the exoskeleton [11,13–15,17,19,21]. One study, that analysed the activity of M. erector spinae in combination with the M. iliocostalis found a reduced peak and mean activity with the exoskeleton during lifting, carrying, and lowering tasks [22]. In this study, an active exoskeleton was used while most other studies used passive exoskeletons.

A few studies used the same exoskeletons to determine muscle activity, allowing a comparison between the studies. For the Skelex (Skelex, Rotterdam, The Netherlands) exoskeleton, that supports the shoulder/weight of the arms passively, two studies reported reduced muscle activity in the M. trapezius pars descendens during a variety of movements compared to no exo [12,14]. However, while Baltrusch et al. 2023 only found decreased or no change in muscle activation in the M. trapezius pars descendens compared to no exo [12], de Bock et al. 2021 found an increased muscle activation of the same muscle during Squat. However, the muscle activity was rather small during this task (below 25% of MVC) [14].

Investigating the ShoulderX (SuitX, Emeryville, USA), but different versions, all three studies found a decrease in muscle activation or no change compared to no exo [13,14,19]. The ShoulderX is designed as a passive shoulder exoskeleton. While the two studies that investigated applied movements found a decrease in muscle activation at low activity with the ShoulderX [13,19], only one of these studies found the same effect of the exoskeleton at high activity [13]. On the other hand, the study investigating isolated lifting tasks did find reduced maximal muscle activity for certain lifting tasks [14]. It can be assumed that the ShoulderX does have the potential to reduce muscle activity but, again, the generalizability is limited due to the different methodological approaches in the studies.

Another exoskeleton that was analysed by multiple studies was the Levitate Airframe (Levitate Technologies, San Diego, USA) that also provides passive shoulder support. Both studies report a reduction in muscle activity of the M. anterior deltoideus, M. biceps brachii, or M. trapezius but, again, the tasks and specific variables reported differed between studies. Also, not all studies muscles were affected by the exoskeleton.

An interesting fact is that a study comparing isolated to in-field tasks found that the differences between wearing an exoskeleton (Skelex or ShoulderX) and no exoskeleton are reduced during in-field tasks [14]. While this study was performed with only four participants and, therefore, cannot be generalized, it indicates a need to test the exoskeletons during the actual, in-field task to assess their effectiveness in reducing muscle activity.

In terms of determining the effect of the use of exoskeletons on muscle activity during in-field tasks, there are large inconsistencies between studies which diminished the comparability of the studies and make it impossible to draw practical conclusions. There are indications that certain muscles may have a reduced activity when wearing an exoskeleton which could result in a protection against fatigue and reduced forces in the joint. However, since the opposite effect has been reported for antagonistic muscles, this needs to be explored in future research that studies the specific, in-field tasks.

4.4.2 Physical activity

Physical activity was quantified using heart rate and energy expenditure in different tasks. The three studies that compared exoskeletons to no-exoskeletons did not find a clear benefit of the exoskeletons. Both, exoskeletons supporting the back (Apex, Herowear, Nashville, USA; BackX, SuitX, Emeryville, USA; Ergo-Vest, unknown) as well as the arms (EXO-01, Hilti, Schaan, Liechtenstein; EVO, Ekso Bionics, San Rafael, USA; Airframe, Levitate Technologies, San Diego, USA) were tested.

One study did not find a significant difference between wearing a passive, back-support exoskeleton (Ergo-Vest) and no-exoskeleton in terms of energy expenditure and heart rate during waste collection [23]. The two other studies even found an increase in heart rate with the exoskeleton [24,25]. This indicates that the exoskeletons were unable to reduce the heart rate during the in-field tasks tested. Bennett et al. (2023) did report a reduction in time to complete the task in combination with the increased heart rate [25]. The studies used novice exoskeleton users which may be one factor why the exoskeletons did not provide the expected benefit of reduced energy expenditure or heart rate.

One study did report energy expenditure but without a comparison between exoskeletons and no-exoskeleton [26] and was therefore not further analysed.

Given the small number of studies in combination with small sample sizes (between 4 and 20 participants), it is necessary to perform more extensive research before a conclusion on the effects of exoskeletons on physical activity in occupational settings can be drawn.

4.4.3 Body postures

A variety of exoskeletons designed to support the back have been investigated. There are positive effects of the exoskeletons on body posture reported, namely a reduced pelvic tilt during pushing tasks [25], improved neck and low back position [26], or reduced compression forces and moments at the spine [23]. However, for other tasks the results were either inconclusive [25] or showed a worsening in body position with the exoskeleton [26]. This agrees with the study by Ralfs et al. (2023) that studied 17 different exoskeletons. They concluded that exoskeletons that are designed to support the back can alter the range of motion and movement behaviour of different segments, but the amount of change depends on the functionality of the exoskeleton [18]. The study by Onofrejova at al. (2022) provides an interesting insight. The position of the worker was altered by the exoskeleton, but the workplace had not been adjusted accordingly. This led to reduced ergonomics at the shoulder [26]. This indicates that with the introduction of exoskeletons, workplaces need to be (re-)assessed for ergonomics.

One study compared two different control strategies for the same, active exoskeleton and found that the control strategies may alter the body position differently [22]. Consequently, an assessment of an exoskeleton is only valid for the analysed control strategy. However, since only very few exoskeletons are active, this is less of a concern.

There was also a variety of exoskeletons designed to support the upper extremities studies. Even though the studies investigated different products, they agreed in the fact that exoskeletons may reduce the range of motion of the shoulder, neck, or low back which indicates a restriction of movement [16,19,25]. In order to allow for the work task to be completed, it needs to be analysed if a reduced range of motion allows to perform the work task in an ergonomic setting or if the workplace needs adjustment.

Overall, no exoskeleton was analysed by multiple studies indicating the strong need for further research with these exoskeletons. And similarly to the studies investigating muscle activity, there was a variety of analysed body regions and variables related to body posture. Consequently, more research is necessary that allows a comparison between studies to generalize results.

4.5 Subjective effects of exoskeletons

4.5.1 Perceived body discomfort

Ten studies analysed the perceived body discomfort when wearing the exoskeleton. Three studies reported that the perceived discomfort was low when working with the exoskeleton [11,20,27].

Other studies showed no clear results on discomfort [28], or mixed results: Hensel et al. reported decreased discomfort for lower back and wrists with the Laevo exoskeleton (because participants did not lean forward onto the wrists anymore) but increased discomfort for chest and thighs with high effect sizes [29]. For the chairless chair, study participants noted a perceived discomfort in shoulders, upper arms and hands, but also the feet, lower back and neck, due to the altered body positioning (neck due to sitting lower and feet due to a higher ankle dorsal extension with the legs tied to the chairless chair) [30]. Two studies on the BackX observed increased discomfort for chest, back, upper arm and shoulder with continuous use, although not statistically significant [31,32]. This illustrates that while the discomfort when wearing an exoskeleton was often perceived as low, attention needs to be paid to the potential of increased discomfort at body parts, where the exoskeletons are attached to the users.

4.5.2 Self-efficacy

Self-efficacy was evaluated by two studies. Baltrusch et al. [33] showed a significant difference in self-efficacy scores (7%) between baseline and post-trying exoskeleton scores. In this study, 28% of participants rated higher self-efficacy scores, 60% of the participants reported small or no change in self-efficacy and 12% rated lower self-efficacy scores and most participants rated higher self-efficacy after try-out for the task static forward bending, followed by lifting, repetitive bending, standing and walking. Siedl & Mara [34] showed that on average, pre-test self-efficacy scores (Median = 4.50) exceeded post-trial scores (Median = 4.25), but statistically the positive effect of an exoskeleton on self-efficacy could not be confirmed. They did however find indications of an interaction effect between baseline self-efficacy, perceived physical relief and perceived usefulness – meaning that workers who experienced relief and usefulness were more likely to report growth in self-efficacy beliefs. No clear conclusions can be made based on these two studies with inconclusive evidence.

4.5.3 Musculoskeletal Complaints

Four studies [24,35–37] reported on musculoskeletal complaints, using different measures ranging from subjective pain ratings, subjective rating of musculoskeletal health, to number of medical visits. Three studies reported positive effects of the exoskeleton on musculoskeletal complaints: Kim et al. [35] showed a decrease in probability of a medical visit by 52% when exoskeleton was used. Liu et al. [36] noted a 70% decrease in pain scores collected with the pain inventory on average when surgeons used a shoulder exoskeleton compared to without. Participants in the study of Marino et al. [24] rated a median 4 [IQR 4, 5] out of 5 regarding the agreement that the device helped manage their musculoskeletal health, but no standardized measure was used and no pre-post comparison provided.

One study [37] analysed a group of workers with specific low back pain and one group with non-specific low back pain separately: for the first group, a significant difference between the median value of the difference of VAS index between last and first working day of each week was found. For the second group with non-specific low back pain no difference was found.

4.5.4 Perceived exertion

We distinguish between perceived exertion and perceived effort in the scope of this review because these perceptions are different psychological constructs, albeit related and often used interchangeably in the literature. Five of the included studies captured perceived exertion in a way that it meets the definition of “the degree of heaviness and strain experienced in physical work”, with the scale suggested by Borg ([38], p. 8). Three studies [12,20,23] used the original Borg Rating of Perceived Exertion (RPE) 6-20 Scale and two studies used the Borg CR-10, a Category-Ratio (CR) scale [17,39]. The original Borg RPE Scale ranges from 6 (no exertion at all) to 20 (maximal exertion). The Borg CR scale contains 10 points from 1 (rest) to 10 (maximal exertion). Studies varied in how perceived exertion was conceptualized, some regarded global exertion [23], others local exertion, i.e. only upper limb [20] or dominant/non-dominant extremity [12], or task-specific rate of exertion [17,20]. Ziaei et al. [23] reported a statistically significant reduction of global perceived exertion with the ErgoVest, however the exertion was overall high for the tasks studied with or without wearing an exoskeleton. Similarly, Schröder Jakobsen et al. [39] found a significant decrease in perceived exertion with the ShoulderX compared to without. Pacifico et al. [17] found a significant reduction in exertion of 16% for all tasks investigated. Two studies [20,33] had mixed results with significant reductions in mean rate of perceived exertion for some of the investigated tasks, but not all. These results indicate that there may be a positive effect of wearing an exoskeleton on perceived exertion, but not necessarily for all work tasks.

4.5.5 Perceived effort or workload

Effort has been operationally defined as “the conscious sensation of how hard, heavy and strenuous a physical task is” ([40], p. 380)
Five studies analysed the perceived workload or effort of a task when wearing an exoskeleton. Workload or effort were measured using the NASA-TLX questionnaire [14,25], items from the psychological climate and effort measures questionnaire [28] or self-developed questions [41,42], e.g. “Do you feel the physical burden was reduced?”. The results were either inconclusive [25,41,42] or showed no significant differences in perceived effort between working with and without the exoskeleton [28]. Results differed between the investigated exoskeletons and tasks. One study [25] reported that for one task (pushing gondola) the physical and mental demand measured with the NASA-TLX were lower with than without the exoskeleton, but for another task (installing block) the demand was rated higher for Hilti (mental demand) and Ekso (physical

demand). A second study using the NASA-TLX found that most categories were not influenced when using the ShoulderX and Skelex compared to no exoskeleton. Nurses using a back exoskeleton had high agreement that the physical effort was reduced (100% for Muscle Suit, 66% for HAL) and moderate agreement that the mental burden was reduced (61% for Muscle Suit, 50% for HAL)[41]. DeVries et al. [42] found a reduction in experienced load for three tasks but with small effects, but for other tasks no significant effects of exoskeleton use on experienced load was found. Overall, the results on perceived physical effort appear inconsistent, amplified by an inconsistency in terminology (effort, load, burden) and used measures. The existing studies provide no indication that wearing an exoskeleton reduces perceived mental effort or burden.

4.5.6 Fatigue

Fatigue was an outcome in three studies, measured by an item of the pain inventory [36] or subjective rating of work-related fatigue [24,43]. In one study [43], the median impact of a back exoskeleton on nurses fatigue was rated 7 out of 10. Marino et al. [24] reported agreement on reduced work-related fatigue 4 of 5 [IQR 4, 5] for a back exoskeleton and somewhat agreement on reduced work-related fatigue 4 [IQR 3.5, 5] with a shoulder exoskeleton. In a static holding task during surgery, Liu et al. [36] found a statistically significant lower fatigue score with the Airframe (Levitate Technologies). As only the last-mentioned study offers a pre-post comparison, no conclusions about the effects on fatigue can be drawn.

4.6 Use and implementation

4.6.1 Usage

Four studies reported on usage or use patterns, when participants were allowed to decide the exoskeleton wear time themselves. With the Skelex in construction, de Vries et al. [42] found a significant difference in exoskeleton use between different tasks: the highest usage was reported for tasks performed at the ceiling. Kato et al. [41] collected wear time for two exoskeletons on two separate nursing units. The unit that had the Muscle Suit (INNOPHYS) wore the exoskeleton for 131 min/day of a total work time of 1431 min/day, corresponding to 9% of total work time of unit. The unit that had the HAL (Cyberyne Inc.) wore the exoskeleton for 129 min/day of a total unit work time of 1168 min/day, corresponding to 11% of total work time of unit. On both units, the exoskeleton was mainly used for direct patient care, e.g. transfer assistance, toileting and meal assistance with static forward leaning.
Smets et al. [27] reported high wear time of a shoulder exoskeleton in workers in an automotive assembly, when provided with access to the EVO (EksoBionics): participants chose to wear the device for a mean of 86% of their work shift, i.e. a mean of 7.7h per day (6.4-84).

Jakob et al. [44] identified tasks for which forestry workers would consider using the exoskeleton: felling timber, mechanic work and bending and lifting.

4.6.2 Usability

Usability is a core concept in human-computer-interaction and was measured in more than half of the included studies (n=19). The term can be defined as “the effectiveness, efficiency, and satisfaction with which specified users can achieve goals in particular environments” [41, p. 2]. Since the construct “usability” cannot be operationalized directly [46], studies measured different aspects of usability, such as satisfaction, ease of use, attitudes and perceptions, complexity etc., mostly with self-developed questionnaires. Standardized scales or questionnaires used to capture usability were the (extended) System Usability Scale (SUS) in three studies [11,17,23], the UMUX-Lite (Usability Metric for User Experience) in two studies [29,30], the Questionnaire for the Evaluation of Physical Assistive Devices (QUEAD) in one study [39], and the German Technology Usage Inventory in one study [47].

The few studies (n=2) that did a repeated measurement over the study period interestingly found a decrease in usability scores. Schroder-Jakob et al. [39] found a significant decrease from pre-to post-test in perceived usefulness, emotions, attitude and comfort with the QUEAD, however the ratings decreased regardless of whether the subjects were in the exoskeleton group or not. In another study [29], the UMUX-Lite score significantly decreased in the aspects donning and doffing (at static workplaces) and execution of tasks (in static and dynamic workplaces), while the score for donning and doffing at dynamic workplaces remained stable. Schwerha et al. [48] reported stable usability ratings between two sessions, but with an improvement in ratings regarding balance, overall comfort and fit and range-of-motion in the second exoskeleton session. Smets et al. [27] showed that thermal discomfort declined by 15% and range of motion scores improved by 22% accompanied by slight gains in self-reported task performance.

All three studies using a version of the SUS scale found the scores to be above [17,23] or just below [11] the threshold value considered acceptable for usability, i.e. above 4 on a 7-point Likert scale for the extended SUS and 70/100 for the SUS scale.

The remaining studies reported the median ratings on different Likert scales for global usability or aspects of it, i.e. comfort, ease of use etc. with a tendency to report moderate to good ratings [12,15,24,31,32,37,43,49]. The ratings cannot be compared directly, as different scales were used. The following concerns regarding usability, that were raised by study participants, were reported:

- Thermal discomfort/overheating [22,27,35,37,43,49]
- Not sufficiently discreet [43,50]
- Not sufficiently hygienic [43]
- Balance [35,48]

- Range of motion [35,48]
- Weight and bulkiness [22,33,37]
- Hindrance of movement or other activities, e.g. driving [22,26,42,48]
- Time for donning and doffing [35,51]
- Compatibility exoskeleton and tool kits/safety harness [31,43]

4.6.3 Intention to use

“Intention to use” can be seen as one aspect of usability, but since it was regularly reported separately in the included studies, we present it separately. Intention to use was captured in eleven studies using different measures. Most studies tried to capture intention to use with questions like “Would you use the exoskeleton in the future?” Four studies reported that at least 50% or more of the study participants would use the tested exoskeleton in the future [35,36,42,50], and two studies found 100% of study participants would use the exoskeleton if provided in the future [24,27]. Studies using scores reported moderate agreement with “I intend to use it in the future”, e.g. 5 on a 7-point-Likert scale (1 – do not agree; 7 – completely agree) [17,47,49].

One study on the Laevo [29] found a significant decrease in the intention to use the exoskeleton from begin to end, measured with the UMUX-Lite. The intention to use in this study was influenced negatively by perceived discomfort in body parts where the exoskeleton was in contact with the user and influenced positively by usability. In the 18-month field study by Kim et al., perceived job performance, as well as overall fit and comfort appeared to be key determinants of intention-to-use [35].

Although the results from the different studies cannot be directly compared, we see a trend towards workers being open to continue using exoskeletons in the future. Aspects such as usability and comfort may influence the intention to use a given exoskeleton.

4.7 Other

4.7.1 Productivity

Factors to quantify or describe productivity address “the ability of a device to assist in doing a task better, achieve more in a shorter time, or produce greater work output” [51]. Three studies reported on such factors. The time to complete a specific task was reduced (due to sample size, no statistical analysis was performed) when wearing the Apex (Herowear) for pushing a construction gondola or the Hilti Exo-01 (Hilti) or the EVO (Ekso Bionics) for installation [25]. With the Airframe (Levitate Technologies), no statistically significant differences in the time to completion was reported for surgical tasks [36].

One study addressed productivity qualitatively and reported that some farm workers reported that they assumed they would be able to perform more work and with less fatigue with the exoskeleton compared to no exoskeleton. However, due to the fact that the tested exoskeleton was task specific (Laevo, Laevo BV), they also reported the need to don and doff the exoskeleton depending on the task which would slow them down [51].

Overall, there is only very little information on a small selection of exoskeletons and for very few tasks in relation to productivity. Consequently, no conclusions on the effect of exoskeletons on productivity at work can be drawn.

4.7.2 Factors affecting implementation and adoption

Studies reported different factors that affected the implementation and adoption of the exoskeletons. These factors can be categorized as design barriers, working conditions, individual factors, environment, safety, individual preferences, social factors, and implementation characteristics (Table 4).

Table 4. Factors that were reported in studies as affecting implementation and adoption of exoskeletons

Category	Description	Studies
Design	• Misfit between exoskeleton and required movements, e.g. bending with a metal torso, shoulder straps uncomfortable for certain movements • Wish for a single device with both shoulder and back support • Discomfort • Weight, rigidity, bulkiness • Compatibility with tools • Donning and doffing • Unidirectional support, i.e. for movements in contrary directions the user has to “work against the system”	[18,33,44,48,52]
Working conditions	• High workload • Performance-based payment, e.g. piecework • Short-term employment (e.g. seasonal) • Language barriers due to foreign work force	[33,52]
Individual factors	• Experience of back pain • Wish to prevent musculoskeletal problems • Height/weight/sex excluding from exoskeleton use	[32,52,53]

	• Work preferences	
Environmental factors	• High temperature • Being outside	[31,52]
Safety	• Integration with safety harness • Risk of getting stuck or caught with exoskeleton • Risk of patients holding onto exoskeleton • Trustworthiness and risk of malfunction	[32,48,50]
Implementation characteristics	• Inclusion of workers from the start • Participation of staff at different levels • Challenges to predict for which tasks exoskeleton would be useful • Concerns that exoskeletons requires additional time for maintenance	[51,52]
Social factors	• Criticism or judgement from colleagues/patients • Negative effects on patient/carer relationship	[44]

4.8 Limitations and learnings

Table 5 summarizes the study limitations reported by the study authors. Main limitations regarding the sample reported by study authors were a small sample size (37%), followed by the samples consisting mainly or exclusively of male workers (16%). Nine (24%) studies also stated the missing long-term assessment of the exoskeleton in the field as a limitation.

Recommendations and learnings provided by the authors consequently focussed on the need to assess long-term effects of exoskeletons on health outcomes [13,18,28,54], such as the incidence of musculoskeletal disorders or pain, and on work quality and productivity [15,54]. Additionally, authors called for increasing the sample sizes and diversity of study participants, specifically by including more women [25,53] to also be able to stratify samples and investigate influencing factors such as age, sex, or body type. Other recommendations centred around the design of the devices: relevant specification depending on the occupational context should be defined, e.g. in healthcare or farming, [43,55], exoskeleton design should better accommodate a range of different body types and address several issues regarding discomfort, such as thermal regulation [34,50].

Table 5. Reported limitations from authors' perspectives. N = number and % = percentage of studies.

	Description	N	%
Sample	Small sample size	14	38%

	All or majority male	6	16%
	Selection bias towards workers with interest in exoskeleton	3	8%
	High variability in sample, e.g. regarding back pain diagnosis, height	2	5%
	Limited geographical region	1	3%
	Varying sample sizes	1	3%
	Specific cultural context	1	3%
	Limited experience on the job	1	3%
Design	No long-term evaluation of exoskeleton use	9	24%
	No pre-post exoskeleton comparison	2	5%
	No randomization	2	5%
	No blinding of control group	1	3%
Procedures	Exoskeleton not evaluated over a whole work cycle	1	3%
	Workload not controlled for	1	3%
	Short training phase with exoskeleton	3	8%
	Simulated/standardized work tasks only	2	5%
	Low adherence to exoskeleton protocol	1	3%
	Timing of outcome measure, e.g. exertion only at the end of each shift	1	3%
Outcomes	Important outcomes not evaluated, e.g. productivity, use patterns, objective outcome metrics, psychosocial factors	4	11%
Analysis	Missing data, e.g. through irregular work shifts or sensor errors	3	8%
Exoskeleton	Use of specific exoskeleton not suitable for women, e.g. due to chest plate	2	5%
	Exoskeleton is heavy	1	3%

5 Summary of the expert workshop

The workshop discussed the findings of the literature review to explore aspects that affect the successful implementation of exoskeletons at the workplace and expert gave recommendations on introducing and evaluating these technologies in the workplace.

Regarding the findings of the scoping review, experts gave their feedback on study designs, exoskeletons used and the subjective and objective outcome measures. Muscle activation should be evaluated across the entire body, as exoskeletons can reduce strain in one area but increase it in others. Usability may also depend on whether the exoskeleton is a prototype or a finished product, and ease of donning/doffing is crucial for actual usage. User acceptance and appropriateness, central to successful implementation, are often not thoroughly measured; standardized questionnaires exist but are underutilized. The perceived benefit of exoskeletons is key to their adoption, requiring qualitative data like user-centred interviews, especially in clinical settings. Long-term studies are necessary to understand long-term impacts. Active exoskeletons provide greater force but also pose higher risks, whereas passive ones are safer due to less complexity.

Regarding the implementation of exoskeletons at the workplace, it was emphasized that workplaces should be assessed for possible ergonomic improvements before introducing exoskeletons. Habitual tasks and self-efficacy of affected workers are important considerations; forced changes can reduce perceived competence, so introducing exoskeletons should enhance, not hinder, worker capabilities. Exoskeletons need to be adjusted to each individual user and therefore shared use is impractical. Increased productivity from exoskeleton use should be approached cautiously, particularly in work environments presenting high musculoskeletal risk.

6 Discussion

In the following, the findings of this literature review are discussed and expanded on. Section 6.1 synthetises the results of this review and previous systematic reviews on the topic with the recommendations from the expert workshop. Section 6.2 summarizes existing best-practice guidelines and section 6.3 provides a discussion of the strengths and limitations of this review.

6.1 Main learnings and recommendations

6.1.1 Evaluation of exoskeletons in field studies

- (Long-term) effects of exoskeleton: A preventive effect of exoskeletons on musculoskeletal complaints is not sufficiently proven in the scientific literature to date, neither in terms of primary prevention nor in terms of secondary or tertiary prevention in workers who already have musculoskeletal conditions. Long-term studies are necessary to understand the sustained impact and benefits of exoskeleton use. Currently, no long-term controlled studies investigating the incidence of work-related musculoskeletal conditions have been performed. The majority of studies in this review evaluated short field periods ranging from a few hours to a few days or weeks. Only two articles (reporting on data from the same project) had a long field period of 18 months [28,35]. The lack of long-term studies may be explained by the increased complexity and resource-demand of this study design, and the introduction of exoskeletons into the workplace being rather recent. It has also been suggested, that participant rejection of the intervention presents a major barrier to successfully conducting long-term trials in agriculture [52].

- Types of exoskeletons: Active exoskeletons exert more force on the body, which could increase the benefits in terms of strain relief but also possible risks due to the force generated by the exoskeleton. Passive exoskeletons are typically safer due to the lack of mechanical force application, lower weight, and complexity. To date, passive back-support and upper-limb devices account for the majority of exoskeletons evaluated in field studies. This reflects the overall state of the evidence, with passive exoskeletons being researched more frequently than active exoskeletons in laboratory studies [56]. Similarly, this review provides little information on active exoskeletons, as only 5 studies investigated those. The results on passive exoskeletons cannot be transferred to active exoskeletons. The limited evidence combined with the higher risk profiles of active exoskeletons warrants use with caution.

- Objective outcomes: Regarding the muscle activation and perceived load, experts emphasized the importance of evaluating not only the muscles supported by the exoskeleton, but ideally the entire body, as exoskeletons might alleviate strain in one area but increase the load on other body parts. Metabolic cost demand (heart rate) was assessed in only three of the included studies. Estimation of metabolic cost via oxygen consumption or heart rate may help to obtain an estimate of the overall impact of work on the exoskeleton user [57].

- Subjective outcomes: Although subjective feedback or self-reported outcomes have been collected in most studies, the trials often were too short to allow a thorough assessment of variables that need time to develop, such as discomfort or fatigue. Additionally, these outcomes were seldomly measured thoroughly and systematically. In line with previous literature [57], we have identified potential to integrated standardized scales, such as the Borg RPE scale, or questionnaires, such as the Cornell Musculoskeletal System Discomfort Questionnaire (CMSDQ), NASA-TLX, and Modified Spinal Function Sort. Simple methods, such as visual inspections, e.g. using observational checklists such as *Rapid Upper Limb Assessment (RULA)/Rapid Entire Body Assessment (REBA)* could be beneficial for affordable evaluation, as suggested by Kuber et al. [57]. The benefits of using an exoskeleton as perceived by the users are critical. Qualitative data, such as user-centred interviews, can help assess these benefits.

- Usage: Usability aspects, such as the ease of donning and doffing the exoskeleton is crucial to ensure that workers are willing to wear it. Observations on the actual usage of exoskeletons can indicate their practicality in the workplace, i.e. an exoskeleton that is stored far away from the actual workstation may mean, that it is not regularly in use. The usability of an exoskeleton varies greatly depending on whether it is a prototype or a fully developed product. This should be taken into consideration when interpreting study findings.

6.1.2 Implementation of exoskeletons in the workplace

- Habit and Self-Efficacy: Workers' habitual nature and the repetitive nature of their tasks can make forced changes challenging. The introduction of exoskeletons should emphasize the enhancement of work ease without undermining workers' perceived competence.

- Adjustment and fit of exoskeletons: Exoskeletons must fit the wearer well, and development should ideally consider anthropometric data that covers a broad population range. However, this is not always feasible as a) it is necessary in the early development stages to choose the norm body as a starting point, and b) increased adjustability will also result in the exoskeleton being heavier and more complex. In practice, exoskeletons should be considered as personal protective equipment and therefore individually adjusted for each user. This would imply that shared use of exoskeletons is less feasible and/or desirable.

- Productivity: While the prospect of increased productivity because of the exoskeleton is promising from the employers' perspective, caution is warranted specifically for workplaces with high musculoskeletal risks. Increasing the productivity while physical strain, with the help of the exoskeleton, remains stable, is not in the best interest of workers.

6.1.3 Assessment of workplaces with exoskeletons

- Safety vs. Health: Workplaces with exoskeletons should be assessed regarding both the safety and the health implications. Pressure points and discomfort at the exoskeleton-human interfaces frequently occur. Depending on the activity and the exoskeleton model, musculoskeletal strain and stress in other body regions may increase. Potential hazards introduced by the exoskeleton, such as restrictions on movement, risk of falling, or risk of snatching, need careful consideration.

- Workplace assessment regarding ergonomics: Before the introduction of exoskeletons into the workplace, it's crucial to assess if the work environment can be made more ergonomic by other means. Implementing an exoskeleton should not be driven by trends but by genuine need.

- After the implementation of exoskeletons in occupational settings, a second ergonomic workplace assessment may be necessary as body postures may change with an exoskeleton. For example, kinematic results in the study by Onofrejova et al. [26] showed that the table height needed readjusting when using the chairless chair to avoid increased strain on the upper extremities at the work stations.

6.2 Best practice principles and recommendations

Due to the absence of evidence, making recommendations for the selection and implementation of appropriate exoskeletons in specific application contexts remains complex. Consequently, aids and guidelines have been devised to assist practitioners. In the following section, guidelines or frameworks identified in the scope of this literature review will be shortly presented. Ralfs et al. [58] presented a decision-support matrix that facilitates the characterization of support scenarios by aligning task properties, work profiles, and system characteristics, along with a procedure for implementing exoskeletons based on pivotal indicators [59].
Golabchi et al. [60] developed an industrial adoption framework consisting of six stages: feasibility assessment, task selection, exoskeleton selection, implementation logistics, trial phase and long-term adoption. However, the framework has not been implemented in an industrial setting for long-term validation yet. The German Society for Occupational and Environmental Medicine (DGAUM Deutsche Gesellschaft für Arbeitsmedizin und Umweltmedizin) published several recommendations on the use of exoskeletons in the occupational setting in a S2k-Guideline [61]. The evidence behind the recommendations of this guideline correspond to the findings of this review, e.g. regarding the necessity of adaptability of the exoskeleton to the individual user or the need for a safety evaluation.

6.3 Methodological consideration

The overview presented in this review provides an up-to date scope of existing research around the implementation of exoskeletons in occupational settings, ranging from manufacturing, agriculture to healthcare workplaces. While original studies that yield empirical evidence were included in this review, we also sighted conference abstracts and grey literature, such as manufacturers websites, for additional evidence. Scoping reviews provide an opportunity for stakeholder consultation, which was done here in the form of an expert workshop to discuss and confirm findings from the review and elaborate on issues and future direction of exoskeleton implementation.

Although the search strategy was reviewed and deemed comprehensive by the research team and a librarian, it cannot be excluded that relevant articles were missed e.g. due to the variety of terms used to describe the occupational settings.

Clustering the evidence further, e.g. by exoskeleton type (active, passive), settings, or workplace types (static, dynamic) might have provided additional value, but exceeded the scope of this project.

In a scoping review no rating of the quality of evidence is provided, therefore implications for practice or policy cannot be graded.

7 Conclusion

The current focus of research and implementation in the field of occupational exoskeletons lies on passive back- or upper-limb support devices in industrial manufacturing. Based on the evidence identified in the scoping review, there are indications that supported muscles may have a reduced activity when wearing an exoskeleton which could result in a protection against fatigue and reduced forces in the joint. However, because of the diversity in outcome measures, small sample sizes and lack of long-term follow-up in field studies, it remains unclear whether exoskeletons have any preventive effect on musculoskeletal disorders in manual workplaces. Evaluations of subjective outcomes indicate that workers are often open towards using an exoskeleton, but usability, comfort of the device, organizational factors influence the acceptance or intention to use. No conclusions regarding psychosocial or work-related effects, such as productivity, can be drawn from the few studies investigating these outcomes. There is an apparent need for more scientific evaluations with longer field periods and standardized outcome measures.

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8 Appendix

8.1 Characteristics of included studies

Author & Year **Design**	**Country**	**Sample**		**Sex**		**Age (in years)**		**Height (in cm)**		**Weight (in kg)**		**Occupational setting**	**Exos evaluated**	**Aim**
			n	m	f	M	SD	M	SD	M	SD			
Arnoux 2023 [11] Field Study	France		7	6	1	36.6	8.8	178.9	5.3	85.1	8.9	Healthcare with simulated occupational tasks	Hapo MS (ErgoSanté Technologie)	to analyse the influence of wearing an upper limb exoskeleton on healthcare workers during a task with high repetition, e.g. a surgical tool cleaning task
Baltrusch 2021 [33] Mixed-Method study	Netherlands		19	n.r.	n.r.	43.4	7.3	175	7	82	14	Manufacturing, Logistics	SPEXOR (Ottobock)	to assess the effect on self-efficacy and to assess acceptability of the exoskeleton and explore potential of the device to change behaviour in workers with low back pain
Baltrusch 2023 [12] Experimental study	Netherlands		11	11	0	47	11.8	179	5.6	81	10.8	Construction	Skelex (Skelex)	to determine the potential of wearing an arm-support exoskeleton to support ceiling construction
Bennett 2023 [25] Pilot study	United States		4	4	0	45	14.4	178.9	14.4	95.3	8	Construction	Apex (HeroWear), EVO (Ekso Bionics), Hilti EXO-01 (Hilti)	to investigate, in field settings, the potential usability issues of a passive back-support EXO for completing the task of pushing and emptying a gondola

Dalbøge 2024 [13]	Denmark		26	26	0	35.8	10.2	175.7	8.2	76.2	13.7	Slaughterhouse	ShoulderX (SuitX)	to evaluate the effect of a passive shoulder exoskeleton on muscle activity among slaughterhouse workers and to compare the effect of the shoulder exoskeleton with a lifting glove currently used in the slaughterhouse
Field study														
DeBock 2021 [14]	Belgium		4	4	0	33.4	5.7	179	2	80.9	5.8	Logistics	ShoulderX V2 (SuitX), Skelex V2 (Skelex)	to investigate the effectiveness of two shoulder exoskeletons by assessing the physical load on the human operator during real-life working situation
Field study														
deVries 2023 [42]	Netherlands		39	39	0	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Construction	Skelex (Skelex)	to analyse the use of an arm-support exoskeleton and the perceived experiences of plasterers over a 6-week field period
Field study														
Elprama 2023 [53]	Belgium		n.a.									Manufacturing, Construction	Laevo (Laevo), BackX (SuitX)	to identify different types of users and non-users of occupational exoskeletons
Qualitative research														
Farah 2023 [43]	France		14	2	12	33.3	6.2	n.r.	n.r.	n.r.	n.r.	Healthcare	Japet (Japet Medical Devices)	to investigate how to maintain posture and to reduce pain and fatigue for nurses with an exoskeleton
Pilot study														
Gillette 2019 [15]	United States		6	4	2	41	7	171	8	76	11	Manufacturing	Airframe (Levitate Technologies)	to perform an EMG-based ergonomic assessment for a passive upper body exoskeleton, when used by workers during on-site job tasks at manufacturing facilities
Field study														

Gonsalves 2023 [62]	United States		8	8	0	30.6	n.r.	n.r.	n.r.	n.r.	n.r.	Construction	BackX (SuitX)	to assess a passive back-support exoskeletonfor concrete work in terms of the impact on the body, usability and benefits of the exoskeleton, and potential design modifications
Qualitative research														
Gonsalves 2023 [63]	United States		14	14	0	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Construction	BackX (SuitX)	to assess a back-support exoskeleton for pipework in terms of user perception, level of perceived discomfort (LOD), and usability
Mixed-Method study														
Hensel 2018a [64]	Germany		30	30	0	29.2	10.6	175.3	6.5	76	9	Automotive	Laevo (Laevo)	to evaluate an exoskeleton in production and logistics of AUDI in terms of perceived strain reduction, ease of use and usability
Field study														
Hensel 2018b [49]	Germany	Study 1	18	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Automotive	Laevo (Laevo)	to present the challenges of three field studies at AUDI AG of the implementation of exoskeletons
Field study		Study 2	10	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.		Chairless Chair	
		Study 3	8	8	0	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.		Airframe (Levitate Technologies), Paexo Shoulder (Ottobock)	
Iranzo 2020 [16]	Spain		12	11	1	35	5	175.2	5.3	73.9	4.9	Automotive	Airframe (Levitate Technologies)	to evaluate the protective capacity of an upper extremity exoskeleton for the worker in automotive assembly lines
Field study														
Jakob 2023 [52]	Germany		n.a.										Liftsuit (Auxivo AG), Apex	to detect success and failure factors for the implementation
Mixed-Method study														

												(HeroWear), Hapo (ErgoSanté Technologie)	of passive exoskeletons in agriculture
Kato 2021 [41]	Japan	Group A	18	11	7	38	9	n.r.	n.r.	n.r.	n.r.	Healthcare	MS Muscle Suit (INNOPHYS)	to examine care tasks and operations in two nursing facilities in which two exoskeletons are used on a daily basis
Mixed-Method study		Group B	7	3	4	39	15	n.r.	n.r.	n.r.	n.r.		HAL (Cyberdyne Inc.)	
Kim 2021 [28]	United States	Exo	41	30	3*	38	15	178	10	83.9	21.5	Automotive	EksoVest (EksoBionics)	to examine the effects of arm-support exoskeleton use on perceived physical demands during over-head work at nine automotive manufacturing facilities
Longitudinal study		Control	83	47	14*	38	15	175	10	86.2	23.5			
Kim 2023 [44]	United States		22	21	1	40.1	13.3	n.r.	n.r.	n.r.	n.r.	Forestry	Laevo (Laevo)	to quantify biomechanical stress of timber fellers and assess forestry professionals' awareness and acceptance of exoskeletons
Field study														
Kim 2022 [35]	United States		*41*	*30*	*3**	*38*	*15*	*179*	*10*	*83.9*	*21.5*	Automotive	EksoVest (EksoBionics)	to examine arm support exoskeletonsuser experience over time, identify factors contributing to intention-to-use, and explore whether ASE use can contribute to positive health outcomes
Longitudinal study			*83*	*47*	*14**	*38*	*15*	*175*	*10*	*86.2*	*23.5*			
Liu 2018 [36]	United States		20	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Healthcare	Airframe (Levitate Technologies)	to evaluate the feasibility and efficacy of a non-intrusive progressive arm support exosuit worn by surgeons
Field study														

													under the sterile gown to reduce pain and fatigue during surgery
Marino 2019 [24]	United States		14	11	3	25–47		162-185		62-121		Logistics (sales)	Airframe (Levitate Technologies), BackX (SuitX)	to determine if low back-assist exoskeletons and shoulder-assist exoskeletons could help reduce physiological fatigue among stockers and tire installers
Field study														
Moulart 2022 [37]	France	Group A	30	25	5	42.6		79.8		176.5		Logistics, Healthcare, Automotive	Japet (Japet Medical Devices)	to subjectively quantify the impact of a lumbar exoskeleton on low back pain, in a real work situation
Field study														
Omoniyi 2020 [51]	Canada		15	14	1	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Agriculture	Laevo (Laevo)	xplore farmers' perceptions of the feasibility and practicality of exoskeleton use in prairie grain and livestock farm operations
Qualitative research														
Onofrejova 2022 [26]	Slovakia		4	3	1	51.5	8	84.5	3.5	174	7.2	Manufacturing	Chairless Chair 2.0 (Noonee)	to evaluate the ergonomic risk of using wearable systems by assessing physical workload
Experimental study														
Pacifico 2023 [17]	Italy		10	6	4	40.5	13.9	172	7	78	14	Cleaning	MATE (Comau)	to investigate the in-field efficacy, usability, and acceptance of a spring-loaded upper-limb exoskeleton in cleaning job activities
Field study														
Poliero 2021 [22]	Italy		10	5	5	29.4	4.5	172	10	67.5	15.7	Manufacturing	XoTrunk (*)	to understand the advantages that a versatile exoskeleton has with respect to a non-versatile one, regarding the ability to reduce muscle activation (efficacy) and on its user interaction (dynamic fit)
Experimental study														

Raghuraman 2023 [65]	United States		22	20	2	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Manufacturing, Logistics	EVO (EksoBionics), Airframe (Levitate Technologies), Paexo Shoulder (Ottobock), ShoulderX (SuitX), BackX (SuitX), Laevo (Laevo), Paexo Back (Ottobock)	to compare manufacturing stakeholder perceptions of EXO adoption factors pre-EXO and post-EXO exposure
Qualitative research														
Ralfs 2023 [18]	Germany		n.a.									Logistics	Lucy (*), SoftExo (Hunic), Rakunie (N-Ippin), PowerSuit (*), CrayX (German Bionic), Bionic.Back (hTRIUS), Paexo Shoulder (Ottobock), MATE (Comau), Chairless Chair	(KQ1) How can exoskeletons be evaluated sufficiently and in a structured manner? (KQ2) What recommendations can be derived for using exoskeletons in industrial workplaces?
Mixed-Method study														

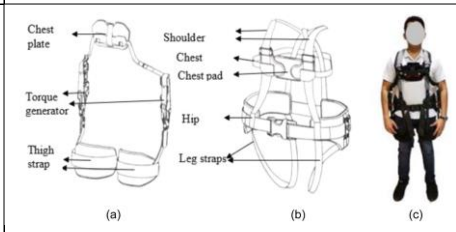
													(Noonee), Liftsuit (Auxivo), Apex (Herowear), Laevo (Laevo), Airframe (Levitate Technologies), Japet (Japet Medical Devices), BackX (SuitX), ShoulderX (SuitX), Skelex (Skelex)	
SchrøderJakobsen 2023 [19] Field study	Denmark		20	19	1	31.6	7.7	181.1	8.6	84.9	13.6	Logistics	ShoulderX (SuitX)	to investigate how a 5-week familiarization period of exoskeleton use can be beneficial to the user in terms of biomechanical changes, acceptance, and usability
Schwerha 2022 [48] Field study	United States		15	14	1	35.7	8.8	180	10.1	92.8	19.4	Manufacturing	Airframe (Levitate Technologies), Laevo (Laevo), BackX (SuitX), EksoVest (EksoBionics)	to gather worker feedback on different EXOs after using them during their actual jobs and to understand what contributes to EXO-use-intention in manufacturing companies;
Siedl 2021 [47]	Austria		31	28	3	35.4	10.9	n.r.	n.r.	n.r.	n.r.		Laevo (Laevo)	

Field study												Manufacturing, Logistics		to explore the effects of exoskeleton use on task-specific self-efficacy beliefs of logistics workers and to relate these effects to usefulness perceptions and technology acceptance
Smets 2019 [66]	United States	Phase 1	8	7	1	31	n.r.	174.3	n.r.	84.4	n.r.	Automotive	EVO (EksoBionics)	to evaluate user acceptance, fit, usability and discomfort of an exoskeleton for overhead automotive assembly tasks
Field study		Phase 2	10	9	1	38	n.r.	178.6	n.r.	91.1	n.r.			
		Phase 3	4	3	1	45	n.r.	171.3	n.r.	80.3	n.r.			
Thamsuwan 2020 [21]	Canada		14	13	1	49	12	176	6	80	13	Agriculture	Laevo (Laevo)	to evaluate how a passive back-support exoskeleton might reduce physical demands on the low back during some farming activities
Field study														
Turja 2022 [67]	Finland		23	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Healthcare	Laevo (Laevo)	examine the acceptance of an exoskeleton among nurses by analyzing the nurses' intention to use the exoskeleton
Qualitative research														
Wang 2021 [20]	Taiwan	Group A	8	8	0	30.3	5.4	170.7	0.2	70	9.8	Agriculture	PULE (*)	to evaluate the ergonomics of a passive upper limb exo to provide auxiliary forces for the upper limb during orchard farming
Experimental study		Group B	10	10	0	50.3	9	166.8	0.5	78.4	11.7			
		Group C	4	4	0	50.5	6.4	170.2	0.4	76	16.9			
		Group D	4	3	1	53	11.9	166	0.5	73	9.6			
Ziaei 2021 [23]	Iran		20	20	0	33.8	5.2	175.2	6.1	72.3	8.2	Waste collection	Ergo-Vest (*)	to determine the biomechanical, physiological,
Field study														

														and subjective effect of a passive exoskeleton among waste collectors

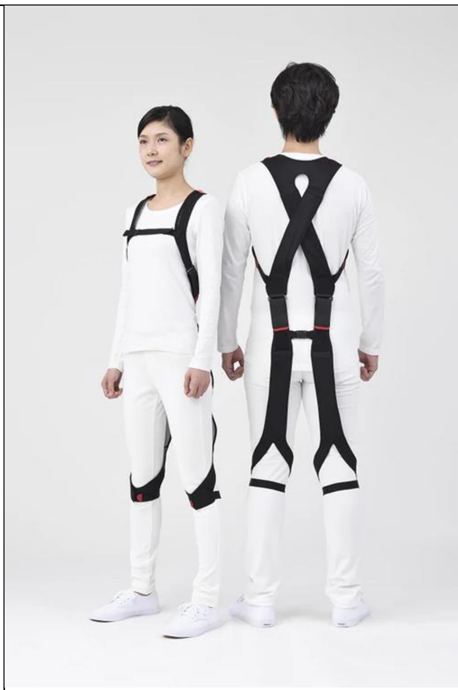
* sex not reported of 8 participants in exo and 22 participants in control group; *non-commercial exoskeleton

8.2 Exoskeletons used in the reported studies

Name	Company	Mode of function	Picture	Studies using this product
Laevo	Laevo BV, Rijswijk, The Netherlands	p	 [49]	[18,21,44,47–49,51,53,64,65,67]
BackX	SuitX, Emeryville, USA	p	 [63]	[18,24,48,53,62,63,65]
Apex	Herowear, Nashville, USA	p	 [52]	[18,25,52]
Japet	Japet Medical Devices, Loos, France	a	 [43]	[18,37,43]

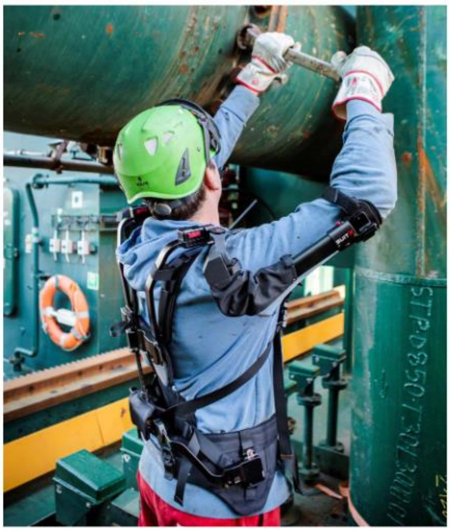
Liftsuit	Auxivo AG, Schwerzenbach, Switzerland	p	 [52]	[18,52]
Paexo Back / SPEXOR	Ottobock, Duderstadt, Germany	p	 [1]	[33,65]
Hapo	Ergo Santé Technologie, Anduze, France	p	 [52]	[52]
SoftExo	Hunic, Baiersbronn, Germany	p	 [2]	[18]

[1] https://orthexo.de/en/exoskeletons/industrial-exoskeletons/paexo-back/
[2] https://hunic.com/en/

Rakunie	N-Ippin, Oestrich-Winkel, Germany	p	 [3]	[18]
Power Suit	Helmut Schmidt University, Hamburg, Germany	a	no picture available	[18]
CrayX	German Bionic, Augsburg, Germany	a	 [4]	[18]
Bionic.Back	hTRIUS, Horb am Neckar, Germany		 [5]	[18]

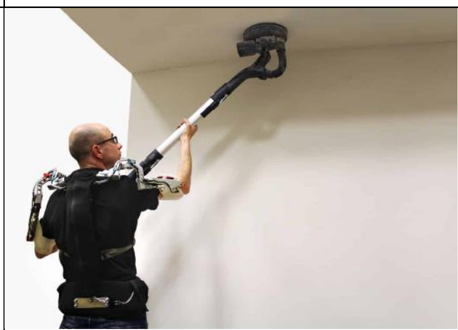
[3] https://www.n-ippin.com/products/rakunie-ruecken-protect-system-neu
[4] https://exoskeletonreport.com/product/cray-x/
[5] https://en.htrius.com/

Muscle Suit	Innophys, Tokyo, Japan	p	 [41]	[41]
Ergo-Vest	-	p	 [23]	[23]
XoTrunk	-	a	 [22]	[22]

HAL	Cyberdyne Inc., Tsukuba, Japan	p	 [41]	[41]
Airframe	Levitate Technologies, San Diego, USA	p	 [36]	[15,16,18,24,36,48,49,65]
ShoulderX	SuitX, Emeryville, USA	p	 [14]	[13,14,18,19,65]
Skelex 360/V2	Skelex, Rotterdam, The Netherlands	p	 [12]	[12,14,18,42]

EksoVest	EksoBionics, San Rafael, USA	p	 [35]	[28,35,48]
Paexo Shoulder	Ottobock, Duderstadt, Germany	p	 [6]	[18,49,65]
EVO	Ekso Bionics, San Rafael, USA	p	 [7]	[25,65,66]

[6] https://ottobockexoskeletons.com/wp-content/uploads/2019/11/Ottobock_Flyer_PaexoShoulder-EN.pdf
[7] https://eksobionics.com/ekso-evo/

MATE	Comau, Grugliasco, Italy	p	 [8]	[17,18]
Hapo MS	Ergo Santé Technologie, Anduze, France	p	 [11]	[11]
Lucy	Helmut Schmidt University, Hamburg, Germany	a	 [9]	[18]
PULE	-	p	 [20]	[20]

[8] https://www.comau.com/en/competencies/robotics-automation/wearable-robotics-mate-xt-exoskeleton/?_gl=1*4mp2c8*_up*MQ..*_ga*MTUwMTQxNzQyLjE3MTU5NTYyMjM.*_ga_9M7B6QBXTC*MTcxNTk1NjIyMy4xLjEuMTcxNTk1NjIzNC4wLjAuMzY1MjM4NTk0
[9] https://innovationorigins.com/en/the-custom-made-exoskeleton-from-a-construction-kit/

Hilti EXO-01	Hilti, Schaan, Liechtenstein	p	 [25]	[25]
Chairless Chair	Noonee, Wendlingen, Germany	p	 [26]	[18,26]

8.3 Documentation of database searches

8.3.1 Cochrane

ID Search Hits

#1 ("exoskeletal device"):ti,ab,kw OR (exoskeleton*):ti,ab,kw OR ("wearable robot"):ti,ab,kw OR (exosuit*):ti,ab,kw 500

#2 (workplace):ti,ab,kw OR (work*):ti OR (workers):ti,ab,kw OR (profession*):ti,ab,kw OR ("work task"):ti,ab,kw 50928

#3 (industr*):ti,ab,kw OR ("construction"):ti,ab,kw OR (assembly):ti,ab,kw OR (manufacturing):ti,ab,kw OR (logistic*):ti,ab,kw 43089

#4 (occupation*):ti,ab,kw OR ("nurse"):ti,ab,kw OR (nursing):ti,ab,kw OR (factory):ti,ab,kw OR (military):ti,ab,kw 66261

#5 ("rehabilitation"):ti,ab,kw OR (therapy):ti,ab,kw OR (training):ti,ab,kw OR ("treatment"):ti,ab,kw 1272775

#6 #2 OR #3 OR #4 145336

#7 #1 AND #6 71

#8 #7 NOT #5 25

8.3.2 Ovid

1 (Exoskeleton* or Exosuit* or exoskeleton device or exoskeletal device or "wearable robot").ab. (4589)

2 (work* or occupation* or profession* or "work task*" or "lifting task*" or "in-field evaluation" or logistics or manufacturing or assembly or construction or building or industr* or military or nurs*).ab. (3193246)

3 1 and 2 (1178)

4 (training or rehabilitation or rehabiliation).ab. (656765)

5 (((Exoskeleton* or Exosuit* or exoskeleton device or exoskeletal device or "wearable robot") and (work* or occupation* or profession* or "work task*" or "lifting task*" or "in-field evaluation" or logistics or manufacturing or assembly or construction or building or industr* or military or nurs*)) not (training or rehabilitation or rehabiliation)).ab. (854)

(((Exoskeleton* or Exosuit* or exoskeleton device or exoskeletal device or "wearable robot") and (work* or occupation* or profession* or "work task*" or "lifting task*" or "in-field evaluation" or logistics or manufacturing or assembly or construction or building or industr* or military or nurs*)) not (training or rehabilitation or rehabiliation)).ab. not (insect* or animal* or chitin*).af. (587)

8.3.3 Scopus

((((TITLE-ABS-KEY (exoskeleton*) OR TITLE-ABS-KEY (exosuit*) OR TITLE-ABS-KEY ("Wearable Robot*") OR TITLE-ABS-KEY ("Exoskeletal device"))) AND ((TITLE (work) OR TITLE-ABS-KEY (workplace) OR TITLE-ABS-KEY ("work task*") OR TITLE-ABS-KEY (occupation*) OR TITLE-ABS-KEY (industr*) OR TITLE-ABS-KEY (manufacturing) OR TITLE-ABS-KEY (assembly) OR TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (nurs*) OR TITLE-ABS-KEY (factory) OR TITLE-ABS-KEY (military)))) AND NOT ((TITLE-ABS-KEY (rehabilitation) OR TITLE-ABS-KEY (training) OR TITLE-ABS-KEY (therapy) OR TITLE-ABS-KEY (treatment))) AND PUBYEAR > 2003 AND PUBYEAR < 2025) AND NOT ((TITLE-ABS-KEY (chitin*) OR TITLE-ABS-KEY (animals) OR TITLE-ABS-KEY (insects))) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "ch") OR EXCLUDE (DOCTYPE , "cr") OR EXCLUDE (DOCTYPE , "bk")) AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO (LANGUAGE , "German"))

8.3.4 Pubmed

7,"(((((((Exoskeleton*[Title/Abstract]) OR (Exosuit*[Title/Abstract])) OR (""exoskeletal device*""[Title/Abstract])) OR (""wearable robot*""[Title/Abstract])) OR (""exoskeleton device*""[Title/Abstract])) AND ((((((((((((((((industry, manufacturing[MeSH Terms]) OR (construction industry[MeSH Terms])) OR (workplace[Title/Abstract])) OR (work*[Title])) OR (occupation*[Title/Abstract])) OR (profession*[Title/Abstract])) OR (logistics[Title/Abstract])) OR (military[Title/Abstract])) OR (assembly[Title/Abstract])) OR (""in-field evaluation""[Title/Abstract])) OR (nurs*[Title/Abstract])) OR (workers[Title/Abstract])) OR (""work task*""[Title/Abstract])) OR (building industries[MeSH Terms])) OR (""occupational use""[Title/Abstract])) OR (healthcare[Title/Abstract]))) NOT ((((training[Title/Abstract]) OR (rehabilitation[Title/Abstract])) OR (therapy[Title/Abstract])))) NOT ((((insect*[Title/Abstract]) OR (chitin*[Title/Abstract])) OR (animal*[Title/Abstract])) OR (crustacean[Title/Abstract])) AND (2004:2024[pdat])",First Author,,"((((""exoskeleton*""[Title/Abstract] OR ""exosuit*""[Title/Abstract] OR ""exoskeletal device*""[Title/Abstract] OR ""wearable robot*""[Title/Abstract] OR ""exoskeleton device*""[Title/Abstract]) AND (""construction industry""[MeSH Terms] OR ""workplace""[Title/Abstract] OR ""work*""[Title] OR ""occupation*""[Title/Abstract] OR ""profession*""[Title/Abstract] OR ""logistics""[Title/Abstract] OR ""military""[Title/Abstract] OR ""assembly""[Title/Abstract] OR ""in-field evaluation""[Title/Abstract] OR ""nurs*""[Title/Abstract] OR ""workers""[Title/Abstract] OR ""work task*""[Title/Abstract] OR ""construction industry""[MeSH Terms] OR ""occupational use""[Title/Abstract] OR ""healthcare""[Title/Abstract])) NOT (""training""[Title/Abstract] OR

""rehabilitation""[Title/Abstract] OR ""therapy""[Title/Abstract])) NOT (""insect*""[Title/Abstract] OR ""chitin*""[Title/Abstract] OR ""animal*""[Title/Abstract] OR ""crustacean""[Title/Abstract])) AND 2004/01/01:2024/12/31[Date - Publication]",244,08:51:04
6,"(((((((Exoskeleton*[Title/Abstract]) OR (Exosuit*[Title/Abstract])) OR (""exoskeletal device*""[Title/Abstract])) OR (""wearable robot*""[Title/Abstract])) OR (""exoskeleton device*""[Title/Abstract])) AND (((((((((((((((industry, manufacturing[MeSH Terms]) OR (construction industry[MeSH Terms])) OR (workplace[Title/Abstract])) OR (work*[Title])) OR (occupation*[Title/Abstract])) OR (profession*[Title/Abstract])) OR (logistics[Title/Abstract])) OR (military[Title/Abstract])) OR (assembly[Title/Abstract])) OR (""in-field evaluation""[Title/Abstract])) OR (nurs*[Title/Abstract])) OR (workers[Title/Abstract])) OR (""work task*""[Title/Abstract])) OR (building industries[MeSH Terms])) OR (""occupational use""[Title/Abstract])) OR (healthcare[Title/Abstract]))) NOT ((((training[Title/Abstract]) OR (rehabilitation[Title/Abstract])) OR (therapy[Title/Abstract])) OR (treatment[Title/Abstract]))) NOT ((((insect*[Title/Abstract]) OR (chitin*[Title/Abstract])) OR (animal*[Title/Abstract])) OR (crustacean[Title/Abstract]))",First Author,from 2004 - 2024,"((((""exoskeleton*""[Title/Abstract] OR ""exosuit*""[Title/Abstract] OR ""exoskeletal device*""[Title/Abstract] OR ""wearable robot*""[Title/Abstract] OR ""exoskeleton device*""[Title/Abstract]) AND (""construction industry""[MeSH Terms] OR ""workplace""[Title/Abstract] OR ""work*""[Title] OR ""occupation*""[Title/Abstract] OR ""profession*""[Title/Abstract] OR ""logistics""[Title/Abstract] OR ""military""[Title/Abstract] OR ""assembly""[Title/Abstract] OR ""in-field evaluation""[Title/Abstract] OR ""nurs*""[Title/Abstract] OR ""workers""[Title/Abstract] OR ""work task*""[Title/Abstract] OR ""construction industry""[MeSH Terms] OR ""occupational use""[Title/Abstract] OR ""healthcare""[Title/Abstract])) NOT (""training""[Title/Abstract] OR ""rehabilitation""[Title/Abstract] OR ""therapy""[Title/Abstract] OR ""treatment""[Title/Abstract])) NOT (""insect*""[Title/Abstract] OR ""chitin*""[Title/Abstract] OR ""animal*""[Title/Abstract] OR ""crustacean""[Title/Abstract])) AND (2004:2024[pdat])",236,08:47:45
5,"(((((((Exoskeleton*[Title/Abstract]) OR (Exosuit*[Title/Abstract])) OR (""exoskeletal device*""[Title/Abstract])) OR (""wearable robot*""[Title/Abstract])) OR (""exoskeleton device*""[Title/Abstract])) AND (((((((((((((((industry, manufacturing[MeSH Terms]) OR (construction industry[MeSH Terms])) OR (workplace[Title/Abstract])) OR (work*[Title])) OR (occupation*[Title/Abstract])) OR (profession*[Title/Abstract])) OR (logistics[Title/Abstract])) OR (military[Title/Abstract])) OR (assembly[Title/Abstract])) OR (""in-field evaluation""[Title/Abstract])) OR (nurs*[Title/Abstract])) OR (workers[Title/Abstract])) OR (""work task*""[Title/Abstract])) OR (building industries[MeSH Terms])) OR (""occupational use""[Title/Abstract])) OR (healthcare[Title/Abstract]))) NOT ((((training[Title/Abstract]) OR (rehabilitation[Title/Abstract])) OR (therapy[Title/Abstract])) OR (treatment[Title/Abstract])))

NOT ((((insect*[Title/Abstract]) OR (chitin*[Title/Abstract])) OR (animal*[Title/Abstract])) OR (crustacean[Title/Abstract]))",First Author,,"(((""exoskeleton*""[Title/Abstract] OR ""exosuit*""[Title/Abstract] OR ""exoskeletal device*""[Title/Abstract] OR ""wearable robot*""[Title/Abstract] OR ""exoskeleton device*""[Title/Abstract]) AND (""construction industry""[MeSH Terms] OR ""workplace""[Title/Abstract] OR ""work*""[Title] OR ""occupation*""[Title/Abstract] OR ""profession*""[Title/Abstract] OR ""logistics""[Title/Abstract] OR ""military""[Title/Abstract] OR ""assembly""[Title/Abstract] OR ""in-field evaluation""[Title/Abstract] OR ""nurs*""[Title/Abstract] OR ""workers""[Title/Abstract] OR ""work task*""[Title/Abstract] OR ""construction industry""[MeSH Terms] OR ""occupational use""[Title/Abstract] OR ""healthcare""[Title/Abstract])) NOT (""training""[Title/Abstract] OR ""rehabilitation""[Title/Abstract] OR ""therapy""[Title/Abstract] OR ""treatment""[Title/Abstract])) NOT (""insect*""[Title/Abstract] OR ""chitin*""[Title/Abstract] OR ""animal*""[Title/Abstract] OR ""crustacean""[Title/Abstract])",244,08:47:37

4,(((insect*[Title/Abstract]) OR (chitin*[Title/Abstract])) OR (animal*[Title/Abstract])) OR (crustacean[Title/Abstract]),First Author,,"""insect*""[Title/Abstract] OR ""chitin*""[Title/Abstract] OR ""animal*""[Title/Abstract] OR ""crustacean""[Title/Abstract]","1,451,115",08:46:54

3,(((training[Title/Abstract]) OR (rehabilitation[Title/Abstract])) OR (therapy[Title/Abstract])) OR (treatment[Title/Abstract]),First Author,,"""training""[Title/Abstract] OR ""rehabilitation""[Title/Abstract] OR ""therapy""[Title/Abstract] OR ""treatment""[Title/Abstract]","7,151,614",08:45:41

2,"((((((((((((((industry, manufacturing[MeSH Terms]) OR (construction industry[MeSH Terms])) OR (workplace[Title/Abstract])) OR (work*[Title])) OR (occupation*[Title/Abstract])) OR (profession*[Title/Abstract])) OR (logistics[Title/Abstract])) OR (military[Title/Abstract])) OR (assembly[Title/Abstract])) OR (""in-field evaluation""[Title/Abstract])) OR (nurs*[Title/Abstract])) OR (workers[Title/Abstract])) OR (""work task*""[Title/Abstract])) OR (building industries[MeSH Terms])) OR (""occupational use""[Title/Abstract])) OR (healthcare[Title/Abstract])",First Author,,"""construction industry""[MeSH Terms] OR ""workplace""[Title/Abstract] OR ""work*""[Title] OR ""occupation*""[Title/Abstract] OR ""profession*""[Title/Abstract] OR ""logistics""[Title/Abstract] OR ""military""[Title/Abstract] OR ""assembly""[Title/Abstract] OR ""in-field evaluation""[Title/Abstract] OR ""nurs*""[Title/Abstract] OR ""workers""[Title/Abstract] OR ""work task*""[Title/Abstract] OR ""construction industry""[MeSH Terms] OR ""occupational use""[Title/Abstract] OR ""healthcare""[Title/Abstract]","1,949,425",08:44:27

1,"((((Exoskeleton*[Title/Abstract]) OR (Exosuit*[Title/Abstract])) OR (""exoskeletal device*""[Title/Abstract])) OR (""wearable robot*""[Title/Abstract])) OR (""exoskeleton device*""[Title/Abstract])",First Author,,"""exoskeleton*""[Title/Abstract] OR ""exosuit*""[Title/Abstract] OR ""exoskeletal device*""[Title/Abstract] OR ""wearable robot*""[Title/Abstract] OR ""exoskeleton device*""[Title/Abstract]","5,124",08:40:51

8.3.5 Web of Science

1: (((TS=(Exoskeleton*)) OR TS=(Exosuit*)) OR TS=("wearable robot*")) AND TS=("exoskeletal device*") Date Run: Wed Nov 22 2023 14:58:38 GMT+0100 (Mitteleuropäische Normalzeit) Results: 24

2: (((ALL=(Exoskeleton*)) OR ALL=(Exosuit*)) OR ALL=("wearable robot")) OR ALL=("exoskeletal device") Date Run: Wed Nov 22 2023 14:59:54 GMT+0100 (Mitteleuropäische Normalzeit) Results: 14462

3: (((AB=(Exoskeleton*)) OR AB=(Exosuit*)) OR AB=("wearable robot")) OR AB=("exoskeletal device") Date Run: Wed Nov 22 2023 15:01:22 GMT+0100 (Mitteleuropäische Normalzeit) Results: 11359

4: #1 OR #3 Date Run: Wed Nov 22 2023 15:02:08 GMT+0100 (Mitteleuropäische Normalzeit) Results: 11362

5: ((((((TI=(work*)) OR AB=("work tasks")) OR AB=("work task")) OR AB=(workers)) OR AB=(occupation*)) OR AB=(profession*)) Date Run: Wed Nov 22 2023 15:04:09 GMT+0100 (Mitteleuropäische Normalzeit) Results: 1561403

6: (((((((AB=(manufacturing)) OR AB=(assembly)) OR AB=(logistics)) OR AB=(industr*)) OR AB=(construction*)) OR AB=(nurs*)) OR AB=(factory)) OR AB=(military)
Date Run: Wed Nov 22 2023 15:05:36 GMT+0100 (Mitteleuropäische Normalzeit)
Results: 3764936

7: #6 OR #5 Date Run: Wed Nov 22 2023 15:05:51 GMT+0100 (Mitteleuropäische Normalzeit) Results: 5086121

8: #4 AND #7 Date Run: Wed Nov 22 2023 15:06:07 GMT+0100 (Mitteleuropäische Normalzeit) Results: 1486

9: ((AB=(rehabilition)) OR AB=(therapy)) OR AB=(training) Date Run: Wed Nov 22 2023 15:07:12 GMT+0100 (Mitteleuropäische Normalzeit) Results: 2962027

10: ((ALL=(chitin*)) OR ALL=(animal)) OR ALL=(insect) Date Run: Wed Nov 22 2023 15:09:22 GMT+0100 (Mitteleuropäische Normalzeit) Results: 2553226

11: ((#8) NOT #9) NOT #10 Date Run: Wed Nov 22 2023 15:10:10 GMT+0100 (Mitteleuropäische Normalzeit) Results: 1119

12: ((#8) NOT #9) NOT #10 and 1991 or 1993 or 1994 or 1995 or 1997 or 1998 or 2001 or 2002 or 1999 or 2003 (Exclude – Publication Years) Date Run: Wed Nov 22 2023 15:11:03 GMT+0100 (Mitteleuropäische Normalzeit) Results: 1091

13: ((#8) NOT #9) NOT #10 and 1991 or 1993 or 1994 or 1995 or 1997 or 1998 or 2001 or 2002 or 1999 or 2003 (Exclude – Publication Years) and Proceeding Paper (Exclude – Document Types)
Date Run: Wed Nov 22 2023 15:11:13 GMT+0100 (Mitteleuropäische Normalzeit) Results: 705

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