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An industrial exoskeleton user acceptance framework based on a literature review of empirical studies

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Highlights

- We identified factors determining the acceptance of industrial exoskeletons.
- Factors include wearing comfort, perceived usefulness, and other factors.
- Considering these factors in the design process can lead to better exoskeletons.
- Exoskeletons should meet requirements of users, their tasks and work environment.
- In turn, this could lead to large scale adoption of exoskeletons in industry.

1 Abstract

Studying the acceptance of exoskeletons in industry has gained increased attention. Exoskeletons (wearable support devices) are envisioned to alleviate heavy work. Examining what factors influence the use of exoskeletons is important, because influencing these factors could positively contribute to the adoption of industrial exoskeletons. The factors identified in this paper have been systematically derived from empirical research with (potential future) end users, most of whom have tried on an exoskeleton. Our framework with factors influencing the acceptance of industrial exoskeletons can be used during the (ideally iterative) design, (re)development and evaluation phase of new or existing exoskeletons. This could improve the quality of exoskeletons since this allows designers to already consider acceptance factors early in the design process instead of finding out what is important late in the design process during (field) testing. In turn, this might accelerate the adoption of exoskeletons. Also, our framework can be used to study the ongoing introduction of exoskeletons at work since it also addresses policy decisions companies interested in implementing exoskeletons should consider.

2 Introduction

Work-related muscle disorders (WRMDs) are a problem for 60% of the Europeans (de Kok et al., 2019). Especially workers in agriculture and factories have an increased risk of health problems, which increases costs for employers (Eurofound, 2017). Companies use different strategies to prevent WRMDs such as using equipment for lifting and moving, providing ergonomic equipment, encouraging breaks and task rotation (de Kok et al., 2019). Regardless of these preventive measures, the high number of people affected by WRMDs suggests that there is room for improvement. Full automation could be a potential solution, however this is not always possible or financially feasible (Maurice et al., 2020). Improving the ergonomic design of a work place is an alternative possibility, but adapting the working height to a worker is not always possible (Groos et al., 2020). Furthermore, assistive devices could also be used such as a lifting device to carry heavy luggage. However, such devices do not contribute to a more ergonomic work environment if they are not being used (Baltrusch et al., 2021).

A potential solution to decrease WRMDs is the use of exoskeletons. Exoskeletons are wearable devices that can support people while making certain movements by delivering a supporting moment at certain body parts, which could potentially allow people to make these movements for a longer period of time and potentially prevent WRMD. *Active* exoskeletons have one or more actuators supporting a person, while *passive* exoskeletons store energy in springs and use it to support a person (de Looze et al., 2017). Examples of passive exoskeletons are Laevo[1] (aimed to supports one's back) and Skelex[2] (to support one's upper body). Various (mainly passive) exoskeletons (e.g. Hensel & Keil, 2019; Smets, 2019), but also prototypes (Baltrusch et al., 2020) are evaluated and tested by workers in industry.

Although scholars (e.g. Graham et al., 2009) have stipulated the importance to study the acceptance of industrial exoskeletons, a grounded framework to study this topic is lacking. However, various frameworks have been suggested for the evaluation of exoskeletons (Moyon et al., 2019; e.g. Torricelli et al., 2020). Our research will focus on the human experience using exoskeletons at work, not on its effectiveness in human support. Our study contributes by proposing a framework to study acceptance of exoskeletons based on a systematic analysis of previous empirical research with (potential) end users.

Such a framework is important for several reasons. Firstly, it is a holistic framework, and it addresses the interaction between the end users and the exoskeleton and it places emphasis on the environmental context in which the exoskeleton will be used, individual aspects of end users, their work-related tasks and aspects related to the policy of the usage exoskeletons at work. Especially for exoskeleton research only conducted in the lab, it is important to also consider the work environment and the diversity of tasks and movements done at work by potential end users. Secondly, our framework can be used during different stages of the development and implementation process of exoskeletons. If exoskeleton designers can already consider solving problems related to the factors early in the design of an exoskeleton, it decreases the chances that exoskeletons will be abandoned.

Finally, by identifying factors important for the acceptance of exoskeletons and addressing issues related to them, our framework could potentially result in improved exoskeletons with a good user experience that meet the requirements of end users. This makes it more likely that exoskeletons are adopted rather than deserted after an initial period of testing them in the field. If end users are willing to use them daily, this could also potentially enable the willingness of end users and their companies to engage in long-term research on the use of exoskeletons. This could, in turn, provide more insight in the long-term benefits of using exoskeletons and in particular the potential to reduce WRMDs. Finally, more evidence on the long-term beneficial effects of exoskeletons could lead to even more end users willing to use exoskeletons as well as more companies interested in purchasing multiple exoskeletons.

If the return on investment of exoskeleton implementation (e.g. the purchasing of an exoskeleton, its maintenance and the training required to introduce it at work) is sufficient (for instance by

[1] https://www.laevo-exoskeletons.com/
[2] https://www.skelex.com/

demonstratable cost savings in terms of costs associated with WRMDs), this could finally benefit the health of workers by supporting them and preventing WRMDs.

Only recently industrial exoskeletons have been tested in the field for a longer period of time (e. g. Smets, 2019). The adoption of industrial exoskeletons in companies is not widespread yet and it is therefore important to understand which factors could speed up this process and which factors are preventing widespread adoption.

This review paper focuses on the following research questions:
- RQ1: How is acceptance of industrial exoskeletons currently studied?
- RQ2: Which factors could hinder or contribute to the adoption of exoskeletons?

To answer these research questions, we first briefly describe existing technology acceptance models and explore which of them have been used in research on industrial exoskeletons. Then, we explain the search strategy used to find relevant papers and how they were analyzed. In the result section, we describe the concepts identified in those papers. They are presented in a framework for studying industrial exoskeletons. Finally, the last section describes our conclusion and discussion. Our framework can be used in future research to study the acceptance of exoskeletons.

3 Technology acceptance models and frameworks

3.1 Technology acceptance models

We discuss the most important technology acceptance models briefly: TAM, TAM2 and UTAUT. In origin most were developed to study the use of information technology. They share the assumption that a number of factors predict the intention to use technology, which is a predictor of actual (Viswanath Venkatesh et al., 2003). Acceptance is often measured by asking about frequency of use (e.g. Davis, 1989; Viswanath Venkatesh et al., 2003).

Davis (1989) developed the Technology Acceptance Model (TAM) and hypothesized that perceived usefulness and perceived ease of use can determine user acceptance or usage of computer software. He found that both factors correlated with self-predicted future usage and self-reported current usage (Davis, 1989).

TAM2 was developed as an extension on TAM by Venkatesh and Davis (2000). Extra factors were added to the TAM2 model, namely: subjective norm, voluntariness, image, job relevance, output quality, result demonstrability and perceived ease of use. TAM2 was adapted and resulted by Venkatesh & Bala (2008) and resulted in TAM3, which includes six additional determinants to explain perceived ease of use.

Venkatesh et al. (2003) unified 8 different technology acceptance models and created the UTAUT model (Unified Theory of Acceptance and Use of Technology). This model consists of: performance expectancy, effort expectancy (similar to ease-of-use), social influence, facilitating conditions, which predict behavioral intention and use behavior (acceptance) and are influenced by moderating variables: gender, age, experience and voluntariness of use.

Although all models discussed before have been cited a lot, they were also criticized. For instance, in their review on the use of TAM, Turner et al. (2010) found that perceived usefulness and perceived ease of use are not very good at predicting actual usage. In contrast, self-predicted future usage (behavioral intention) was found to be a better predictor. Although the models have been originally developed to study the use of information systems, they have been used for studying other technologies and many adaptations of the original models exist. Next, we will discuss how acceptance of industrial exoskeletons has been studied so far.

3.2 Existing frameworks or models specific to industrial exoskeletons

Elprama et al. (2020) investigated the intention to use exoskeletons by workers using a modified version of the UTAUT model. The factors used are: performance expectancy, effort expectancy, social influence, facilitating conditions, attitude towards the use of technology and intention to use.
Fox et al. (2019) also identified factors required for the successful implementation of industrial exoskeletons via a literature review. The factors are: musculoskeletal condition, psychomotor skill, technological self-efficacy, robotics not feasible practical or viable (load appropriate), load characteristics, work space features. It is not clear how these factors were extracted from the literature review.
Moyon et al. (2019) based their acceptance model on a mix of different methods (including focus group(s) with experts and end users). Their model aims to support the evaluation of exoskeletons and it consists of: physical, occupational, cognitive and affective aspects. It also proposes a way to measure them subjectively and objectively. Although the step-by-step description of the development process of the model is presented, the description lacks details. This makes it hard to ascertain *how* it was decided why certain (sub)factors were in- or excluded in the final model. Furthermore, although the categories identified seem very relevant to study acceptance of exoskeletons, it is not clearly explained why the extra factors (e.g. hygienic and compatible with equipment) identified in one of the final stages were not added to the model. Finally, all factors lack a detailed description to understand what aspects would fit into a category.
Although some concepts appear in multiple frameworks, there does not seem to be a consensus. Also, a detailed description of each concept is often lacking, which makes it difficult to ascertain what each concept is and how it could be measured. We, therefore, aim to create a framework with clearly defined factors predicting acceptance based on existing literature. In the next section, we will explain our methodology to identify these concepts via literature research.

4 Literature search

Since we focus on user experience, we studied concepts that can be measured or evaluated in a subjective way (both qualitatively and quantitatively).

4.1 Search strategy

We searched in the Web of Science Core Collection (WoSCC)[3] in the period 1955 – 2021 on the 16th of June, 2021 for journal papers and conference proceedings. The keywords 'industrial exoskeleton' resulted in 224 papers and a second search with the keywords 'exoskeleton' and 'acceptance' resulted in 69 papers. After filtering out 12 double results, we had 281 different documents. The abstracts, titles and full papers were screened. Subjective data from users had to be collected to be included. This criterion was used to exclude papers only focusing on technical development of an exoskeleton. Articles that did not collect their own subjective empirical data (such as review papers) or that focused on developing methods to assess exoskeletons were excluded. Papers focusing on exoskeletons used for rehabilitation purposes (including assisting reintegration at the work floor) and not used for doing labor at work were excluded. From our own Mendeley library and from recommendations from colleagues in the field, we added 7 papers (Amandels et al., 2019; Ferreira et al., 2020; Kim et al., 2019; Moyon et al., 2020; Omoniyi et al., 2020; Smets, 2019; Upasani et al., 2019) that also met the inclusion criteria. This resulted in 35 papers that were read in depth (Table 1).

4.2 Analysis

All 35 papers were coded using MaxQDA 2020. We only focused on the result sections of the papers and used an approach as described in Charmaz (2006). We assigned labels to fragments of text, a process called open coding. Once multiple labels seemed to be related, a larger theme was created under which the relevant fragments were sorted. We wanted to keep an open mind in this research phase and let the categories come from the data (e.g. grounded theory) rather than puzzling how the

[3] http://www.webofknowledge.com

data fits existing concepts. After labelling all 35 papers, saturation was reached (e.g. we did not identify new themes). Charmaz (2006) described having reached saturation when including new data (in our case papers) is not leading to new properties of categories or categories or creating new theoretical insights. In addition to identifying factors, we also listed relevant variables related to the study (such as the method and the number of participants).

5 Identifying important factors for exoskeleton acceptance

In this section, we first briefly describe characteristics of the included papers. Then, we discuss which factors were identified that could potentially influence the acceptance of exoskeletons and which papers explicitly discussed using technology acceptance frameworks.

Table 1 shows an overview of characteristics of the studied papers. Only 80 of the 850 participants is female. Fourteen articles (40%) used **potential future users** (e.g. manufacturer employees and farmers). Some studies excluded participants because the body of the participant did not meet the specifications provided by the exoskeleton size (e.g. Gilotta et al., 2019; Spada et al., 2017). Most studies were **short term research** (ranging from 5 minutes to 8 hours). Only three studies took place over a longer period of time, namely a period of 4 weeks (Ferreira et al., 2020; Hensel & Keil, 2019) and of 3 months (Smets, 2019). There were 22 experiments, 8 interviews, 7 focus groups and finally surveys and observations were used in 5 or less papers. Using questionnaires was used by most papers (31/35) to collect data.

5.1 Categorizing factors

By organizing the data with themed codes, we identified 5 main themes related to technology acceptance (intention to use and use): 1) physiological, 2) psycho-social, 3) work related, 4) policy related and 5) implementation related factors (see Figure 1).

The **physiological factors** include personal history of physical complaints of a person and wearing comfort. The **psycho-social factors** include factors such as maintenance duration and compatibility of exoskeletons with tasks. Finally, **policy related factors** include mandatory use of exoskeleton, strategies for MSDs prevention and personal vs. shared exoskeleton. Table 2 shows an overview of all 35 papers and which factors occurred in each paper. Table 3 gives an overview of how each concept can be described with examples from the papers.

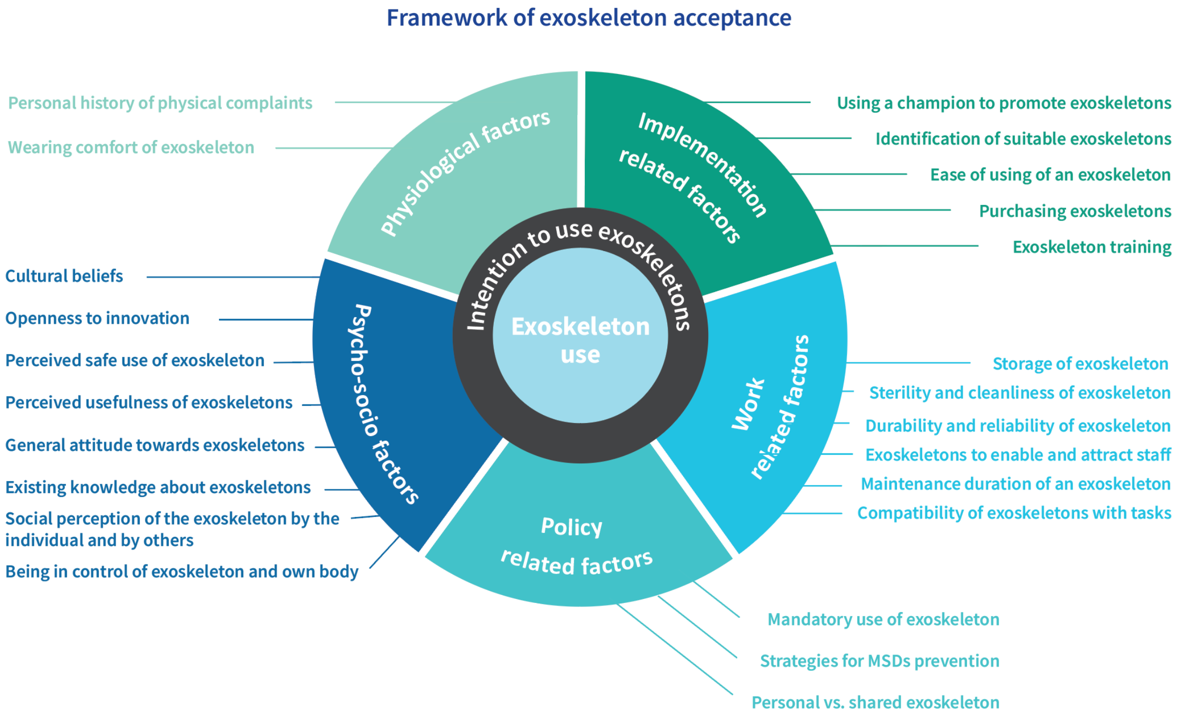

Figure 1 The framework of exoskeleton acceptance assumes that factors related to acceptance can be divided in the themes physiological factors, work related factors, policy related factors, implementation related factors and psycho-socio factors and we hypothesize that they can predict the intention to use exoskeletons. These relationships as well as the assumed relationship between intention to use exoskeletons and exoskeleton use still needs to be validated in future research.

Table 1 Overview of all 35 papers included in the literature review and information related to participants and the type of research.
• indicates that this was done in a paper

- not applicable for the type of research

? not reported

	Tried exoskeleton?	*Potential future users*	*Total # of participants*	*Sex*		*Lab or field?*			*Method used*				
	Answer	**Answer**	**#**	**Male**	**Female**	**Lab**	**Field**	Questionnaire	Survey	Focus group	Observation	Interview	Experiment
Amandels et al. (2018)	Yes	Yes	9	9	0	•	•	•					
Baltrusch et al. (2018)	Yes	No	18	18	0	•		•					•

Baltrusch et al. (2021)	Yes	Yes	19	19[4]	0	•		•		•		•	
Cha et al. (2019)	Yes [5]	Yes	14	7	7	•		•		•		•	
De Bock et al. (2021)	Yes	Yes	4	4	0		•	•					•
De Looze (2016)	No	No	8	?	?	-	-					•	
Dezman et al. (2018)	Yes	No	7	7	0	•		•					•
Elprama et al. (2020)	No	Yes	124	111	13	-	-	•	•				
Ferreira et al. (2020)	Yes	Yes	88	?	?		•	•					
Gilotta et al. (2019)	Yes	Yes	29	?	?	•		•		•	•	•	•
Giustetto et al. (2021)	Yes	No	13	13	0	•		•					•
Grazi et al. (2020)	Yes	No	10	10	0	•		•					•
Groos et al. (2020)	Yes	No	17	10	7	•		•					•
Hensel & Keil (2019)	Yes	Yes	30	30	0		•	•					
Huysamen et al. (2018)	Yes	No	11	11	0	•		•					•
Kim et al. (2019)	No	No	26	?	?	-	-					•	
Ko et al. (2018)	Yes	No	9	9	0	•		•					•
Kozinc et al. (2021)	Yes	No	22	11	11	•		•					•
Luger et al. (2019 a)	Yes	No	45	45	0	•		•					•
Luger et al. (2019 b)	Yes	No	45	45	0	•		•					•
Luger et al. (2021)	Yes	No	36	36	0	•		•					•
Marino (2019)	Yes	No	14	11	3		•	•					•
Maurice et al. (2018)	No	Yes & no	10	5	5	-	-			•		•	
Maurice et al. (2020)	Yes	No	12	12	0	•		•		•		•	•
Moyon et al. (2019)	Yes	No	36	18	18	•		•					•
Näf et al. (2018)	Yes	No	3	3	0	•		•					•
Omoniyi et al. (2020)	Yes	Yes	15	14	1		•					•	
Otten et al. (2016)	Yes	No	20	18	2	•		•					•
Otten et al. (2018)	Yes	No	11	?	?	•		•					•
Qu et al. (2021)	Yes	Yes	8	8	0	•		•					•
Schwerha et al. (2021)	Yes	Yes	67	57	10	-	-	•		•			
Smets (2019)[6]	Yes	Yes	22	19	3		•	•					
Spada et al. (2017)	Yes	Yes	29	29	0	•		•		•		•	•
Upasani et al. (2019)	No	No	18	?	?	-	-	•	•				
Yan et al. (2021)	Yes	No	10	10	0	•		•					•

[4] It is not explicitly mentioned how many participants were male, but since it was a subset from another study in which only male participants participated, we assume that all participants in this study were also all male.
[5] 10 out of 14 participants tried the exoskeleton on.
[6] We summed up the participants from all three phases, but it was not explicitly mentioned in the paper whether a participant could take part in multiple phases of the research.

Avg. per publication			24.3	20.3	2.8								
Total	*30*	*14*	*850*	*590*	*80*	*32*	*7*	*31*	*2*	*7*	*1*	*9*	*22*

5.1.1 Acceptance: exoskeleton use and intention to use exoskeletons

Exoskeleton use can be described as the use (or non-use) of an exoskeleton (found in 3/35 papers). It refers to an objective measure such as the number of hours an exoskeleton has been worn or the percentage of a full shift an exoskeleton has been worn (e.g. Hensel & Keil, 2019; Smets, 2019).

Intention to use an exoskeleton is a subjective measure (12/35). It refers to the willingness to use (or not use) an exoskeleton and could be an indicator of real use. Less than half of the included papers contained this concept and most of the participants in those papers state to be willing to use exoskeletons. Only two papers (Ferreira et al., 2020; Hensel & Keil, 2019) measured intention to use at two points in time and they found that the willingness to use exoskeletons decreased over time probably due to the experiences with using the exoskeleton.

Factor		**Paper Frequency**
Exoskeleton use		3
Intention to use an exoskeleton		12
Work related factors	Exoskeletons to enable and attract staff	4
	Sterility and cleaniness of exoskeleton	4
	Compatibility of exoskeleton with tasks	21
	Storage of exoskeleton	4
	Durability and reliability of exoskeleton	7
	Maintenance duration of an exoskeleton	2
Policy related factors	Mandatory use of exoskeleton	4
	Personal vs. shared exoskeleton	1
	Strategies for MSD prevention	5
Psycho-social factors	Openness to innovation	3
	Cultural beliefs	1
	Existing knowledge about exoskeletons	2
	Being in control of exoskeleton and own body	3
	Social perception of the exoskeleton by the individual and by others	9
	Perceived safe use of exoskeleton	11
	General attitude towards exoskeletons	6
	Perceived usefulness of exoskeleton	28
Implementation related factors	Ease of using an exoskeleton	17
	Exoskeleton training	7
	Identification of suitable exoskeletons	2
	Using a champion to promote exoskeletons	4
	Purchasing exoskeletons	5
Physiological factors	Personal history of physical complaints	13
	Wearing comfort of an exoskeleton	29
	Total:	207

Table 2 Shows that the wearing comfort of an exoskeleton is often mentioned in the result section of papers, followed by the perceived usefulness of an exoskeleton and compatibility of exoskeleton with task.

5.1.2 Physiological factors

This group of factors refers to the physiological aspects of an exoskeleton such as how comfortable it feels to wear an exoskeleton, but also the personal history of physical complaints of a person.

5.1.2.1 Wearing comfort of an exoskeleton

The most frequent (29/35 of the papers) occurring subjective concept is the **wearing comfort of an exoskeleton**. Some papers found that the evaluated exoskeleton was (rather) comfortable (Ko et al., 2018; Luger, Cobb, et al., 2019) whereas other papers concluded that some discomfort was perceived (e. g. Näf et al., 2018). Hensel and Keil (2019) found that participants were less willing to use exoskeletons if they perceived discomfort. Pressure, pain, and irritation are all indicators of perceived discomfort. These sub concepts determine whether an exoskeleton feels (un)comfortable:

Perceived weight of an exoskeleton. In general, the participants agreed that an exoskeleton should be as light as possible (e. g. Cha et al., 2020).

Perceived thermal comfort. A reoccurring theme was the concern that an exoskeleton would be too warm (especially in summer, Gilotta et al., 2019). This was the most frequently mentioned reason for participants in Smets (2019) to not wear the exoskeleton. Wearing multiple layers of clothing (e.g. staff in the OR) could also influence thermal comfort (Cha et al., 2020).

Perceived person-exoskeleton fit. The participants in Smets (2019) stopped using an exoskeleton due to fit issues.

The noise of an exoskeleton could also influence wearing comfort (Groos et al., 2020).

5.1.2.2 Personal history of physical complaints of a person

Personal history of physical complaints (13/35 papers) refers to the extent to which a person perceives existing physical discomfort not caused by an exoskeleton. A person could already be suffering from back pain or another musculoskeletal disorder. This discomfort could be reduced by wearing an exoskeleton and the body part location of this discomfort is usually reported. Kozinc et al. (2021) and Baltrusch et al. (2021) report that people with existing pain are more willing to use exoskeletons.
Several papers report that discomfort was reduced when wearing the exoskeleton (Goffredo et al., 2019; e. g. Groos et al., 2020; Marino, 2019). Hensel and Keil (2019) reported slightly (not significant) more discomfort in the lower back and shoulders at the end a four-week trial. The participants of Smets (2019) reported a similar level of discomfort in the lower body during phase 2 and phase 3 of his study. Hensel and Keil (2019) found a rather weak correlation (r = 0.3) between intention to use exoskeletons and discomfort.

5.1.3 Psycho-socio factors

5.1.3.1 Perceived usefulness of an exoskeleton

The perceived usefulness of an exoskeleton refers to how useful an exoskeleton seems to a person. The expectation that an exoskeleton can help with reducing physical discomfort is reported by multiple papers (e. g. Cha et al., 2020).

5.1.3.2 General attitude towards exoskeletons

The general attitude towards exoskeletons refers to the opinion a person has with regard to exoskeletons (6/35). Most papers mention a positive attitude towards exoskeletons, but some participants in Maurice et al. (2018) also had mixed feelings about exoskeletons and one participant was very negative about exoskeletons.

5.1.3.3 Perceived safe use of an exoskeleton

Perceived safe use of an exoskeleton is the perception of the exoskeleton being safe or dangerous and the potential risks of wearing an exoskeleton (11/35). The three main risks that were identified are getting caught by objects in the work environment (e. g. Kim et al., 2019), a risk of falling (Kim et al., 2019; Upasani et al., 2019) and a concern for developing new musculoskeletal disorders (Upasani et al., 2019) or muscular atrophy (Maurice et al., 2018).

5.1.3.4 Social perception of the exoskeleton by the individual and by others

This concept refers to how the design and the associated image of the exoskeleton by others might influence the use of an exoskeleton (9/35). This social perception of an exoskeleton mostly had a negative connotation such as "*looked funny*" (Cha et al., 2020, p. 384) but also how aesthetically pleasing the design of an exoskeleton is (Amandels et al., 2019). Only one example was found where this social perception was rather positive ("looked 'cool'", Cha et al., 2020, p. 384).

5.1.3.5 Being in control of exoskeleton and own body

Whether people (dis)like being in control of the exoskeleton in their movements occurred in three papers. In one of the cases this was discussed as a contrast with working with collaborative robots, when the worker loses control of a task while with an exoskeleton on, they are still in control of the movements made (Maurice et al., 2018).

5.1.3.6 Existing knowledge about exoskeletons

This concept (2/35) refers to what people already know from exoskeletons. This could be information they have seen online or in the press or movies.

5.1.3.7 Cultural beliefs

Cultural beliefs (1/35) refer to aspects such as religion and tradition that could influence whether people would adopt exoskeletons. In Upasani et al. (2019) they were seen as potential barriers for farmers to adopt exoskeletons.

5.1.3.8 Openness to innovation

Individual curiosity (3/35) was seen as an important aspect of adopting exoskeletons (Cha et al., 2020) and this concept could also refer to how open people are for innovations.

5.1.4 Work related factors

5.1.4.1 Durability and reliability of an exoskeleton

This concept (7/35) refers to how durable (resistant against breaking) an exoskeleton is and also that it can be used in different weather and environmental conditions. Although it is expected from an exoskeleton that it can withstand bumping into objects without breaking and that it is resistant to these different conditions (Baltrusch et al., 2021; Upasani et al., 2019), some participants expressed concerns whether this is the case (e. g. Schwerha et al., 2021). Other sub themes include the battery charging and capacity and trust. The former refers to how fast the battery can charge and how long it will last (Upasani et al., 2019). This factor will mainly be relevant for active, battery powered exoskeletons. The latter refers to whether people feel like they can trust how exoskeletons work and include whether they think exoskeletons are dependable and predictable.

5.1.4.2 Exoskeletons to enable and attract staff

This concept (4/35) refers to the belief that exoskeletons could enable staff to perform tasks they are normally not capable of or could keep doing for a longer time (e.g. women, older adults, people with injuries or physical disabilities). This concept also includes the belief that using exoskeletons could reduce turnover and attract new workers. Note that arguing that an exoskeleton is mainly suitable for certain target groups can be considered as stigmatizing.

5.1.4.3 Maintenance duration of an exoskeleton

The topic of maintenance duration of an exoskeleton (2/35) describes how long an exoskeleton would be unavailable, for instance due to repairs. If the exoskeleton would be unavailable for a longer time, participants were worried this would lead to technology abandonment.

5.1.4.4 Storage of exoskeleton

This concept (4/35) refers to where an exoskeleton is stored such that it is available and easily accessible for the workers when they need it (Cha et al., 2020; e. g. Smets, 2019). Farmers explain doing tasks in different locations and wonder how they would manage keeping their exoskeleton near and ready for use when they do need it (Omoniyi et al., 2020).

5.1.4.5 Sterility and cleanliness of exoskeleton

The sterility of exoskeletons (4/35) refers mainly to the concerns related to keeping the exoskeletons clean. On the one hand, this could be a requirement for the work environment (such as in the OR or in places where food is processed), but it also refers to cleaning the exoskeletons, especially when shared with colleagues.

5.1.4.6 Compatibility of exoskeleton with tasks

The compatibility of exoskeletons with tasks refers to the extent to which an exoskeleton is or is not suitable to do a particular task (21/35). Some papers concluded that the exoskeleton is compatible with the tasks required for the job (e. g. Baltrusch et al., 2021; Luger, Cobb, et al., 2019), while in other papers concerns were expressed that the exoskeleton might be hindering for some tasks (Schwerha et al., 2021). In some papers, **specific objects** (e.g. tools and clothing) were mentioned that could be (in)compatible with an exoskeleton. Also, the **size of the exoskeleton** (the (extra) space around a person's body) and a person's **perceived range of motion** are important (e.g. Kim et al., 2019; Maurice et al., 2018, 2020; Näf et al., 2018; Smets, 2019). Finally, some papers describe the potential impact an exoskeleton could have on work quality. The papers that evaluate this concept do not think this is an issue (Moyon et al., 2020).

5.1.5 Policy related factors

5.1.5.1 Mandatory use of an exoskeleton

Whether the use of an exoskeleton should be voluntary or mandatory was discussed in four papers. In Baltrusch et al. (2021) one participant argues that the use of exoskeletons for luggage handlers should be mandatory just like the use of safety shoes, while participants in their focus group agreed that its use should be voluntary (Gilotta et al., 2019).

5.1.5.2 Strategies for MSDs prevention

This concept refers to strategies (e.g. lifting devices) used to prevent MSDs (6/35), but also improved awareness of current practices. Some companies have a coach to advice workers on proper lifting techniques and assistive devices.

5.1.5.3 Personal vs. Shared exoskeleton

This concept (1/35) refers to the internal company's policy on exoskeleton usage, in particular if an exoskeleton is a device that will be shared among colleagues or not.

5.1.6 Implementation related factors

This group of factors refers to the different steps needed to implement exoskeletons. The comments under this theme are either based on assumptions or experiences with implementing other solutions to improve ergonomics at work.

5.1.6.1 Ease of using an exoskeleton

The ease of using an exoskeleton refers to how easy it is to (learn how to) wear, adjust, don and doff the exoskeleton and this topic came up in 17/35 papers. In general, exoskeletons were considered to be easy to use (e. g. Luger et al., 2021). However, an exoskeleton was sometimes also evaluated as being cumbersome (e.g. Cha et al., 2020; Gilotta et al., 2019). This concept also includes the importance of the perceived speed of donning and doffing an exoskeleton and includes adjusting the exoskeleton to the worker (e. g. Baltrusch et al., 2021). If an exoskeleton would be a shared commodity, it will probably take more time to put an exoskeleton on, since adjusting is needed.

5.1.6.2 Purchasing exoskeletons

This theme (5/35) describes the considerations that are made to decide whether to buy exoskeletons. Potential expected benefits are considered such as improvements in quality, productivity, reduced costs associated with injuries or disorders and safety (Kim et al., 2019; e. g. Schwerha et al., 2021). The cost of an exoskeleton was seen as a barrier for adoption (Kim et al., 2019).

5.1.6.3 Exoskeleton training

Training how to use an exoskeleton (7/35) is important, since it is expected that getting acquainted helps with adoption and confidence (Upasani et al., 2019) and that it could help to convince people to use it (Kim et al., 2019). It has shown to have a positive effect on donning an exoskeleton (Moyon et al., 2020).

5.1.6.4 Using a champion to promote exoskeletons

This concept refers to using a person to promote the use of exoskeletons by sharing their experience with exoskeletons (4/35).

5.1.6.5 Identification of suitable exoskeletons

This concept refers to mapping work tasks to the exoskeletons that are currently available (2/35).

6 Discussion

We believe that our framework can benefit the exoskeleton community, and in particular the following groups: exoskeleton designers, researchers interested in studying the adoption of technology, companies interested in implementing exoskeleton and potential future end users.

For **exoskeleton designers**, our framework serves as a checklist for designers in different stages of their exoskeleton development. Considering the factors in our framework during the (ideally iterative) human-centered design, (re)development and evaluation phase of new or existing exoskeletons, is expected to increase the use and acceptance of exoskeletons at work. Requirements can be derived from the different factors in the framework such as the need for quick donning and doffing and exoskeletons that are easy to adjust and in a proper way such that the exoskeleton is supporting the person wearing it. The framework will hopefully stimulate designers, often with an engineering background without a lot of field experience, to design from the end user perspective and not only from an engineering perspective.

For researchers interested in the adoption of technologies such as exoskeletons the framework can serve as inspiration for an interview guide to discussing factors with end users in an interview or observation or create questionnaires investigating the acceptance of exoskeletons. Themes insufficiently addressed in existing empirical research (such as the role of cultural beliefs) can be investigated in more detail. Those researchers could also extend this framework to other application domains such as for exoskeletons in rehabilitation. **Companies interested in implementing exoskeletons** should consider what the usage policy of their exoskeletons will be.

All factors discussed in the framework directly influence the **end users**, so it is the role of the other stakeholders that they make and implement exoskeletons that fit their requirements of the end users. Ideally, these end users are involved and consulted already early on during the design process, when a prototype but maybe not fully functional exoskeleton can be tested and evaluated. The factors already encourage end users to reflect where they would store an exoskeleton at work and if that is even feasible given the size of the prototype. When a final, functioning prototype is already available, it is much harder and less cost efficient to adapt the design.

Finally, the strength of our framework is that it is holistic and that it addresses topics relevant to the individual, the work environment, and the tasks an individual must execute. This makes it more likely that exoskeletons will be accepted and not abandoned for reasons such as discomfort. In the future, if exoskeletons are used, they could prevent WRMDs, which would benefit workers and reduce costs associated with WRMDs.

The research on factors influencing the acceptance of exoskeleton use is still in its infancy and moreover there is a lack of long-term research done on this topic. Based on the reasons why people stop using exoskeletons (e.g., perceived discomfort), we have reason to believe that comfort is a very important factor for initial adoption of exoskeletons. However, since long term research (more than 3 months) does not exist (yet), we cannot say with certainty which factors play a larger role in the adoption of exoskeletons.

The identification of these factors from empirical research by our colleagues is a first step and even they cannot say for certain which factors are most important for long term use (although they do reflect on what they consider to be important, as well as what the participants in their research consider to be important). Using appropriate statistical techniques including structural equation modeling will allow us to investigate how the factors influence each other and which are more important (as can be demonstrated with statistical analysis). This is not to say that only quantitative measures can help us further in this research. Qualitative research investigating the adoption of exoskeletons can also provide us more insight in which factors are important in long term use of exoskeletons, for instance by conducting long term ethnographic research (observation, interviews).

We understand that designing an exoskeleton is a balancing act, where the designer tries to find the ultimate balance between the factors identified in our framework. Nonetheless, based on our experience with this topic, we think the following factors deserve initially more attention from exoskeleton designers such as the wearing comfort of the exoskeleton and the compatibility of exoskeletons with tasks. However, the other factors also deserve attention in process of designing, evaluating and implementing an exoskeleton since empirical research of our colleagues have indicated that they are important.

7 Conclusion

We analyzed literature on industrial exoskeletons to create an exhaustive framework to study acceptance and we identified 5 themes (physiological factors, work related factors, policy related factors, psycho-socio factors and implementation related factors) that could potentially influence acceptance. There is a need for such a framework since existing exoskeletons do not sufficiently meet the factors listed in the model which could explain why exoskeletons are not being used daily.

Our framework combines factors from existing technology frameworks with factors that are more specific to the technology at hand such as wearing comfort. Although we based the framework mainly on research discussing passive exoskeletons, it can still be a basic framework to study the future adoption of active industrial exoskeletons (e.g. battery charging time and capacity).

Our framework is a starting point for more standardized and exhaustive assessment of acceptance of industrial exoskeletons. Other researchers have already created test batteries to evaluate exoskeletons that allow comparing different exoskeletons (e.g. Kozinc et al., 2020). However, these batteries are limited to a selection of subjective measures while our framework is more exhaustive.

We have identified the following shortcomings in research on this topic which should be addressed in future research:

- Lack of theoretical foundation and lack of addressing relations between concepts
- Operationalization is not standardized
- Low number of participants (and even less females)
- Lack of long-term research
- Use (acceptance) rarely measured

The qualitative research papers included in our literature review gave most valuable contributions to the framework, because they discuss concepts in more depth. Especially the topics not addressed frequently should be included in future qualitative research methods such as interviews and focus groups.

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Factor	**Definition**	**Indicators**	**Example quote from qualitative data in articles**	**Example quantitative measure**
Exoskeleton use	The use or non-use of an exoskeleton at work.	Whether or how often they used the exoskeleton (quantitative indicators: a reference to the % or hours an exoskeleton has been used); reasons why people stopped using an exoskeleton.	Participants in the press shop only used the system briefly *"for physically demanding work tasks"* (Hensel & Keil, 2019, p. 216)	"*For what amount of time would you be comfortable wearing the ASE? (h)*" (Smets, 2019, p. 5)
Intention to use	The willingness of a person to use an exoskeleton.	When people explain that they are willing to use or not use exoskeletons.	"*Fifteen of the 17 interviewed persons **would decide to use** the "Chairless Chair" for such a type of work.*" (Groos et al., 2020, p. 79)	"*A final question asked whether they would use the exoskeleton if it was provided to them, and if "yes" whether this would be for the entire shift or only part of it.*"(Marino, 2019, p. 285)
		PHYSIOLOGICAL FACTORS		
Wearing comfort of exoskeleton	How comfortable or uncomfortable an exoskeleton feels.	Low wearing comfort can coincide with pressure (points), pain and (skin) irritation. Wearing comfort is influenced by the perceived weight of an exoskeleton, its thermal comfort, the noise, and exoskeleton makes, and the perceived person-exoskeleton fit. When mentioning that an exoskeleton feels uncomfortable, a body part is often reported.	"*They were only concerned about the **comfort**.*" (Maurice et al., 2018)	The Cornell Musculoskeletal Discomfort (MSD) Questionnaire (Hedge et al., 1999) was used in Smets (2019).
Personal history of physical complaints	The extent to which a person feels (no) physical discomfort in their body.	When a reference is made to the discomfort level of a person (and not how comfortable or uncomfortable wearing an exoskeleton feels). This level of discomfort can be measured across time and increase, decrease or remain the same.	"*... the workers declared that with the exoskeleton they perceived less fatigue...*" (Spada et al., 2017, p. 1260).	This was measured in Hensel & Keil (2019) with a 7-point Likert scale with 1 (no physical discomfort) and 7 (strong physical discomfort). This question was asked about all important body regions.

Factor	**Definition**	**Indicators**	**Example quote from qualitative data in articles**	**Example quantitative measure**
		PSYCHO-SOCIO FACTORS		
Perceived usefulness of an exoskeleton	How useful or helpful an exoskeleton seems to a person by providing physical support or by making a person more efficient/effective.	When a person mentions that an exoskeleton is useful or helpful, that (mental) support is perceived and that it might allow person to work for a longer time, that less effort is needed, or that it makes a person more efficient.	"*workers affirmed that the exoskeleton **can be useful** in carrying out work activities*" (Spada et al., 2017, p. 1261)	Support by the system was measured "*on a scale from 1 to 10 (1 ="Did not feel supported at all, 10 ="System supported me a lot")*" (Otten et al., 2016)
Attitude of a person towards exoskeleton	Opinion on exoskeleton (positive, negative or mixed).	When a person describes their opinion on exoskeleton.	"*I liked it*" (Gilotta et al., 2019, p. 931)	"*Using exoskeletons is a good idea*" (1 – agree – 5 – disagree) (Elprama et al., 2020, p. 341)
Perceived safe use of exoskeletons	Whether it is rather safe or dangerous to use an exoskeleton.	Remarks related to the perception of the exoskeleton being safe or rather dangerous and potential risks such as getting caught or an increased expected fall risk.	"*can be dangerous as it could **get caught on something***"(Gilotta et al., 2019, p. 931)	The feeling of safety was measured on a 9-point scale ranging from -4 (sad smiley) via 0 (neutral smiley) to +4 (happy smiley)(Groos et al., 2020).
Social perception of exoskeleton by the individual and by others	How the design and the associated social image of the exoskeleton might influence whether people will keep or start using an exoskeleton.	When remarks are made about the design of the exoskeleton by employees themselves or by other people's (often negative) perception of exoskeletons.	"*... four respondents mentioned religion, tradition, **peer judgment**, and ridicule as barriers to adoption ...)* (Upasani et al., 2019, p. 227)	Attractiveness was measured on a 7-point scale ranging from attractive (-3) to unattractive (+3) (Amandels et al., 2019)
Existing knowledge about exoskeletons	This concept describes the existing knowledge people have about exoskeleton (e.g. such as what they have seen online, in the press, at a trade show or in the movies).	When comments are made about what they already know about exoskeletons.	"*Of the 15% of participants who did indicate some previous knowledge, most noted that they had either seen them in the movies, at a trade show, read a little about them, knew that the military used them, or understood a little bit about them from seeing them online.*" (Schwerha et al., 2021, p. 3)	-
Exoskeletons to enable and attract staff	The belief that exoskeletons could enable staff to perform	When it is discussed that using exoskeletons could	"*With regard to personnel, participants indicate*	-

Factor	Definition	Indicators	Example quote from qualitative data in articles	Example quantitative measure
	a wide variety of tasks they are normally not capable of but also to reduce turnover and attract new workers.	allow workers to do more tasks or attract and keep more staff.	*that they believed EXO use could improve (i.e., reduce) turnover, enable older or female employees to perform tasks they would not normally be capable of improve morale, and expand the worker pool, and enable personnel with a wider range of abilities to be able to perform the jobs.*" (Schwerha et al., 2021, p. 5)	
Being in control of exoskeleton and own body	That people like or dislike being in control of the exoskeleton and their movements.	When comments are made about liking or disliking being in control while using an exoskeleton.	"*... factory workers liked the fact that with exoskeletons the user could keep full control of the gesture."* (Maurice et al., 2018, p. 134)	"*Ability for the user to regulate, control, and operate the product*" (Han et al., 2001, p. 147)
Cultural beliefs	Influence of religion and tradition on the adoption of exoskeletons.	When aspects such as religion and tradition are considered potential factors that influence the use of exoskeletons.	"*A notable finding is that although four respondents mentioned religion, tradition, peer judgment, and ridicule as barriers to adoption..."* (Upasani et al., 2019, p. 227)	-
Openness to innovation	How open people are to innovations.	When the innovativeness of exoskeletons is discussed.	"*In addition, individual curiosity (57%) and awareness of MS ergonomics problems (100%) were found as facilitators of intervention adoption in the OR.*" (Cha et al., 2020, p. 384)	-
		WORK RELATED FACTORS		
Durability and reliability of an exoskeleton	This concept refers to how durable and reliable an exoskeleton is, how resistant to breaking and how suitable it is to be used in different working conditions such as in outdoor environments with dirt, water and corrosive. It can also refer to how long the battery of an exoskeleton lasts.	When comments are made about being able to bump into something with an exoskeleton without it becoming damaged or breaking and about use in different weather conditions.	"*The team leader noted that the exoskeleton should be **wear-resistant**, [...] you are working [in the luggage hall] you can hit a cart, and then it's **damaged** and then it's not usable anymore.*" (Baltrusch et al., 2021, p. 136)	
Maintenance duration of an exoskeleton	This concept refers to the duration it takes	When comments are made about the exoskeleton being in	"*If the technology has to be sent a considerable distance for repair or maintenance and is away*	

Factor	**Definition**	**Indicators**	**Example quote from qualitative data in articles**	**Example quantitative measure**
	for an exoskeleton to be repaired.	repair and not available for use at work.	*from the worksite more than a few weeks, it could lead to technology abandonment.*" (Upasani et al., 2019, p. 226)	
Storage of exoskeleton	Where an exoskeleton is stored.	When the storage location of an exoskeleton is discussed.	"*Participants also discussed storage space for EXOs as a barrier.*" (Schwerha et al., 2021, p. 5)	-
Compatibility of exoskeleton with tasks	The extent to which an exoskeleton is (not) suitable to do a particular task.	When examples are given of how the exoskeleton is (not) hindering the execution of task or when tasks cannot be executed due to the exoskeleton. This could impact the quality of work. For example, if sitting in a vehicle is not possible with an exoskeleton on.	"*There was a consensus that the exoskeleton is not suitable for all tasks*" (Omoniyi et al., 2020, p. 3)	"For range of motion participants got asked "Are you restricted in your freedom of movement?" with a VAS scale ranging from "not restricted" to "heavily restricted."" (Näf et al., 2018, p. 10)
Sterility and cleanliness of exoskeletons	Concerns related to cleaning the exoskeletons for hygiene reasons.	When concerns are discussed regarding the cleanliness of exoskeletons for work-related reasons or for reasons of personal hygiene.	"*Hygiene concerns were brought up at nearly every company, especially for those who expected employees might need share EXOs.*" (Schwerha et al., 2021, p. 4)	-
		POLICY RELATED FACTORS		
Mandatory use of exoskeleton	Whether the use of an exoskeleton should be mandatory or not.	When it is discussed whether wearing an exoskeleton should be voluntary or obligatory.	"but the use should be non-mandatory" (Spada et al., 2017, p. 1261)	"*My boss shouldn't ask me to use the device*" was measured in Gilotta et al. (2019, p. 930) with a 7-point Likert scale ranging from (1) strongly disagree to (7) strongly agree (item originates from Venkatesh and Davis (2000)).
Personal vs. shared exoskeleton	Whether an exoskeleton would be an item shared with	When comments are being made about whether an	"Participants asked hypothetically whether the technology would be	-

Factor	Definition	Indicators	Example quote from qualitative data in articles	Example quantitative measure
	colleagues or only used for personal use.	exoskeleton would be used for personal use of whether it will be shared with colleagues.	better fitted as a personal device or would be interchanged among workers." (Cha et al., 2020, p. 384)	
Strategies for MSD prevention	Existing company strategies to prevent MSDs.	When various strategies to prevent MSDs are discussed.		
IMPLEMENTATION RELATED FACTORS				
Exoskeleton training	The training given about an exoskeleton in which topics are addressed such as donning, doffing, and adjusting an exoskeleton.	When remarks are made about the importance of training and the impact this training could have on adoption of exoskeletons.	"*Specifically, hands-on training and rote practice were emphasized, because this would improve understanding of the limitations and strengths of the technology.*"(Upasani et al., 2019, p. 227)	-
Purchasing exoskeletons	Whether an exoskeleton should be purchased or not.	When the different considerations are discussed.	"*In spite of the negative aspects pinpointed, only two subjects disagreed when the moderator directly asked "Should we buy it? The remaining 13 responded in a positive manner, especially for some specific activities.*" (Gilotta et al., 2019, p. 931)	-
Using a champion to promote exoskeletons	Using peers to promote the use of exoskeletons.	When different examples are given of how the use of exoskeletons could be promoted by peers.	"*The majority of the participants (57%) emphasized that the implementation of exoskeletons would require a champion at an institution to spearhead the efforts.*" (Cha et al., 2020)	-
Identification of suitable exoskeletons	The process of mapping tasks to exoskeletons that are currently available.	When the capabilities of exoskeletons are discussed in relation to the tasks that are required to be completed. By doing this, some type of exoskeletons could be ruled out because they do not provide the support required for a task.	*"The top three exoskeleton modules that would be used frequently on farms, as identified by the respondents, were the back, knee, and hand modules."* (Upasani et al., 2019, p. 225)	-

Factor	**Definition**	**Indicators**	**Example quote from qualitative data in articles**	**Example quantitative measure**
Ease of use	How easy it is to (learn how to) wear, don and doff the exoskeleton.	When a person mentions how easy (and fast) or difficult it is or rather cumbersome to wear, and don and doff an exoskeleton.	"*Service providers suggested that an ideal assistive device would be simple...*" (Upasani et al., 2019, p. 225)	"*The exoskeleton was easy to handle*" (1 – completely disagree, 10 – completely agree) (Luger, Cobb, et al., 2019, p. 180)

Table 3 Describes how the concepts identified in the papers were used.

APPENDIX A Table showing frequency of factors per paper

Factor	Exoskeleton use	Intention to use an exoskeleton	Work related factors						Policy related factors		
			Exoskeletons to enable and attract staff	Sterility and cleanliness of exoskeleton	Compatibility of exoskeleton with tasks	Storage of exoskeleton	Durability and reliability of exoskeleton	Maintenance duration of an exoskeleton	Mandatory use of exoskeleton	Personal vs. shared exoskeleton	Strategies for MSD prevention
Amandels et al. (2019)	0	0	0	0	0	0	1	0	0	0	0
Baltrusch et al. (2018)	0	0	0	0	1	0	0	0	0	0	0
Baltrusch et al. (2021)	0	0	0	0	1	0	1	0	1	0	1
Cha et al. (2020)	0	1	1	1	1	1	1	1	0	1	1
De Bock et al. (2021)	0	0	0	0	0	0	0	0	0	0	0
De Looze (2016)	0	0	1	0	1	0	0	0	0	0	1
Dezman et al. (2018)	0	0	0	0	1	0	0	0	0	0	0
Elprama et al. (2020)	0	1	0	0	0	0	0	0	0	0	0
Ferreira et al. (2020)	0	1	0	0	1	0	0	0	0	0	0
Gilotta et al. (2019)	0	1	0	0	1	0	1	0	1	0	0
Giustetto et al. (2021)	0	0	0	0	0	0	0	0	0	0	0
Grazi et al. (2020)	0	0	0	0	0	0	0	0	0	0	0
Groos et al. (2020)	0	1	0	0	1	0	0	0	0	0	0
Hensel & Keil (2019)	1	1	0	0	0	0	0	0	0	0	0
Huysamen et al. (2018)	0	0	0	0	0	0	0	0	0	0	0
Kim et al. (2019)	0	1	1	1	1	0	1	0	0	0	0
Ko et al (2018)	0	0	0	0	0	0	0	0	0	0	0
Kozinc et al. (2021)	0	0	0	0	1	0	0	0	0	0	0
Luger et al. (2019a)	0	0	0	0	1	0	0	0	0	0	0
Luger et al. (2019b)	0	0	0	0	0	0	0	0	0	0	0
Luger et al. (2021)	0	0	0	0	1	0	0	0	0	0	0
Marino et al. (2019)	0	1	0	0	0	0	0	0	0	0	0
Maurice et al. (2018)	0	0	0	0	1	0	0	0	1	0	0
Maurice et al. (2020)	0	1	0	0	1	0	0	0	0	0	0
Moyon et al. (2020)	0	0	0	0	1	0	0	0	0	0	0
Näf et al. (2018)	0	0	0	0	1	0	0	0	0	0	0
Omoniyi et al. (2020)	0	0	0	1	1	1	0	0	0	0	0
Otten et al. (2016)	0	0	0	0	0	0	0	0	0	0	0
Otten et al. (2018)	0	0	0	0	0	0	0	0	0	0	0
Qu et al. (2021)	0	0	0	0	0	0	0	0	0	0	0
Schwerha et al. (2021)	0	1	1	1	1	1	1	0	0	0	1
Smets (2019)	1	1	0	0	1	1	0	0	0	0	0
Spada et al. (2017)	0	1	0	0	1	0	0	0	1	0	0
Upasani et al. (2019)	1	0	0	0	1	0	1	1	0	0	1
Yan et al. (2021)	0	0	0	0	0	0	0	0	0	0	0
Total:	3	12	4	4	21	4	7	2	4	1	5

(table continues below)

Factor	Psycho-social factors							
	Openness to innovation	Cultural beliefs	Existing knowledge about exoskeletons	Being in control of exoskeleton and own body	Social perception of the exoskeleton by the individual and by others	Perceived safe use of exoskeleton	General attitude towards exoskeletons	Perceived usefulness of exoskeleton
Amandels et al. (2019)	1	0	0	0	1	0	0	1
Baltrusch et al. (2018)	0	0	0	0	0	0	0	1
Baltrusch et al. (2021)	0	0	0	0	1	1	0	1
Cha et al. (2020)	1	0	1	0	1	1	1	1
De Bock et al. (2021)	0	0	0	0	0	0	0	0
De Looze (2016)	0	0	0	0	0	0	0	1
Dezman et al. (2018)	0	0	0	0	0	0	0	1
Elprama et al. (2020)	0	0	0	0	1	0	1	1
Ferreira et al. (2020)	0	0	0	0	0	0	0	1
Gilotta et al. (2019)	0	0	0	1	1	1	1	1
Giustetto et al. (2021)	0	0	0	0	0	0	0	1
Grazi et al. (2020)	0	0	0	0	0	0	0	1
Groos et al. (2020)	0	0	0	0	0	1	0	1
Hensel & Keil (2019)	0	0	0	0	0	0	0	1
Huysamen et al. (2018)	0	0	0	0	0	0	0	1
Kim et al. (2019)	0	0	0	0	1	1	0	1
Ko et al (2018)	0	0	0	0	0	0	0	1
Kozinc et al. (2021)	0	0	0	0	0	0	0	0
Luger et al. (2019a)	0	0	0	1	0	1	0	0
Luger et al. (2019b)	0	0	0	0	0	0	0	0
Luger et al. (2021)	0	0	0	0	0	0	0	0
Marino et al. (2019)	0	0	0	0	0	0	0	1
Maurice et al. (2018)	0	0	0	1	0	1	1	1
Maurice et al. (2020)	0	0	0	0	0	1	0	1
Moyon et al. (2020)	0	0	0	0	0	0	0	1
Näf et al. (2018)	0	0	0	0	0	0	1	1
Omoniyi et al. (2020)	0	0	0	0	0	1	0	1
Otten et al. (2016)	0	0	0	0	0	0	0	0
Otten et al. (2018)	0	0	0	0	0	0	0	1
Qu et al. (2021)	0	0	0	0	0	0	0	1
Schwerha et al. (2021)	0	0	1	0	1	1	0	1
Smets (2019)	0	0	0	0	0	0	0	1
Spada et al. (2017)	1	0	0	0	1	0	1	1
Upasani et al. (2019)	0	1	0	0	1	1	0	1
Yan et al. (2021)	0	0	0	0	0	0	0	0
Total:	3	1	2	3	9	11	6	28

(table continues below)

	Implementation related factors					Physiological factors	
Factor	Ease of using an exoskeleton	Exoskeleton training	Identification of suitable exoskeletons	Using a champion to promote exoskeletons	Purchasing exoskeletons	Personal history of physical complaints	Wearing comfort of an exoskeleton
Amandels et al. (2019)	1	0	0	0	0	0	1
Baltrusch et al. (2018)	1	0	0	0	0	0	1
Baltrusch et al. (2021)	1	0	0	0	0	1	1
Cha et al. (2020)	1	1	0	1	1	1	1
De Bock et al. (2021)	0	0	0	0	0	0	1
De Looze (2016)	0	0	0	0	0	0	0
Dezman et al. (2018)	0	0	0	0	0	0	1
Elprama et al. (2020)	1	0	0	1	0	0	0
Ferreira et al. (2020)	0	0	0	0	0	0	1
Gilotta et al. (2019)	1	0	0	0	1	1	1
Giustetto et al. (2021)	0	0	0	0	0	0	1
Grazi et al. (2020)	0	0	0	0	0	0	0
Groos et al. (2020)	0	0	0	0	0	1	1
Hensel & Keil (2019)	1	0	0	0	0	1	1
Huysamen et al. (2018)	0	0	0	0	0	0	1
Kim et al. (2019)	1	1	0	1	1	0	1
Ko et al (2018)	0	0	0	0	0	0	1
Kozinc et al. (2021)	0	0	0	0	0	1	1
Luger et al. (2019a)	1	0	0	0	0	0	1
Luger et al. (2019b)	0	0	0	0	0	0	1
Luger et al. (2021)	1	0	0	0	0	0	1
Marino et al. (2019)	1	0	0	0	0	1	1
Maurice et al. (2018)	0	0	0	0	0	0	1
Maurice et al. (2020)	1	1	0	0	0	1	1
Moyon et al. (2020)	1	1	0	0	0	1	0
Näf et al. (2018)	0	0	0	0	0	0	1
Omoniyi et al. (2020)	1	0	0	0	0	0	1
Otten et al. (2016)	0	0	0	0	0	0	0
Otten et al. (2018)	0	0	0	0	0	0	0
Qu et al. (2021)	0	0	0	0	0	0	1
Schwerha et al. (2021)	0	1	1	0	1	1	1
Smets (2019)	1	1	0	0	0	1	1
Spada et al. (2017)	1	0	0	0	0	1	1
Upasani et al. (2019)	1	1	1	1	1	1	1
Yan et al. (2021)	0	0	0	0	0	0	1
Total:	17	7	2	4	5	13	29

Table A Shows that the wearing comfort of an exoskeleton is often mentioned in the result section of the papers in the review, followed by the perceived usefulness of an exoskeleton and compatibility of exoskeleton with task.