



Long-term effects and user acceptance of back-support exoskeletons in the workplace

Julia Riemer¹ · Sascha Wischniewski¹

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Abstract

The aim of our study was to evaluate the long-term effects of back-support exoskeletons (BSEs) in occupational settings. Valuable insights were gained through repeated in-depth interviews with occupational safety professionals over a one-year period regarding the use and impact of BSEs over a one-year period. The results highlight a significant lack of user acceptance, primarily due to movement restrictions and discomfort. Passive BSEs (PassEXO) were reported to be sometimes uncomfortable, restricting mobility and causing pressure point discomfort, while quasipassive soft BSEs (SoftEXO) received more positive feedback. In addition, factors such as proper fit, adjustability, hygiene maintenance, and the ease of donning and doffing were identified as key determinants of employee acceptance of BSEs. By gaining a deeper understanding of these factors, organisations can facilitate a successful and sustainable integration of BSE technology into the workplace.

Keywords Safety specialists · Periodic interviews · Field study · Subjective evaluation · Factors influencing use

1 Introduction

Work-related musculoskeletal disorders affecting the upper body are often caused by manual material handling, static work postures, or repetitive tasks (Chen et al. 2022; Vraa et al. 2022). Back-support exoskeletons (BSEs) are body-worn devices that might reduce work-related musculoskeletal disorders (Theurel et al. 2018). However, the applicability of BSEs in the workplace is influenced by several factors that may potentially lead to low user acceptance and reluctance to use them. These factors include the perceived physiological support and wearing comfort of the BSE, as well as its compatibility with work tasks (Elprama et al. 2022). Understanding how these factors change over a long period of use and what influences them is essential when implementing BSEs in companies.

Previous research on BSEs has primarily focused on evaluating their short-term physiological support, confirming their effectiveness in reducing muscle strain in specific areas of the body (Ulrey and Fathallah 2013; Bosch et al., 2016; Koopman et al. 2020; Kim et al. 2020; Madinei et al. 2020). In addition, studies have shown a reduction in perceived back strain (Graham et al. 2009; Baltrusch et al., 2021). However, negative effects, such as increased muscle activity in other body regions and changes in movement kinematics, have also been reported (e.g., Picchiotti et al. 2019; Luger et al., 2023). Some studies conducted over longer periods (three to four weeks) suggest relief in the lower back region and improved endurance capacity, particularly during static activities, but accompanied by increased strain in the legs and chest area (Hensel and Keil 2018; Marino 2019). Nevertheless, these evaluations have also revealed concerns about movement quality and a perceived reduction in work performance due to the BSE, as well as discomfort in the back, chest, and thigh areas (Amandels et al. 2018).

A comprehensive long-term evaluation of the effects of BSE use has not yet been conducted, with only two studies investigating the use of arm and shoulder-assisting supporting exoskeletons (Kim et al. 2021, 2022). There are several prerequisites for demonstrating long-term relief or strain on the musculoskeletal system as a result of wearing

✉ Julia Riemer, M.Sc.
riemer.julia@baua.bund.de

Dr. Sascha Wischniewski
wischniewski.sascha@baua.bund.de

¹ Unit Human Factors, Ergonomics, Federal Institute for Occupational Safety and Health (BAuA), Friedrich-Henkel-Weg 1–25, 44149 Dortmund, Germany

Table 1 Back-supporting exoskeleton-models used and their context of use

Expert	EXO	Use case
A	PassEXO	<i>Manufacturing</i> In the production of aircraft parts, BSEs are used when hanging sheets and assembly sheets of various sizes have to be transported, max. 2 kg; 3–4 times per minute with breaks
B	PassEXO and SoftEXO	<i>Construction</i> In track construction and concrete work, the BSEs are used when concreting rails in a kneeling position with continuous trunk bending
C	SoftEXO	<i>Manufacturing</i> At a logistics service provider, the BSEs are used for packing and picking parts and cartons, max. 1–2 kg, several hundred times a day
D	SoftEXO	<i>Healthcare</i> The BSEs are used in daily care, especially when transporting and transferring residents e.g., from bed to toilet or wheelchair

BSEs (Crea et al. 2021). Although biomechanical research methods have been tested for long-term studies (Riemer et al. 2023), a significant limitation is the low prevalence of BSEs in the field, which limits references to pilot or research settings. Furthermore, as the use of BSEs in companies is voluntary and often not used by workers, conducting a biomechanical evaluation under field conditions is very challenging.

To address this challenge and nevertheless gain insight into a long-term use of BSEs, as well as identify any issues that may prevent employees from using them in the workplace, we have developed an alternative approach: We conducted a study to assess the long-term effects of BSEs and identify workplace factors that hinder their long-term user acceptance over a one-year period through repeated interviews with occupational safety professionals who interact with BSE users.

2 Materials and method

Guided expert interviews were used as a method in this research. These provide a structured and systematic method of gathering information from safety experts using open-ended questions and identifying, through their expert judgement, various factors that limit the long-term use of BSEs.

The experts interviewed are people who have experience of the use of BSEs in workplaces, such as health and safety managers or occupational safety specialists. These experts are responsible for the monitoring and use of BSEs in their organisations and regularly interact with workers who use BSEs in their workplaces.

We had originally planned to interview workers who use a BSE at work, but this approach was not feasible for a number of reasons: None of the participants had been using the BSE regularly for more than a year. One factor contributing to this is the potential disadvantages of BSEs that affect their voluntary use, as described in several publications (e.g., Crea et al. 2021, Elprama et al. 2022). In addition,

companies typically do not have an adequate number of BSEs for all employees, resulting in different frequencies of use for different individuals. As a result, we decided to conduct an expert survey to gather subjective opinions from safety professionals, who regularly interact with workers and can report on use of BSEs in the workplace.

The expert interviews were conducted with intervals of eleven to fourteen weeks between each interview, resulting in four interviews with each expert over the course of one year.

2.1 Selection of the expert group

The study involved interviewing experts who work in the field of occupational health and safety and who are responsible for employees that use BSEs in their workplace. These experts were identified through contacts with BSE manufacturers and online recruitment. The sample consisted of four experts from different industries who supervised the use of BSEs by between 50 and 400 volunteer users. Table 1 provides an overview of the industries represented by the experts and the types of BSE use cases for which they were responsible for.

We sought to ensure diversity in our sample by selecting experts from different industries and use cases. The experts included a health and safety coordinator (Expert A), occupational health and safety professionals (Experts B and D), and a nursing education coordinator (Expert C). All of the experts were responsible for monitoring the use of BSEs in their respective companies or care facilities and were in regular contact with the users of BSEs.

In the following analysis, the results for classic passive BSEs (PassEXO) and quasipassive soft BSEs (SoftEXO) are presented separately. PassEXOs have rigid, force-conducting structures, while SoftEXOs have soft elements such as straps and fabrics in their structure. However, these BSEs are lightweight and can be worn underneath clothing. The main reason for the distinguishing between these two types

of BSEs is that they have different effects on the body and different attachment points.

2.2 Interview procedure

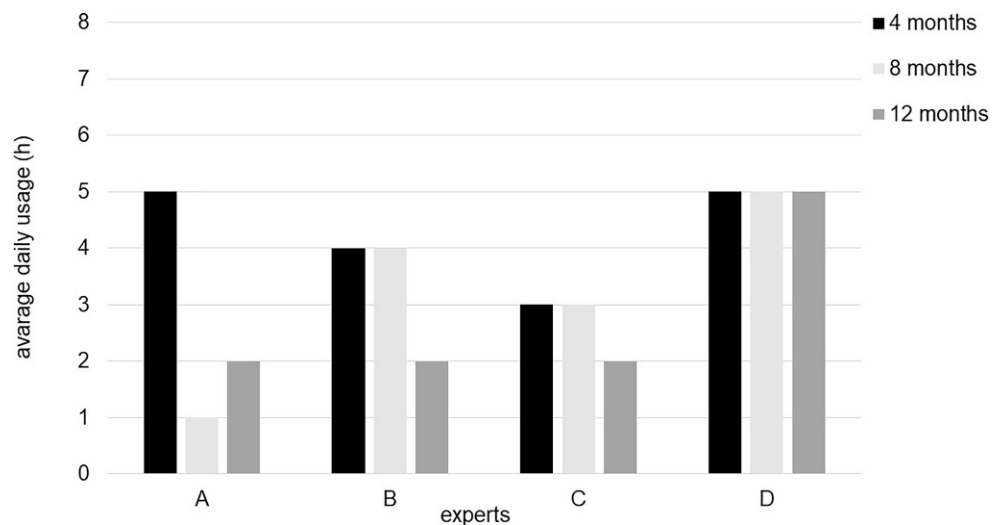
Prior to the first interview, all experts signed a consent and privacy form, which included a commitment not to disclose any identifying information about individual BSE users or workers in the companies. The interviews were conducted by telephone and lasted approximately 60 min each. During the interviews, questions were asked about the experts’ assessment of the average duration of BSE use and the specific tasks performed with the BSE in the experts’ companies. The experts were also asked about their perceptions of the physical support and comfort provided by the BSE. These answers primarily reflect their personal professional judgement and were generated through close interaction with the users of the BSE in the companies.

The interview data were analysed using established qualitative methods and a semi-open interview guide. After verbatim transcription, the textual material was analysed using content analysis methods (Mayring and Brunner, 2007), by creating a category scheme through which the material is searched and evaluating relevant passages. The following guiding categories for long-term BSE use were selected to address the research questions: Willingness to Use, Discomfort, Adjustment and Fitting. All direct quotes used were translated into English.

3 Results

The results obtained from the expert interviews are substantially vary considerably depending on the BSE used in the experts’ companies. For further interpretation, we distinguished the two types of BSEs in the further results.

Fig. 1 Reported average working hours per day spent wearing the back-supporting exoskeleton since the last interview, according to experts informations



3.1 Willingness to use

At the beginning of the survey, all the experts unanimously reported that the employees in their companies showed a positive inclination and willingness to use the BSEs. “[...] when they work with [the BSE], the feedback is positive” (Expert A); “At the beginning we did a survey among the employees who would be willing to wear [the BSE], and those who wanted to were allowed to do so. Initially, the user acceptance and motivation were very high and the expectations of the employees were also very high” (Expert B).

However, the willingness to use of the BSEs diminished over time. After eight months, employees displayed a growing reluctance to use the technology, despite the companies’ efforts to motivate them and make necessary adjustments “The people who have been wearing (...) [SoftEXO] from the beginning continue to use it. The others are harder to motivate. Unfortunately, acceptance is not very high. Out of 50 employees, only 3 use it” (Expert C); “We evaluated the activities and saw where it made sense to use the PassEXO. [...] the (...) [PassEXOs] are now provided for particularly stressful work [...] and also for employees with health problems or who are already older” (Expert B).

A promising factor of employees’ willingness to use BSEs is the duration of voluntary use. Figure 1 shows the average number of hours per day reported by the experts that employees spent wearing the BSE at each time point in the survey. It is important to note that the number of hours represents the time elapsed since the last survey. Duration of use at the start of the first interview is not shown because assessed the use in the period indicated and some companies start testing exoskeletons after the first survey date. From the data presented, it can be seen that the average duration of BSE daily use tends to decrease with the survey continuing over time. In particular, experts A and B

observed the largest decrease (≥ 2 h) in PassEXO use from 4 to 12 months.

In contrast, the experts from companies using SoftEXOs reported a decrease in PassEXO use of 1 h in BSE use from month 4 to 12 (Expert C) or a constant number of hours of BSE use throughout the survey period (Expert D). It appears that workers who used SoftEXOs continued to use the BSEs at the end of the study “*Employees don’t really have any reservations. If they see the benefit, they use the [SoftEXO]*” (Expert C); “*The people who have tried it usually use the [SoftEXO]*” (Expert D), while one company reported at the final survey date that it would stop using the PassEXOs. “*Employee response is so low because of the lack of convenience of the [PassEXO], and from the company’s point of view it’s a cost issue at some point*” (Expert B).

3.1.1 Disability in work activities

Throughout the study, the experts consistently reported that the PassEXOs primarily aided in the specific activities for which they were purchased and were not considered to be useful beyond those activities “[...] *they work the part of the shift in the same place and have it on. When they rotate, they can take it off, because the exoskeleton makes no sense for other activities*” (Expert A).

Two experts also described the BSE as unsuitable, particularly for activities involving rotation “*The PassEXO is clearly a hindrance for many bending and rotating movements. And the exoskeleton itself is also a major limitation to the range of motion*” (Expert B).

For the SoftEXOs, on the other hand, there are fewer disadvantages are apparent in other work activities “*They [...] even go on break with the (...) [SoftEXO] and leave it on*” (Expert D), but again, one expert notes the task-specific use: “*In the meantime, people know for which task they wear the [SoftEXO] and for which task they do not. When sitting, especially if the chair has a back, it is very annoying. People use it mainly when they are standing*” (Expert C).

Furthermore, the experts also expressed safety concerns regarding the limited mobility of employees when using PassEXOs “[...] *they also complain, for example, that they have little space on the lifting platform and that they are afraid of hitting their colleagues with the [PassEXO]*” (Expert B).

3.1.2 Frequent donning and doffing

The additional effort required to don and doff the BSE is a significant deterrent for many employees. “*Employees have reservations, especially about donning. The problem is fitting the [PassEXO] because people are always changing their workstation. They have to do something extra and most of them don’t have the motivation to do that*” (Expert A).

“*This is also difficult, especially because the SoftEXO always takes a few minutes to adjust, which is sometimes difficult in the daily shift routine. Putting it on and adjusting it is a time factor that has already been mentioned to me by management*” (Expert D).

Due to its limited applicability and potential interference with other tasks, PassEXOs often need to be put on and taken off frequently. This additional inconvenience makes the BSE less appealing to employees and ultimately leads to a lower frequency of use “*As I said, employees are no longer so keen to experiment. In the activities where it works, they use it. But for new activities they usually don’t use it anymore*” (Expert B).

However, expert B also emphasised that he prefers voluntary use in order not to put additional pressure on employees: “*I also think it’s good that we don’t have one for all employees, I think that would only create pressure to wear it*” (Expert B).

3.2 Discomfort

Experts reported complaints of pressure in the chest, shoulders, hips, and leg shells. In particular, all experts whose companies used PassEXOs reported discomfort at all times during the survey “[...] *some report relief in the back and others find that the [PassEXO] cuts into the thighs*” (Expert A); “*People have pressure points with the (...) [PassEXO] on the leg shells, the plastic is too hard there [...]. This was not the case with the (...) [SoftEXO]*” (Expert B).

The SoftEXOs generally received positive feedback in terms of comfort, but complaints were still reported, particularly at the beginning of the survey and after 3 months. However, these issues were mostly resolved through adjustments to the SoftEXOs “*The (...) [SoftEXO] sometimes presses a little in the chest area, as I was told*” (Expert D); “*It still takes some getting used to under the arms, but we have now stuck on pads from the manufacturer. This has definitely made it more comfortable to wear*” (Expert C).

Several employees expressed relief when using both PassEXOs and SoftEXOs. One expert stated “*Posture is improved and the colleague who always wears the [SoftEXO] also reports relief in her knees*” (Expert C), while another noted, “*I always say it depends, but the [PassEXO] is definitely helpful. Especially for the older staff members as well*” (Expert A). However, despite these reports, the survey did not identify any significant or consistent physical improvements throughout the interview period. Expert C mentioned specific complaints and pain in the lower back area of the SoftEXO-using employees, which the expert attributes primarily to myalgia. In addition, one employee experienced knee pain with the SoftEXO, “[...] *one employee also had knee pain because he had bent his knees*

with the (...) [SoftEXO]” (Expert C). However, it was not possible to determine any connection or development of these symptoms over the course of the survey.

3.2.1 Environmental influences

As the study progressed, it became clear that temperature had a significant impact on wearing comfort. In the summer months, three experts noted that sweating under the BSE reduced comfort *“In summer we had the problem with chafing because of sweating [...]”* (Expert A); *“[...] in the summer we had chafing on the chest because there is quite a lot of material there”* (Expert C).

Conversely, an expert whose employees frequently work outdoors reported that winter clothing also resulted in poor comfort with the PassEXO *“There are still pressure points on the hips and shoulders, but the staff do not wear it permanently. In winter with the clothes on, you have less of that, of course, but it is very uncomfortable”* (Expert B).

3.3 Adjustment and fitting

Because not enough BSEs were purchased for all employees in each company, the BSEs had to be shared. All experts recognised that the need to frequently adjust the BSE to fit individual users was a time-consuming process that had a negative impact on user acceptance: *“[...] we do not have personalized exoskeletons and fitting is also perceived as strenuous”* (Expert C).

Furthermore, the fit of the BSEs appears to be inadequate for some workers, which reduces their willingness to wear them. This applies to both the PassEXOs: *“We also have an employee with a slightly larger belly, the exoskeleton then presses a little and he therefore does not wear it”* (Expert A), and the SoftEXOs *“For small, petite people, the [SoftEXO] is already very annoying with the large structure on the back and hips”* (Expert D).

3.3.1 Hygiene

The aspect of hygiene when using the same BSE is also mentioned by two experts in this context *“People are skeptical, the sweat of other employees is mentioned as a reason not to wear the [PassEXO]”*. (Expert A), *“One thing that’s really annoying is that you can’t change the pads on the [SoftEXO]. Mainly because of the sweat”* (Expert C). The aspects of hygiene are addressed by the employees themselves, and for some, it is a reason not to use the BSE.

4 Discussion

This study had the main goal to assess the long-term effects of BSEs in the workplace. To achieve this, we conducted periodic interviews with occupational safety specialists responsible for supervising workers regularly wearing BSEs. This approach allowed us to include feedback from a wide range of BSE users in our study while obtaining a comprehensive perspective from experts on their use and impact. We specifically examined the use of classic passive BSEs (PassEXO) and quasipassive soft BSEs (SoftEXO), as their effects on the body and various attachment points differ significantly, yielding model-dependent results. By conducting realistic assessments of BSE utilization and behavior, we aimed to uncover key workplace factors that may hinder their adoption.

The survey results clearly indicated a low level of user acceptance for BSEs due to movement restrictions and discomfort. PassEXOs were found to be inconvenient, causing difficulties in bending, rotating movements, and overall mobility, whereas SoftEXOs had fewer disadvantages in various work activities. PassEXOs resulted in discomfort due to pressure points and abrasion at the chest, shoulders, hips, and leg shells. On the other hand, SoftEXOs generally received positive feedback regarding comfort, although some initial complaints were resolved through adjustments. Previous studies conducted over longer durations (three to four weeks) under real working conditions corroborate our findings. For instance, Hensel and Keil (2018) demonstrated increased strain in the legs and chest region, with negative ratings for comfort at the body contact points. Similarly, Marino (2019) found that a four-week use of PassEXOs led to concerns about limitations in movement quality, work performance, and subjective comfort, as also confirmed by Kazerooni et al. (2019). Amandels et al. (2018) reported discomfort in the upper back, chest, and thigh areas. Furthermore, prior investigations have reported good user comfort with SoftEXOs due to their lighter weight (Heydari et al. 2013) and suitability for wearing underneath clothing (Lamers et al. 2018). The various seasons with changing temperatures were discovered to have a significant impact on wearing comfort. In summer months, sweat and friction became concerns, while winter clothing affected comfort with PassEXOs. Liu et al. (2021) confirmed increased discomfort when using BSEs in particularly hot or cold environmental temperatures. However, our results could not be fully supported by previous findings, potentially due to the limited duration of prior BSE studies, which did not span across different seasons.

The frequent need for adjustments and the inadequate fit of the BSEs have been identified as time-consuming and negatively affecting the users. This aspect has also been addressed in previous publications (see Toxiri et al., 2019;

Sposito et al. 2021). To address these issues, it is necessary to make appropriate adjustments to the BSEs, specifically focusing on their adaptability to different body dimensions, as described in Riemer and Wischniewski (2022). Additionally, challenges related to variations in body sizes and shapes have been encountered, along with concerns regarding hygiene when sharing the same BSEs among employees using both PassEXOs and SoftEXOs. Models should be developed that allow for the cleaning of the parts that come into contact with the body (Kim et al., 2022, Elprama et al. 2022), as long as an insufficient number of BSEs are available for individual use by each employee.

Furthermore, the additional effort required to don and doff the BSEs, particularly PassEXOs, has acted as a deterrent for many employees, as confirmed by Junius et al. (2017), Moyon et al. (2019) and Schwerha et al. (2021). Specifically, the inflexibility of the BSEs in real-world scenarios, as highlighted by Bosch et al. (2016), leads to the frequent need to turn the BSEs on and off in order to perform other tasks without the constraints imposed by the BSE.

Undoubtedly, the findings of this study are subject to certain limitations due to the subjective perception of the survey respondents, as direct interviews with the users were not conducted. Thus, the survey does not collect user-specific and individual effectiveness of the BSE, but rather offers expert assessments from different use contexts and companies. Furthermore, the diverse durations of BSE use and variations in work contexts pose challenges when attempting to compare and generalize the results. Still, this study highlights various factors, including comfort, fit, adjustability, and hygiene, influencing employee acceptance and willingness to use BSEs over a one-year period. The results suggest that SoftEXOs have a higher rate of worker willingness to be used compared to PassEXOs, which can be attributed to differences in their structural design. The soft and flexible nature of SoftEXOs allows for greater freedom of movement, thereby making them more comfortable for extended periods of wear. The factors uncovered in this study offer valuable insights that can contribute to facilitating the sustained integration of BSEs within organizations in the future.

5 Conclusion

The study's findings provide valuable insights for the implementation of back-support exoskeletons in companies and serve as guidance for organizations aiming to implement BSEs over the long-term. Understanding the importance of comfort, fit, adjustability, and hygiene can aid in the development and selection of back-support exoskeletons for work places. It is recommended for future research

to incorporate direct user interviews and explore the effects of back-support exoskeletons use across diverse work environments, with a specific focus on soft back-support exoskeletons. By further investigating and refining the factors influencing user acceptance, organizations can pave the way for the successful and sustainable integration of back-support exoskeletons technology in the workplace.

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