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Effects of different implementation approaches on the acceptability of a passive exoskeleton for workplace health promotion: An intervention study using the MATE-XT®

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ABSTRACT

The aim of this intervention study was to examine the effects of two different implementation approaches of a passive, upper-limb exoskeleton (MATE-XT®) on the acceptability of the exoskeleton by participants and participants' health in a workplace health promotion setting.

Participants were assigned to one of two groups and underwent either an exoskeleton application training (AT, N = 9) or standardized briefing (SB, N = 9) over a period of 4 weeks. Outcomes of interest, i.e., acceptability of the exoskeleton and participants' health, were assessed using the Technology Usage Inventory and the Short-Form 12 Health Survey before, immediately after, and approximately one year after the 4-week implementation period. Wearing time was tracked over the 4-week implementation period.

AT participants reported significantly higher usefulness and usability, greater curiosity, reduced skepticism, and had a higher wearing time in the last two weeks of the implementation. In addition, they perceived the exoskeleton as more useful, and reported higher physical health outcomes than SB participants. At one-year-follow-up, AT participants continued to perceive the exoskeleton as more valuable.

1. Introduction

Musculoskeletal disorders have a high prevalence in occupational settings among adults in Germany (European Agency for Safety and Health at Work, 2019), and the number of sick leave days due to musculoskeletal disorders was reported to be 354.1 per 100 insurance years in 2022 (Hildebrandt et al., 2023). In Germany, musculoskeletal disorders result in estimated economic production loss costs of 20.5 billion Euros, and estimated lost gross value added due to incapacity for work of 35.2 billion Euros (BAuA, 2022). In Europe, the yearly loss due to musculoskeletal disorders is estimated to be about 240 billion Euros in the working-age population, and musculoskeletal disorders account for 40–50 % of costs for work-related health issues (Bevan, 2015). Studies among industry workers, i.e. those employed in the food industry, as well as plant and machine operators and assemblers, have revealed a 12-month prevalence of 60 % for back problems and 54 % for work-related shoulder and neck problems (Govaerts et al., 2021).

Previous studies have demonstrated a relationship between physically demanding tasks, such as manual handling activities, including lifting, carrying, pushing, and pulling, and musculoskeletal disorders in industrial and healthcare settings. Consequently, the implementation of mechanical aids to reduce heavy physical demand is suggested as an approach to reduce these risks (Van der Molen et al., 2005; De Looze et al., 2001).

In recent years, there is also growing interest in exoskeletons for workplace health promotion (De Looze et al., 2015), and exoskeletons are regarded as promising alternative to existing, traditional solutions such as external manipulators which have limited feasibility (Toxiri et al., 2019). An exoskeleton is a supportive device which can be used in an occupational setting to decrease muscle activity (Gräf et al., 2024) and potentially prevent work related injuries of employees by reducing physical strain (Terstegen and Sandrock, 2019). In general, exoskeletons can be categorized based on their function and operation mode, as well as supported limbs or muscle groups (DGUV, 2019). For example, active

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exoskeletons are motorized, whereas passive ones do not require electrical power and have only mechanical functionality (DGUV, 2019).

To date, exoskeletons are being used in various occupational fields and for different work-related activities (Moeller et al., 2022), including but not limited to construction (Kim et al., 2020; Zhu et al., 2021), cleaning (Ilaria Pacifico et al., 2023), sanding operations (Moyon et al., 2018), agriculture and forestry (Harith et al., 2021), healthcare (Arnoux et al., 2023), mining (Dempsey et al., 2018), waste collection (Ziaei et al., 2021), and the automotive industry (Iranzo et al., 2020; Spada et al., 2017). A growing body of research has demonstrated favorable effects of passive exoskeletons on different body functions, i.e., decreased fatigue (Bär et al., 2021; Bock et al., 2022; Schmalz et al., 2019; Vries and Looze, 2019) or reduced muscle load and activity (Hensel and Keil, 2018; Schwerha et al., 2022). Exoskeletons also demonstrated potential benefits in reducing low-back muscle activity for workers during certain tasks such as precision (Madinei et al., 2020) and load shifting (De Looze et al., 2015; Picchiotti et al., 2019). However, while exoskeletons may have benefits, there are also some challenges when implementing them into workplaces. For example, little is known about exoskeleton acceptability in a real operational setting, mainly because most prior studies were conducted in laboratory settings. Furthermore, while several studies have examined the effectiveness of exoskeletons, only few studies to date have systematically investigated potential factors that may impact the intention to use such a device and the regularity of use on a voluntary basis. The intention to use exoskeletons in occupational settings is influenced by a variety of factors. Before initial use, key determinants include expected effort, performance expectancy, and social influence (Elprama et al., 2020). After practical use, factors such as perceived comfort, task-technology fit, perceived safety, and perceived usefulness become more relevant (Schwerha et al., 2022). Studies have shown that in the automotive sector, perceived usability and discomfort during use are significant predictors of the intention to use an exoskeleton (Hensel and Keil, 2019), whereas during sanding operations, back and arm comfort of upper-body exoskeleton play an important role (Moyon et al., 2018).

A long-term survey conducted among occupational safety experts highlighted additional practical considerations such as accuracy of fit, interference with work tasks, workplace availability, and overall wearing comfort (Riemer et al., 2024). Exoskeleton use has also been associated with increased self-efficacy in luggage handlers, particularly among those experiencing low back pain (Baltrusch et al., 2020), which is an established predictor of technology acceptance (Davis, 1989). Conversely, the perception of exoskeletons as a symbol of physical vulnerability may negatively affect utilization (Baltrusch et al., 2021). Furthermore, negative assumptions and occupationally specific biases have been reported to reduce acceptance across different work environments (Hoffmann et al., 2022; Wioland et al., 2021). Finally, according to the Technology Acceptance Model (TAM), perceived ease of use and usefulness are important determinants of user behavior and the acceptance of novel devices including but not limited to exoskeletons (Davis, 1989).

Another important factor that impacts the acceptability of exoskeletons is the implementation approach. To this end, research suggests that a personalized approach, which includes supervision, behavioral coaching, and sufficient adjustment time, is more effective in ensuring the correct use of exoskeletons and improving acceptability compared to a basic standardized briefing (Baltrusch et al., 2020, 2021; Steinhilber et al., 2020).

To date, limited research in the field is available on different exoskeletons implementation approaches and how these approaches may affect users' acceptability. Therefore, the aim of this study was to examine the effects of two different, 4-week implementation approaches, i.e., application training (AT) versus standard briefing (SB), on the acceptability of a passive exoskeleton for the upper limbs (MATE-XT®), and on participants' health outcomes as a secondary outcome. Specifically, we compared exoskeleton acceptability and health of participants who underwent the application training (duration of about 4.5 h; including modules based on theory of planned behavior) versus standardized briefing (duration of about 1.5 h; similar to training courses offered by exoskeleton manufacturers which were also optionally available). Outcomes of interest were assessed at baseline and two different follow-up time points (i.e., immediately after the implementation period and after about one year). Both groups used the exoskeleton for 4 weeks between baseline and immediate follow-up. We hypothesized that the acceptability of the exoskeleton would increase after both implementation approaches but would be higher after the application training as compared to standardized briefing as it reflects a more individualized and extensive approach using behavior change techniques. We also assumed that, after one year, the acceptability of the AT group would be higher and more sustainable than of the SB group. In addition, we also anticipated an improved health status among participants who underwent the application training as compared to the standardized briefing after the 4-week implementation.

2. Methods

2.1. Study setting and participants

This one-year intervention study was carried out in workshops at the Karlsruhe Institute of Technology (KIT), a public research university in the state of Baden-Wuerttemberg, Germany. A pre-selection of possible workshops was made in collaboration with the head of the KIT-wide health network (author CH), as well as the administrative units of medical services, and occupational safety at KIT. At the same time, additional workshop managers were contacted to inquire about the possibility of conducting the intervention study in their workshops. Six institutes were contacted and provided with basic information about the research project. In a next step, a meeting was held with persons responsible for the institutes, in which the project was explained in more detail and questions were addressed. The workshops were then inspected by the investigators to determine whether the use of the MATE-XT® exoskeleton in the given workshop would be feasible for the purpose of this study.

Study participants were technical and laboratory workers at different institutes of the KIT, i.e., persons working on steel and timber constructions as well as soil and rock mechanics. During their regular work, they performed both, fine motor activities such as assembling components, and gross motor activities such as lifting and carrying heavy objects. Care was taken to ensure that employees performed tasks in their daily work during which the effect of the MATE-XT's mode of action could be noticeable, e. g., when working at and above shoulder height. Inclusion criteria of study participants were no prior experience using exoskeletons, an age of ≥18 years, and not having acute musculoskeletal, neurological, or cardiovascular diseases. A total of 21 participants (2 females, 19 males) met the eligibility criteria and were included in the study. All participants were informed about the purpose and content of the study and provided written informed consent. The study was approved by the ethics committee of the KIT, Karlsruhe, Germany.

2.2. Passive exoskeleton

In this study, we used the Muscular Aiding Tech Exoskeleton eXTreme (MATE-XT®), which is a passive exoskeleton developed by Comau S.p.A. (see Fig. 1). The exoskeleton has a weight of 3 kg and is made of breathable fabrics. The MATE-XT® was designed for the upper limbs, and may be used to provide support as well as reduce fatigue during flexion-extension overhead movements. The exoskeleton is adjustable to accommodate users shorter than 179 cm and taller than 190 cm, as well as different shoulder widths. The exoskeleton consists of several components, including a spring mechanism, a waist belt, and arm loops. These are designed to ensure an optimal range of movement for the user. The support can be adjusted and selected from eight

Fig. 1. MATE-XT exoskeleton by Comau.

different assistance levels, depending on users' height and weight (Comau, 2021).

2.3. Study design and exoskeleton implementation

At baseline, all participants completed a pretest survey, assessing demographic information, exoskeleton acceptability (Technology Usage Inventory by Kothgassner et al., 2012), as well as physical and mental health (SF-12 Health Survey by Morfeld et al., 2011). Participants were then assigned to one of two groups undergoing different exoskeleton implementation approaches over a period of 4 weeks, i.e., application training (AT) and standardized briefing (SB). Participants were allocated based on the respective workshops' availability in terms of time. The implementation, as well as the questionnaire, was conducted during working hours.

AT participants underwent a theory-based application training (duration: 4.5 h). The theory of planned behavior (Ajzen, 1991) and transtheoretical model (Prochaska and Di Clemente, 1984) were used as a basis for developing the training which provided an extensive explanation on the correct use and handling of the exoskeleton. The transtheoretical model is a framework for behavior change and has six stages: precontemplation, contemplation, preparation, action, maintenance, and termination. Based on the theory of planned behavior, information was provided about medical and anatomical functionality of the spine and the shoulders, as well as ergonomic basics of lifting and carrying in order to increase participants' understanding of the potential benefits of an exoskeleton from ergonomics and anatomical view, and thus make its use more attractive. Each participant received a personalized exoskeleton fitting, followed by a guided individual adjustment to the exoskeleton, and mobilization as well as stretching exercises for the shoulder and spine were demonstrated and practiced. These exercises should help to mobilize and loosen the structures and muscles that are stressed and strained at work. Participants were given the opportunity to familiarize themselves with the exoskeleton, and internalize the received information using a lifting and carrying parkour and ask questions, if needed. This practical instruction served to increase the perceived behavioral control. The parkour contained different objects such as dumbbells, ropes, and boxes, which were used for four different tasks using the exoskeleton, i.e., to lift dumbbells to shoulder height, stack boxes on a table, untie knots over shoulder height and carry objects. This was followed by an interactive phase in which participants were asked to identify potential barriers of the exoskeleton and propose possible solutions. Participants were then asked to wear the exoskeleton for 4 weeks as outlined in a written wearing plan. According to this plan, participants were asked to successively increase the exoskeleton wearing time every week, i.e., participants started with 45–60 min per day in week 1, then increased to 90–120 min in week 2, then to 120–180 min per day in week 3, and to 240 min per day in week 4. Participants were free to decide during which work tasks they use the exoskeleton. During the training, both the device and its functionality were explained in detail to help participants make informed decisions about its use. In addition, a workplace inspection took place after the first two weeks, during which participants had the opportunity to ask questions about the exoskeleton and discuss problems they may had encountered. At the end of the training, participants had passed through all six stages of the transtheoretical model which may help to change behavior sustainably. On the other hand, SB participants received a standardized briefing (duration: approximately 1.5 h) at baseline as it is generally offered by companies. Accordingly, they received information on the correct use and handling of the exoskeleton, along with an individual adjustment. However, no wearing schedule was provided for the 4-week implementation period, as well as no further information about lifting and carrying ergonomics. Also, no mobilization and stretching exercises were shared with participants and no familiarization parkour was carried out. Participants in both groups were instructed to not exceed an exoskeleton wearing time of more than 4 h per day. Two follow-up assessments were then conducted with all participants; one immediately after the 4-weeks implementation period, and one after approximately one year (see Fig. 2).

2.4. Assessment of study outcomes at baseline and follow-up

2.4.1. Exoskeleton acceptability

Acceptability of the exoskeleton was assessed using the Technology Usage Inventory (TUI), a 30-item, self-reported questionnaire assessing technology-specific and psychological factors across 8 scales, i.e., curiosity, anxiety, interest, usability, immersion, usefulness, skepticism, accessibility, and additionally the scale intention to use (Kothgassner et al., 2012). We slightly adapted the TUI to align with the study objectives, removing the immersion and accessibility scales. The survey was administered before, immediately after, and approximately one year after the 4-week implementation period. At baseline, we assessed anxiety, interest, curiosity, skepticism, and usefulness; at follow-up measurements, we assessed curiosity, skepticism, usefulness, intention to use, and usability. At 1-year follow-up, we assessed anxiety, interest, curiosity, skepticism, usefulness, intention to use, and usability using the TUI. For statistical analysis, we created a score for each TUI scale, with higher scores indicating higher degrees of acceptability on all scales. After the 4-week implementation period, when the exoskeletons were collected, we also received short feedback from five participants of both

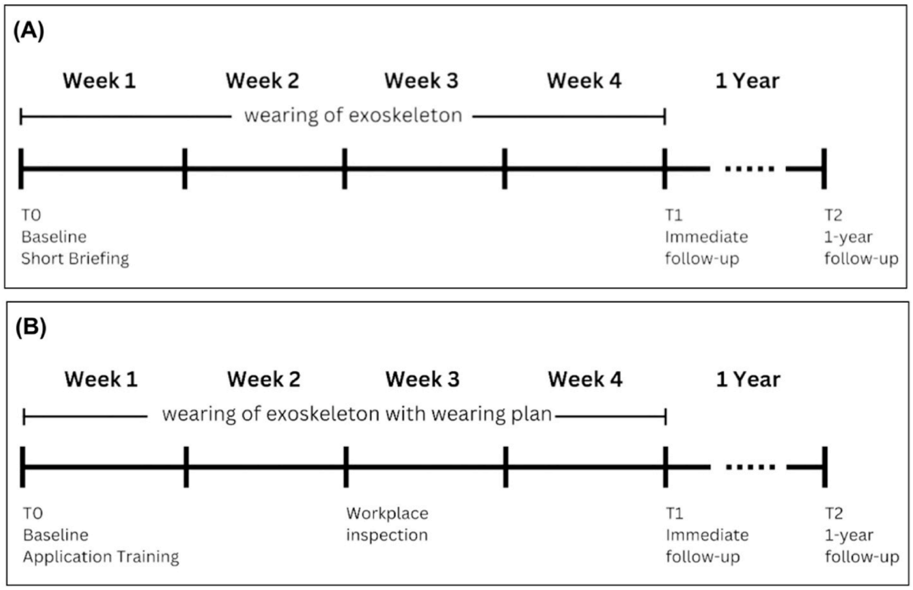

Fig. 2. Study Design and measurement timeline for (A) standardized briefing group (SB; N = 9) and (B) application training (AT; N = 9). The figure illustrates the timing of assessments *at* baseline *(*T0*)*, immediate follow-up *(T1)* and 1-year follow-up *(*T2) *as well as key procedural differences between the two groups. Participants in the AT group received a wearing* log *and workplace inspection, whereas SB participants did not.*

groups with regard to the overall impression of the exoskeleton.

2.4.2. Experience during exoskeleton instruction

At immediate follow-up, we also assessed participants' intention to use an exoskeleton, as well as their experience during the exoskeleton's instruction that had taken place at baseline. With regard to the training, participants were asked to provide feedback on the content presented during the training, the organization and structure of the training, as well as the comprehensibility, using self-developed questions rated on a 7-point Likert scale (Likert, 1932). To this end, AT and SB participants completed 8 questions on the application training and standardized briefing, respectively. These 8 questions were then evaluated and compared between the groups. With regard to participants' experience during the exoskeleton's introduction, higher scores indicated a better experience and satisfaction with the introduction procedures. AT participants were asked to answer 8 additional questions, relating to the different content of the individualized application training, e.g., about medical background discussed, about balancing and stretching exercises provided, and test parkour carried out.

2.4.3. Physical and mental health

Participants' physical and mental health at all assessment points (i.e., baseline, immediate follow-up and 1-year follow-up) was assessed using the 12-item, self-reported Short-Form 12 Health-Survey (SF-12; Morfeld et al., 2011). The SF-12 consists of two scales, i.e., 'Physical' and 'Mental Health', which are derived from four subscales as follows: Physical Health includes physical functioning, role limitations due to physical health problems, bodily pain, and general health; Mental Health includes the subscales vitality (energy/fatigue), social functioning, role limitations due to emotional problems, and mental health (psychological distress and psychological well-being). The scoring algorithm results in two sum scores for physical and mental health, respectively, with each score ranging from 0 to 100. The SF-12 is a valid instrument for measuring health-related quality of life (Drixler et al., 2020) with an internal consistency (Cronbach's α) ranging from 0.72 to 0.91 (Ballmer et al., 2019; Wirtz et al., 2018). For statistical analysis, we created a score for both SF-12 subscales, with higher scores indicating higher physical and mental health status, respectively (Ware et al., 1996).

2.4.4. Exoskeleton wearing times

Both AT and SB participants were asked to document their exoskeleton wearing times for four weeks using a written protocol. It should be noted that the exoskeleton was only worn during the four weeks intervention (between the baseline and immediate follow-up measurement), and was no longer available afterwards.

2.5. Statistical analysis

Descriptive statistics such as arithmetic means (M) and standard derivations (SD) were calculated, as well as one-way analyses of variance (ANOVA) with repeated measures, one-way ANOVA, and effects sizes (Cohen, 1988). A Shapiro-Wilk and Mauchly Test was performed to examine normal distribution and sphericity. For variables that were not normally distributed, we ran Friedman, Mann-Whitney-U and Wilcoxon tests. Participants who only completed the first measurement point (i.e., baseline) were removed from the study and considered in separate analyses. To control for Type 1 error due to multiple comparisons, a Bonferroni correction was performed in all applicable statistical analyses, e.g., pairwise comparisons.

We considered two different follow-up periods for the analysis: We examined exoskeleton acceptability, assessed via TUI scores, and health status, assessed via SF-12 scores. The analysis included: 1) all AT and SB participants who completed the baseline (T0) and immediate follow-up measures (T1; N = 18); and 2) all AT and SB participants who completed all three measuring points, i.e., baseline, immediate follow-up and 1-year follow-up (T2; N = 10).

For the first follow-up period, we compared mean values of the respective TUI and SF-12 scores at T1 with T0 measurements for both AT and SB participants separately. In addition, we compared mean values of the respective TUI and SF-12 scores of AT versus SB participants at T0 and T1 (N = 18). Similarly, with regard to the second follow-up period, we compared mean values of the respective TUI and SF-12 scores at T0, T1, and T2 for both AT and SB participants separately (N = 10). Furthermore, we compared mean values of the respective TUI and SF-12 scores of AT versus SB participants at T0, T1 and T2 (N = 10).

We also compared AT versus SB participants' wearing times as well as scores related to participants' experience during the exoskeleton's introduction at T0, by performing T-Tests for independent variables and Mann-Whitney-U tests, respectively, depending on whether the variables were normally distributed or not. We only considered participants who had prepared a protocol for at least three weeks of the 4-week implementation period, and we calculated average daily wearing times for each week and for each implementation group (i.e., AT versus SB participants).

Missing data were imputed by using the mean values over all AT or SB participants, respectively, for the specific analysis model. If a participant had numerous missing data, the data was not considered for statistical analysis. All analyses were conducted using IBM SPSS Statistics software Version 27.0. Significance levels were set to $p < 0.05$ for all tests.

3. Results

3.1. Study demographics

We included 18 participants (AT: N = 9; SB: N = 9) with valid baseline and immediate follow-up measurements. Of these, 10 participants (AT: N = 5; SB: N = 5) also had valid baseline, immediate follow-up and 1-year follow-up measurements.

3.2. Results regarding exoskeleton acceptability and health

3.2.1. Analyses comparing baseline and immediate follow-up

An overview of all scores (mean values and standard deviation of variables on acceptability and health), stratified by analysis and implementation approach group is presented in Table 1.

The independent-samples *t*-test and the Mann-Whitney-U-test (mental health) showed that there were no statistically significant differences between AT and SB group at baseline (see Table 2). The paired-samples *t*-test revealed that AT participants reported higher curiosity ($p < 0.001$; $d = 2.38$) at immediate follow-up than at baseline. There were no statistically significant differences between baseline and immediate follow-up for skepticism, usefulness, physical and mental health for AT participants as revealed by a paired-samples *t*-test and Wilcoxon-test (physical and mental health).

In contrast, the paired-samples *t*-test showed that, SB participants reported higher skepticism ($p = 0.032$; $d = 0.87$) and lower usefulness ($p < 0.001$; $d = 2.01$) at immediate follow-up as compared to baseline. There were no statistically significant differences between immediate follow-up and baseline for curiosity, physical and mental health for SB participants as revealed by the paired-samples *t*-test and Wilcoxon-test (curiosity).

Furthermore, the independent-samples *t*-test and the Mann-Whitney-U-test (curiosity, physical health and usability) revealed that the AT group reported higher curiosity ($p = 0.002$; $r = 0.71$), usefulness ($p < 0.001$; $d = 2.39$), usability ($p = 0.040$; $r = 0.51$), physical health ($p = 0.042$; $r = 0.48$), mental health ($p = 0.002$; $d = 1.19$) and lower skepticism ($p = 0.001$; $d = 1.83$) than the SB group at immediate follow-up. There were no statistically significant differences between AT und SB participants for intention to use at immediate follow-up (independent-samples *t*-test).

3.2.2. Analyses comparing baseline, immediate follow-up and 1-year follow-up

The Friedman-test revealed that AT participants curiosity was higher ($p = 0.022$; $r = 0.54$) at immediate follow-up than at baseline. There

Table 1
Study demographics.

Baseline (T0) and immediate Follow-up (T1)	Group AT (N = 9)	Group SB (N = 9)
Gender		
Male	8	8
Female	1	1
Age [years]		
18–29	1	3
30–39	2	–
40–49	3	1
50–59	1	3
≥60	2	2
Baseline (T0), immediate Follow-up (T1) & 1-year follow-up (T2)	**Group AT (N=5)**	**Group SB (N=5)**
Gender		
Male	5	4
Female	–	1
Age [years]		
18–29	1	2
30–39	2	–
40–49	1	1
50–59	–	2
≥60	1	–

Table 2
Overview of mean values of participants' exoskeleton acceptability, physical and mental health scores at baseline, immediate follow-up and 1-year follow-up.

	Analysis sample: Baseline and immediate follow-up (N = 18)		Analysis sample: Baseline, immediate follow-up and 1-year follow-up (N = 10)	
Baseline (T0)	AT - Mean (SD)	SB - Mean (SD)	AT - Mean (SD)	SB - Mean (SD)
TUI Curiosity	18.00 (2.69)	20.11 (1.83)*	17.80 (3.03)	20.80 (1.79)*
TUI Skepticism	8.67 (2.96)	10.00 (3.61)	8.40 (1.82)	10.20 (3.83)
TUI Usefulness	21.33 (3.43)	22.11 (3.95)	20.40 (3.29)	20.60 (2.88)
TUI Anxiety	6.78 (2.54)	8.00 (2.69)	6.80 (2.39)	7.40 (2.19)
TUI Interest	23.11 (3.37)	22.44 (3.68)	21.8 (2.39)	22.00 (4.30)
SF-12 Physical Health	47.84 (10.14)*	40.99 (12.86)	51.57 (2.62)	44.05 (11.43)
SF-12 Mental Health	52.10 (7.74)	52.92 (9.91)	47.46 (5.48)	57.19 (3.56)
Immediate follow-up (T1)	AT - Mean (SD)	SB - Mean (SD)	AT - Mean (SD)	SB - Mean (SD)
TUI Curiosity	25.33 (1.80)	21.67 (1.73)	25.00 (1.73)*	22.60 (0.55)*
TUI Skepticism	8.44 (3.24)	14.01 (2.82)	7.60 (2.61)	15.60 (2.30)*
TUI Usefulness	19.44 (4.90)	9.14 (3.61)	20.20 (2.86)	9.20 (4.44)
TUI Usability	20.11 (1.36)*	17.22 (3.67)	20.00 (1.41)*	18.6 (2.07)
Intention to use	9.78 (3.42)	7.25 (3.67)	9.60 (2.30)	7.6 (2.41)
SF-12 Physical Health	52.94 (1.78)	39.35 (10.35)*	52.92 (1.07)	39.30 (10.05)
SF-12 Mental Health	54.85 (4.01)	49.41 (14.60)	55.15 (3.23)	57.50 (7.30)
1-year follow-up (T2)	AT - Mean (SD)	SB - Mean (SD)	AT - Mean (SD)	SB - Mean (SD)
TUI Curiosity	–	–	23.40 (2.61)	22.15 (1.69)
TUI Skepticism	–	–	10.20 (2.77)	12.15 (2.29)
TUI Usefulness	–	–	18.80 (2.77)	10.85 (4.73)
TUI Anxiety	–	–	9.40 (4.04)	9.00 (3.81)
TUI Interest	–	–	20.60 (5.13)	21.60 (4.04)
TUI Usability	–	–	17.20 (3.27)	15.00 (4.53)
Intention to use	–	–	8.60 (1.14)	8.60 (3.65)
SF-12 Physical Health			43.56 (9.65)	42.30 (13.50)
SF-12 Mental Health			48.47 (7.46)*	52.61 (13.80)*

Abbreviations: AT = application training; SB = standardized briefing; SD = standard deviation; TUI subscales, higher scores indicate higher degrees of acceptability on all scales as assessed through Technology Usage Inventory; SF-12 physical and mental health scales, higher scores indicate higher degrees of health on both scales as assessed through Short-Form Health Survey. *not normally distributed.

were no significant differences for usefulness, skepticism, physical and mental health shown by the ANOVA with repeated measures (skepticism, usefulness) and the Friedman-test. For SB participants, skepticism was higher ($p = 0.013$; $r = 0.57$) at immediate follow-up than at baseline (one-way analyses of variance (ANOVA) with repeated measures). There were no statistically significant differences between curiosity, skepticism, usefulness, mental, and physical health.

The independent-samples *t*-test and the Mann-Whitney-U-test showed that there were no statistically significant differences between AT and SB participants for curiosity and physical health (Mann-Whitney-U-test), usefulness, skepticism, anxiety and interest at baseline except for mental health ($p = 0.010$; $d = -2.10$).

The AT group reported higher usefulness ($p = 0.002$; $d = 2.95$) and physical health ($p = 0.017$; $d = 1.91$) than the SB group at immediate follow-up (independent-samples *t*-test). In addition, for AT participants skepticism was lower ($p = 0.008$; $r = 0.84$) than for the SB group at immediate follow-up (Mann-Whitney-U-test). There were no statistically significant differences between AT and SB participants for curiosity, usability, intention to use as well as mental health at immediate follow-up.

Furthermore, AT participants reported higher usefulness ($p = 0.012$; $d = 2.05$) than the SB group at 1-year follow-up (independent-samples *t*-test). There were no statistically significant differences between AT and SB participants for curiosity, skepticism, anxiety, interest, usability, intention to use, as well as physical and mental health at 1-year follow-up (see Figs. 3 and 4).

3.3. Results regarding experience during exoskeleton instruction

The mean score based on all 8 questions regarding the experience (content, organization, structure, and comprehensibility) during the exoskeleton instruction, is higher for AT participants ($p = 0.012$; $d = 1.34$; 54.78 ± 1.86) than SB participants (51.11 ± 3.41). Furthermore, when considering each of the respective questions, AT participants ($p = 0.007$; $d = 1.59$; 61.63 ± 1.60) also had higher mean scores for each of the 8 questions than SB participants (57.50 ± 3.30).

3.4. Results regarding exoskeleton wearing time

SB participants reported longer exoskeleton wearing times than AT participants during week 1 (SB: 71.60 ± 90.22 min/day; AT: 37.14 ± 22.40 min/day) and 2 (SB: 82.00 ± 86.02 min/day; AT: 69.00 ± 41.78 min/day). Whereas, in week 3 (SB: 57.80 ± 76.38 min/day; AT: 85.43 ± 6.70 min/day) and 4 (SB: 44.00 ± 80.62 min/day; AT: 80.00 ± 77.84 min/day), AT participants had longer wearing times than SB participants. All differences were not statistically significant. These results indicate that SB participants wore the exoskeleton 93 % longer than AT participants in week 1, and 18 % longer in week 2. In week 3, AT participants wore the exoskeleton 48 % longer than the SB group and in week 4, the difference increased to 82 % (see Fig. 5).

4. Discussion

The purpose of this intervention study was to examine how two different implementation approaches of a passive, upper-limb exoskeleton (MATE-XT®) impact both the acceptability of the exoskeleton among participants and their health outcomes. Of note, the study took place under real working conditions and not in a laboratory setting, and included a total of 18 participants.

Our study showed that participants who underwent the comprehensive, theory-based and more individualized application training, reported higher curiosity, reduced skepticism, and perceived the exoskeleton as more useful and user-friendly, between baseline and immediate follow-up assessment, compared to participants who received the standardized briefing. This finding also held true at the 1-year follow-up, during which participants who had completed the application training continued to view the exoskeleton as more beneficial than those who received the standardized briefing. Perceived usefulness has already been described as an important factor for users' acceptability and intention to use an exoskeleton (Davis, 1989; Schwerha et al., 2022; Turja et al., 2022; Luger et al., 2023). For example, one study showed that acceptance of exoskeletons is positively linked to technology-induced self-efficacy, which in turn is influenced by perceived strain relief and usefulness (Siedl et al., 2021). Also, it was reported, that perceived usefulness and not ease of use was important for workers' intention to use an exoskeleton in an occupational setting (Siedl et al., 2024). Although the usefulness as measured by technology usage inventory in our study cannot be directly compared with perceived usefulness as defined in the technology usage model due to differences in scope and context, it still shows a clear trend in users' positive evaluation of the exoskeleton. Considering the fact that AT participants showed better scores on the different dimensions of the TUI, it can be concluded that acceptance was higher in this group compared to the SB group. Furthermore, in our study, AT participants also reported higher physical health at immediate follow-up, and were able to gradually increase exoskeleton wearing time in the first three weeks and

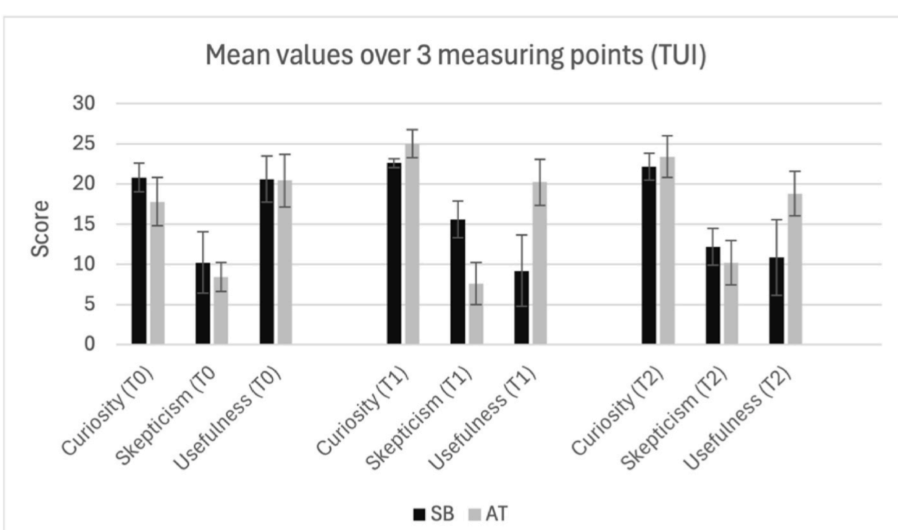

Fig. 3. Mean TUI scores over all three measuring points (baseline, immediate follow-up and 1-year follow-up (N = 10).

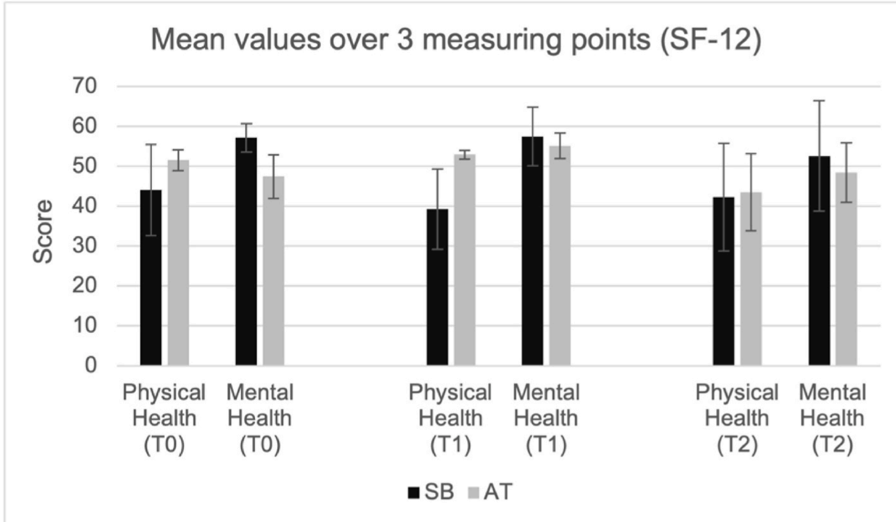

Fig. 4. Mean SF-12 scores over all three measuring points (baseline, immediate follow-up and 1-year follow-up) (N = 10).

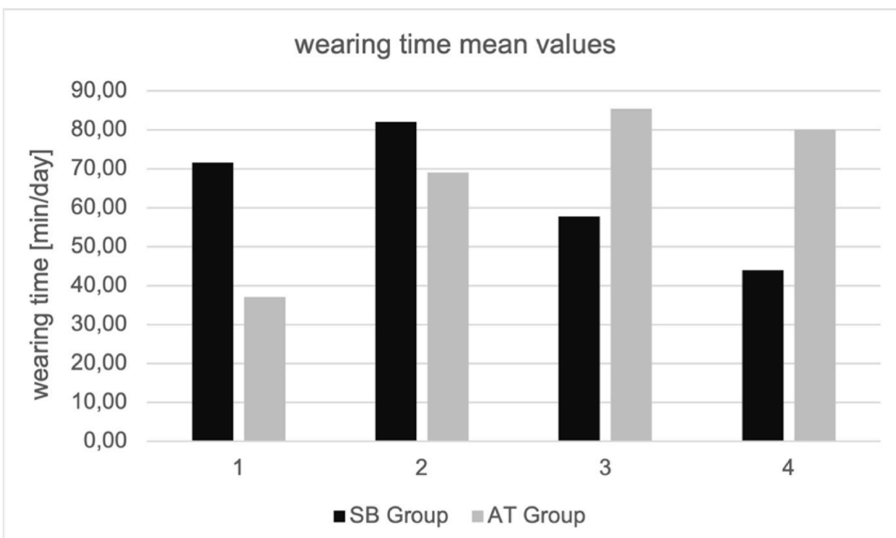

Fig. 5. Wearing time mean values for SB and AT group across the 4 week implementation period.

stagnated in the 4th week over the 4-weeks implementation period, while the SB participants' wearing time declined after the second week. Nevertheless, wearing time differences between AT and SB were not statistically significant.It should also be noted that the AT participants had been instructed to gradually increase their wearing time as part of the study protocol. This opposing trend in wearing time may be attributed to factors such as absence due to illness, vacation or reduced motivation from the perceived lack of utility for specific activities. It should also be noted that, even if the results were not statistically significant, we cannot be certain that the wearing protocols were filled out correctly, albeit participants were instructed on how to complete the protocol. Future studies may want to record the wearing time using objective tools. It must also be taken into account that participants themselves were able to choose when and during which tasks they used the exoskeleton. Accordingly, participants in the AT group may have perceived the exoskeleton to be useful more often and during more tasks than SB participants. More research is thus needed to examine whether different exoskeleton implementation approaches are associated with differences in wearing times. Although the workshops were observed and deemed as appropriate environments for upper limb exoskeleton testing, precise data on the proportion of overhead work and details regarding specific tasks were not collected, which limits the study's ability to draw conclusions about task-specific effectiveness. Also, SB participants reported higher mental health at baseline than AT participants. However, this was not detected at immediate follow-up and 1-year follow-up. It should also be mentioned that the more detailed training for AT participants may have increased their health awareness, which could in turn have led to higher overall health reported by AT compared to SB participants, although the exoskeleton was only worn for 4 weeks during the implementation phase by both groups. However, it also should be highlighted that mental and physical health tend to stagnate or change negatively over the course of a year, and this may be dependent on numerous factors. Also, it should be noted that there were only significant differences between AT and SB participants in terms of physical health, but not in terms of mental health. One possible explanation is that AT participants may have used the exoskeleton more skillfully due to the more extensive training, which in turn may have had a positive effect on their physical health. In addition, AT participants may have felt more confident in using the exoskeleton compared to SB participants and may also have believed more in the possible positive effects of the exoskeleton than SB participants, which is also evidenced by the participants' feedback provided after the 4 weeks implementation. Knibbe and Friele (1999) also showed that lifting devices and lifting coordinators (facilitation) as well as training (education) and assessment forms resulted in a significant reduction in physical work demands and reduction of 12-month prevalence of back pain among care nurses. Furthermore, although there were no significant differences with regard to anxiety in our study, the exoskeleton's potential impact on mental health should not be underestimated. It is possible that the SB participants in particular could have been overwhelmed since they received much less detailed information, which also reflected in lower perceived competence to operate the exoskeleton correctly.

In secondary analyses (data not shown), we observed that AT participants completed the wearing log more frequently than the SB group, which may indicate greater motivation. However, this result should be interpreted with caution, as the AT group but not SB group was visited at the workplace after 14 days and reminded of completing the wearing log. Also, it should be noted that an unfilled wearing log could be due to various reasons, i.e., a participant may have forgotten to fill it, was ill or was not assigned any tasks on a given day during which he determined wearing the exoskeleton to be useful. In addition, participants who underwent the AT rated the implementation better than SB participants in terms of content, organization, structure, and comprehensibility. This is in line with research by Baltrusch et al. (2020) who showed that implementation approaches including supervision, behavioral coaching, and sufficient time of adjustment may be more likely to increase acceptability of exoskeletons. Furthermore, the instruction for AT participants also included educational information related to workplace ergonomics and health and exoskeletons which are important when implementing ergonomic devices and tools (Van der Molen et al., 2005). Moeller et al. (2022) also mentioned that individuals may benefit from a longer familiarization period by learning how to use the exoskeletons and adapt their movement to them. In line with this, Moyon et al. (2020) reported that the use of an exoskeleton is not intuitive, and familiarization should take place in order to increase user acceptance and eventually lead to quicker adoption in companies. We postulate that this may be one explanation for the aforementioned observed differences in favor of the application training versus standardized briefing in our study. As Pacifico et al. (2020) have already shown, the MATE-XT® exoskeleton reduces muscle activity in the upper limbs, i.e., anterior deltoid, medial deltoid trapezius ascendens as well as pectorialis major while working overhead. Similarly, Pinto et al. (2021) also reported that muscle activity was decreased while using the MATE-XT® exoskeleton at shoulder level. Nevertheless, it must also be noted that, on average, participants in our study regardless of implementation group perceived the MATE-XT® as not very useful within their specific work domain because the exoskeleton could not provide support during a variety of tasks, as it was only designed for overhead movements. However, it should also be noted that participants who received the application training still rated the exoskeleton as more useful during the survey. This may be because they recognized the exoskeleton's benefits through the training and parkour experience. It should also be taken into account that a study by Perez Luque et al. (2020) showed that the MATE-XT® provided participants with the lowest range of motion when comparing it to other devices, and led to back and shoulder discomfort, limited support in overhead position, as well as a clumsy and "being stuck" feeling while wearing the exoskeleton during movements. Accordingly, in future research, care must be taken to ensure that the selection of the exoskeleton aligns with the respective activity (Hoffmann et al., 2021) and that its use is associated with as few disadvantages as possible.

Our study, albeit conducted in a specific workplace setting confirms earlier assumptions by Steinhilber et al. (2020) also in a real-life setting and extends the current literature by showing, that a comprehensive, theory-based and more individualized implementation approach may be more favorable than a standardized briefing with regard to acceptability of an exoskeleton and individuals' health. This may have implications for health promotion or safety managers who plan to introduce exoskeletons to support workers in their companies or factories and potentially even improve employees' health, which in turn could make exoskeletons even more attractive to companies. For example, they should ensure that the introduction includes detailed information about the relevant anatomical structures and gives participants the opportunity to familiarize themselves with the exoskeleton. A workplace inspection may also be helpful to address any questions that may arise during the first weeks of using the exoskeleton. Preferably, an exoskeleton used in a workplace setting should fit the work-related activities and tasks, should be comfortable to wear and provide the user with a perceived (subjective) or preferably objective benefit or relief while performing their tasks. In addition, the wearing time should be gradually increased over a certain period of time. The results also provide suggestions for future research. For example, when investigating acceptability in the field or real-word setting, technical aspects such as wearing comfort, suitability for the tasks etc. should be taken into account, along with the implementation process and its content, as the aim is to bring about a change in user behavior.

A strength of our study is the rigorous study design and methodology including careful selection of validated assessment tools as well as the fact that real workers from different age groups were examined.

4.1. Limitations

Limitations pertain to the small convenience sample of only 18 participants. Furthermore, only 2 females were included in the study, one of whom was excluded for the analyses including the 1-year follow-up assessment. Therefore, it is difficult to conclude about the effects of different implementation approaches on the acceptability of a passive exoskeleton for workplace health promotion in women, and more research is needed in larger samples and also including a higher number of females, in order to be able to translate the results to the overall population and interpret potential gender-specific effects more precisely. Another limitation of our study with possible consequences on interpretation is the use of imputed data which may have led to bias and loss of data variability. We also did not record whether participants were absent from work due to illness or other reasons on specific days. This could have biased the wearing time results and significantly limits our ability to interpret them, as reduced exoskeleton usage cannot be solely attributed to a lack of motivation. In addition, our study was done using a specific exoskeleton (i.e., MATE-XT®), and some participants rated the exoskeleton as not helpful with their work-related activities and tasks. Thus, it is questionable whether our observed findings are transferable to other exoskeletons, or to other workplace settings. Rather, it is likely that different exoskeletons may lead to different results, which are also highly dependent on the specific workplace setting. More research is thus warranted, with exoskeletons carefully selected for the workplace setting and tasks, and including larger and more diverse samples. Furthermore, an initial, task-specific analysis should have been carried out for each possible workstation to determine whether the exoskeleton fits the workstation before deciding on a device. This would allow to examine whether the coordination between tasks and capabilities of the exoskeleton influences its acceptability. In addition, in terms of assessing health outcomes, fatigue and pain related to the use of the exoskeleton, a visual analog scale for pain/discomfort of the affected body regions, or a muscle fatigue scale could have been used. Such tools may have provided more specific information than the SF-12 used in our study, which only broadly measures overall physical and mental health. Another limitation of this study is the baseline difference in mental health scores between the SB and AT groups, with SB participants reporting higher initial scores. This imbalance may have influenced health outcomes at the immediate follow-up and 1-year follow-up. Although adjusting for baseline mental health status could improve the robustness of the analysis, this was not incorporated in the current models because health status was considered a secondary outcome.

Future studies should consider including baseline measures as covariates in statistical models to better account for potential confounding effects.

4.2. Conclusion

Various factors that may impact the acceptance of exoskeleton implementation in the occupational setting have been established in literature. Therefore, our study examines the differences in acceptability between two different implementation approaches for an upper limbs exoskeleton. In summary, it was shown that a comprehensive, theory-based and individualized approach to implement the passive upper-limbs exoskeleton MATE-XT®, including information about the structures of shoulder and spine, the correct lifting and carrying of loads using an exoskeleton, as well as an intensive familiarization with the device, may be associated with higher acceptability and physical health, as well as more sustainable wearing times. Future research in larger, more diverse samples and different workplace settings is needed to confirm these preliminary observations, and to also examine whether differences between implementation approaches persist over longer follow-up periods.

CRediT authorship contribution statement

Manuel Fleps: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Max Hörandel:** Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Melina Fischer:** Writing – original draft, Formal analysis, Data curation. **Janina Krell-Roesch:** Writing – original draft, Supervision, Methodology, Formal analysis, Data curation. **Pascal Senn:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Klaus Boes:** Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Claudia Hildebrand:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Co-Author P.S. is owner and CEO of IDAG GmbH, which provided support for the design and conduct of the study (please also refer to "funding information and acknowledgment"). The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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