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Biomechanical changes, acceptance, and usability of a passive shoulder exoskeleton in manual material handling. A field study

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ABSTRACT

Occupational exoskeletons contribute to diminish the biomechanical load during manual work. However, familiarization to the use of exoskeletons is rarely considered, which may lead to failure of acceptance and implementation. In this study, ten logistic workers underwent a 5-week progressive familiarization to a passive shoulder exoskeleton, while ten workers acted as controls. Tests pre and post the familiarization applied measurements of muscle activity and kinematics of back, neck, and shoulder, perceived effort, and usability-ratings of the exoskeleton. Exoskeleton use resulted in lower muscle activity of anterior deltoid (13–39%) and upper trapezius (16–60%) and reduced perceived effort. Additionally, it induced an offset in shoulder flexion and abduction during resting position (8–10°). No conclusions on familiarization could be drawn due to low adherence to the protocol. However, the emotions of the workers towards using the exoskeleton decreased making it questionable whether the shoulder exoskeleton is suitable for use in the logistics sector.

1. Introduction

The industrial world is facing major changes due to automation and digitalization, which have great impact on how companies run their product lines. Yet, manual materials handling (MMH) retains a major role in the logistics sector where the level of automation continues to be low to accommodate the big variety of goods (Danko and Straka, 2022). The work often includes strenuous tasks causing a high physical impact on the workers (Skals et al., 2021a,b). A result of the physical impact on the workers is overexertion leading to a high rate of sickness absence and work-related musculoskeletal disorders (WMSDs) (Yang et al., 2020). Neck/shoulder pain is considered a WMSD caused by biomechanical factors, such as heavy workload, awkward postures, and repetitive arm movement (van der Windt et al., 2000), as well as individual and psychosocial factors (Punnett and Wegman, 2004). Still, the biomechanical load of the neck/shoulder during MMH is considered the largest contributor to development of WMSD in the shoulder girdle (Qureshi et al., 2019).

Wearable assistive systems like occupational exoskeletons are seen as an attractive solution to the problems caused by the biomechanical loads imposed on the worker during MMH. Exoskeletons result in reduced muscle activity and discomfort during work tasks within mechanics, manufacturing, and construction work (McFarland and Fischer, 2019; van der Have et al., 2022). The decrease in biomechanical load during MMH could also result in a slower development of muscle fatigue (Theurel and Desbrosses, 2019). Yet, several limitations of using exoskeletons have been underlined. These limitations comprise modifications of the kinematics (i.e., lower range of motion) and mixed effects of unloading a specific joint that may result in increased loading of other joints, leading to higher perceived exertion and increased heart rate (Theurel et al., 2018; de Looze et al., 2016; Hondzinski et al., 2018). However, most of the research on occupational exoskeletons has been conducted in laboratory settings simulating work tasks in standardized conditions investigating the acute effects, while in-field use of exoskeletons to reflect real-life settings is rarely investigated (Bär et al., 2021; Schwerha et al., 2022). This underlines an urgent need to clarify the effects of occupational exoskeletons related to specific tasks in real work situations. Moreover, it is important to determine the working

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tasks requiring physical assistance[1] as the same exoskeleton can both have positive and negative effects depending on the task performed (van der Have et al., 2022).

Another aspect lacking scientific attention is the implementation process of the exoskeletons at the workplace. The implementation of exoskeletons contains many different phases, including analysis of the workstation, task specific selection, proper fitting, and familiarization of the exoskeleton use (Crea et al., 2021). Familiarization is a complex and important matter with physical and perceptional aspects of the interplay between body and technology affecting both preferences and physical performance (Maslow, 1937; Lavcanska et al., 2005). Previous studies emphasize that the use of exoskeletons is not intuitive, but a skill that needs to be adopted based on improved performance, reduction in global physical load, perceived strain, as well as a reduction of the added cognitive load (e.g., Moyon et al., 2019). Observations have shown that companies buy exoskeletons without considering the familiarization procedure, thus increasing the risk of acceptance failure (Moyon et al., 2019; Diamond-Ouellette et al., 2022). Only a few studies (e.g., Moyon et al., 2019; Diamond-Ouellette et al., 2022) have addressed familiarization. They have found that a thorough familiarization protocol does not only affect practical matters like donning and doffing but also significantly decreases the global physical load and metabolic cost. This emphasizes the idea that familiarization may have a positive effect on several aspects related to the use of exoskeletons. However, previous familiarization protocols have been based on short training sessions in controlled settings. To the best of our knowledge, no study has addressed the effects of a familiarization period of several weeks in field conditions.

This field study investigated a familiarization period with a progressive use of a passive shoulder exoskeleton (PSE) during MMH. The aim was to investigate how a 5-week familiarization period of exoskeleton use can be beneficial to the user in terms of biomechanical changes, acceptance, and usability. It was hypothesized that the familiarization would induce a reduction in workload and increase the acceptance of the users (Moyon et al., 2019; Diamond-Ouellette et al., 2022). No previous studies have investigated the effect of exoskeleton familiarization on kinematics. However, several studies report immediate changes in kinematics as a result of exoskeleton use (De Bock et al., 2023; Ojelade et al., 2023). Based on these findings and the changes found in metabolic cost and workload (Moyon et al., 2019; Diamond-Ouellette et al., 2022), we further hypothesized that modifications of kinematics would appear after the 5-week familiarization period.

2. Methods

2.1. Participants

A total of 20 able-bodied asymptomatic adult workers volunteered to participate (19 males and 1 female, age: 31.6 ± 7.7 years, height: 181.1 ± 8.6 cm, body mass: 84.9 ± 13.6 kg, working experience: 6.9 ± 6.8 years). All workers were full-time employees of a Danish wholesale logistics company. The current health status of the workers was evaluated and reported using a Danish simplified version of the Nordic Musculoskeletal Questionnaire (Kuorinka et al., 1987). All participants were novices using exoskeletons. All workers provided written informed consent as per the guidelines of The North Denmark Region Committee on Health Research Ethics (LBK nr. 1083) and the Declaration of Helsinki. The study was conducted following approval from the secretariat of The North Denmark Region Committee on Health Research Ethics.

2.2. Exoskeleton design

The PSE used in the present study was the ShoulderX (Version 3, mass: 3.2 kg, Ottobock SE & Co. KGaA, Duderstadt, Germany). The ShoulderX is a spring-based exoskeleton designed to lower the load of the shoulder muscles when handling different materials at shoulder level or above (Kazerooni et al., 2019; Van Engelhoven et al., 2018). The PSE is designed to redistribute a part of the load from the shoulders onto the hips. The springs can be adjusted to aid at a maximum of 15 Nm (De Bock et al., 2020) and have two settings ("off" and "on"). Additionally, the peak angle of support can be changed between 60 and 120° to accompany the desired working task. The support is activated when moving the arm upwards antagonizing the gravity force when raising the arm. The design of the exoskeleton is adjustable to accommodate anthropometric characteristics.

2.3. Study design

The participants were divided into two groups: a control group (n = 10, age: 32.2 ± 9.6 years, height: 180.3 ± 9.7 cm, body mass: 82.4 ± 17.5 kg, working experience: 8.2 ± 9.0 years) and an intervention group (n = 10, age: 33.3 ± 7.5 years, height: 181.9 ± 8.0 cm, body mass: 87.4 ± 8.5 kg, working experience: 7.7 ± 6.0 years). Stratified randomization was used with age and work experience as strata. The intervention group took part in a 5-week familiarization period of the PSE, while both groups participated in a weekly workshop concerning ergonomics. The familiarization consisted of an introduction session informing the participants of the concept of exoskeletons (30 min), an instruction session comprising donning, doffing, maneuvering, and free use of the PSE (60 min). Finally, the familiarization comprised a 5-week period during which the participants were to increase the use of the PSE in their daily work from 7.5 h/week to a full workweek (37 h/week). The schedule of the progression of the exoskeleton use for the intervention group is stated in Table 1. The adherence to the familiarization protocol was estimated using day-by-day self-reporting of hours using the PSE.

The participants in the intervention group performed a test pre and post the familiarization period, whereas the control groups performed a test pre and post two different occasions approx. five weeks apart. All tests were conducted in-field in a company warehouse. The pre-test was conducted at baseline (before initiating the familiarization) while the post-test was made five weeks later (after the familiarization period for the intervention group). A flowchart of the experimental phase of the research is stated in Fig. 1.

The pre- and post-tests consisted of standardized tasks designed as a replication of real work scenarios carried out by the logistic workers. The tasks consisted of loading a truck with wholesale merchandise. The tasks were chosen based on observations, data, and conversations with operation coaches and industry stakeholders. The tasks were conducted with (EXO) and without (NoEXO) using the PSE and were performed in a randomized balanced order with equal number of workers starting at each condition. Two different types of movements were studied: 1) lifting an item from a 100 cm shelf to a 170 cm truck height, and 2) lifting an item from a 15 cm shelf to a 100 cm truck height. As the truck was located behind the worker, both movements included carrying the item from the shelf to the truck in a rotational motion (180°). Loading of the truck was conducted with two different items: 1) paper cups (total mass of 4.6 kg), and 2) a wine box (total mass of 17.6 kg), resulting in a total of four tasks. Further descriptions of the tasks combining movements and items are given in Table 2. The order of the tasks was randomized for the first test session and fixed for the specific worker throughout the study.

Before the test sessions, anthropometrics and demographics of the workers were obtained including specified body dimensions (used for scaling the motion capture). Furthermore, the PSE were introduced and properly fitted to the workers in both groups by an external expert not involved in the study. The peak angle of support was set at the default settings (90°) as recommended by a company representative (Ottobock SE & Co. KGaA) for the present type of work. Additionally, the level of support (on a scale from 1 to 5) was adjusted to accommodate the size

[1] https://en.inrs.fr/dms/inrs/PDF/ED6376.pdf/ED6376.pdf.

Table 1
Familiarization protocol. Time for exoskeleton use during the 5-week familiarization period.

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
1st week of familiarization	1 h and 30 min of exo use	1 h and 30 min of exo use	1 h and 30 min of exo use	1 h and 30 min of exo use	1 h and 30 min of exo use	7 h and 30 min of exo use
2nd week of familiarization	3 h of exo use	3 h of exo use	3 h of exo use	3 h of exo use	3 h of exo use	15 h of exo use
3rd week of familiarization	4 h and 30 min of exo use	4 h and 30 min of exo use	4 h and 30 min of exo use	4 h and 30 min of exo use	4 h and 30 min of exo use	22 h and 30 min of exo use
4th week of familiarization	6 h of exo use	6 h of exo use	6 h of exo use	6 h of exo use	6 h of exo use	30 h of exo use
5th week of familiarization	7 h and 45 min of exo use (All day)	7 h and 45 min of exo use (All day)	7 h and 45 min of exo use (All day)	7 h and 45 min of exo use (All day)	6 h of exo use (All day)	37 h of exo use (Full workweek)

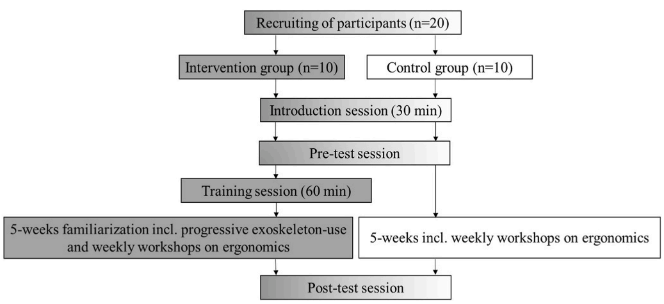

Fig. 1. Flow chart of the experimental phase of the research. The grey boxes indicate sessions or actions only involving the intervention group (n = 10), while the white boxes indicate the same for the control group (n = 10). The grey/white shaded boxes indicate sessions or actions involving both groups.

Table 2
Abbreviations and descriptions of the work tasks included in the pre- and post-tests. The table includes information regarding the shelf height, truck height, and the specifications of the items (characteristics, mass, and dimension).

Work tasks	Condition	Items	Starting Position (cm)	Stacking Height (cm)	Mass (kg)	Dimension (L x W x D)
1	4.6 kg 100–170 cm	Paper Cups	100	170	4.6	25 × 18 x 42
2	4.6 kg 15–100 cm	Paper Cups	15	100	4.6	25 × 18 x 42
3	17.6 kg 100–170 cm	Wine	100	170	17.6	29 × 28 x 39
4	17.6 kg 15–100 cm	Wine	15	100	17.6	29 × 28 x 39

and preference of the users. This was conducted individually based on trials and a dialogue between the company representative and the workers. The measurement equipment was mounted before initiating a series of normalization tasks for the sEMG data analysis. The motion capture system was calibrated after preparation of the participant. The participants were instructed to perform the work tasks in a controlled manner as close to their everyday routine as possible (lifting the items using both hands).

2.4. Measurements

2.4.1. Kinematics

3D kinematic data were recorded using a motion capture setup based on inertial measurement units (IMUs) (Xsens Awinda hardware, Xsens Technologies BV, Enschede, The Netherlands). The data were analyzed in Xsens MVN Analyze 2021.0.1 software (Xsens Technologies BV, Enschede, The Netherlands). The system consisted of 17 IMUs sampling at 60 Hz enabling a full body kinematic analysis. The strap-based IMUs were placed according to the guidelines of Xsens Technology BV.[2] The IMU data were used to drive the kinematics of a model consisting of 23 segments. The model was individually scaled to the participant based on manually measured anthropometrics (Skals et al., 2021a).

2.4.2. Surface electromyography

Surface electromyographic (sEMG) signals were sampled at 1500 Hz using a wireless Telemyo DTS system (Noraxon USA Inc., Scottsdale, USA). The recordings were synchronized with the kinematic data recordings. Surface electrodes (Neuroline 720 72000-S/25 type, AMBU, Ballerup, Denmark) were placed bilaterally on the following muscles according to SENIAM recommendations (Hermens et al., 1999): erector spinae longissimus, upper trapezius, and deltoideus anterior. The electrodes were aligned with an inter-electrode distance of 2 cm on abraded ethanol-cleaned skin (shaved when necessary) along the direction of the muscle fibers. After placing the electrodes and visually inspecting the sEMG signals, a series of normalization tasks were initiated to estimate the maximum isometric voluntary contractions (MVC) of the applied muscles. Three-second MVC tasks were performed three times each with 1-min between tests to avoid fatigue development (Stephens and Taylor, 1972). Estimation of the MVC was conducted in agreement with previous studies (Vera-Garcia et al., 2010; Johansen et al., 2013; Al-Qaisi and Aghazadeh, 2015).

2.4.3. Additional measurements

Subjective scores were obtained during the test sessions. A Borg CR10 scale was used to obtain the perceived global effort of the work tasks. Additionally, the participants filled in a 16-statement *Questionnaire for the Evaluation of Physical Assistive Devices* (QUEAD) to examine the usability, ease of use, comfort, and acceptance of the PSE (Schmidtler et al., 2017). The questionnaire is a seven-point Likert scale stating from "entirely disagree" to "entirely agree" and it was translated to the native tongue of the participants using published guidelines (Tsang et al., 2017). The questionnaire was filled in after each test session. Before analysis of the QUEAD, the questions were divided into clusters related to 1) perceived usefulness, 2) perceived ease of use, 3) emotions, 4) attitude, and 5) comfort based on an established procedure (Schmidtler et al., 2017).

2.5. Data analysis

The kinematic data were processed in the Xsens MVN Analyze 2021.0.1 software using the HD Reprocessing Engine. The recorded sequence was segmented to the movement using the whole-body center of mass (COM). The workers were asked to stand still before and after

[2] MVN User Manual (xsens.com).

each task. Onset of a movement was defined by the first time the acceleration of the COM exceeded 0.4 m/s^2 (threshold based on the maximum acceleration measured during quiet standing), while offset of the movement was set to the last time the acceleration went below the threshold. Bilateral joint angles of shoulder flexion, shoulder abduction, and back (L5-S1) flexion were extracted from the data. The joint angles were chosen to investigate the effect of the PSE on target areas during MMH and to match movements involving the muscles included in the sEMG analysis. Subsequently, the 10th and 90th percentile of the joint angles were calculated as described by Szeto et al. (2009).

The sEMG data were processed using MATLAB (The MathWorks, Natick, MA, USA). The signal was detrended and filtered using a 4th order Butterworth [10–500 Hz] bandpass filter. A full wave rectification was conducted and a moving average over 50 ms was applied through the full sequence. Finally, the data were normalized to the data obtained during MVC of the respective muscle and segmented to the movement using the kinematic data. Subsequently, the 10th and 90th percentile of the amplitude of sEMG signals were calculated to estimate the PSE effect at low and high efforts of work, respectively (Szeto et al., 2009). Left and right joint angles and sEMG amplitudes for left and right muscles were processed separately throughout the subsequent analysis.

2.6. Statistical analysis

All data were statistically analyzed in SPSS version 26 (IBM corp., Armonk, NY, USA). Normality was assessed using Shapiro-Wilk tests. If the data were considered normally distributed, the statistical procedure was initiated. A two-way repeated measures (within-between interaction) analysis of variance (2RM-ANOVA) was conducted to assess the effects of familiarization and exoskeleton use within and between the groups. The analysis was performed with the different dependent variables (sEMG amplitude and joint angle percentiles, and perceived effort), with exoskeleton use (EXO/NoEXO) and familiarization (pre-familiarization/post-familiarization) as independent factors and group (intervention/control) as the between-subject factor. The QUEAD scores were analyzed in the same manner but only with familiarization as the independent factor. The tests were performed with an alpha-level $<.05$.

3. Results

3.1. Effects of exoskeleton use

The use of the PSE did not affect the duration of any of the tasks conducted in the test sessions. A figure stating NoEXO/EXO temporal changes is included in the supplementary material (Online Appendix 1).

3.1.1. Muscle activity

Mean values ± SD of the muscle activity and the results of the statistical analysis are reported in Table 3. The 2RM-ANOVA revealed significant decreases in the 10th percentile of the sEMG amplitude of the left anterior deltoid at the 4.6 kg 15–100 cm, 17.6 kg 100–170 cm, and 17.6 kg 15–100 cm work task for the EXO compared with the NoEXO ($p < .037$) condition. Additionally, significant decreases were revealed in the 10th percentile of the sEMG amplitude of the right anterior deltoid at the 17.6 kg 100–170 cm and 17.6 kg 15–100 cm work task ($p < .021$). Significant decreases were seen in the 90th percentile of the sEMG amplitude of the left anterior deltoid at three work tasks for EXO compared with NoEXO (4.6 kg 100–170 cm, 4.6 kg 15–100 cm, 17.6 kg 100–170 cm; $p < .024$) and in all four work tasks for the right anterior deltoid ($p < .030$). Further, a significant decrease was detected in the 10th percentile of the sEMG amplitude of the upper trapezius in all four work tasks for EXO compared with NoEXO for the left ($p < .048$) and the right muscle ($p < .028$). Significant decreases were found in the 90th percentile of the sEMG amplitude of the right upper trapezius for the 17.6 kg 15–100 cm work task for the EXO compared with NoEXO ($p = .042$). Finally, there was a significant decrease in the 90th percentile of

Table 3
The effects of the passive shoulder exoskeleton use on muscle activation. The table includes mean ± SD of 10th and 90th percentiles of the normalized average rectified sEMG values for NoEXO and EXO conditions of left and right anterior deltoid, upper trapezius, and erector spinae. Additionally, the results of the repeated measures ANOVA are reported, including the f-values, p-values, and eta partial squared (η^2) effect sizes.

Variable	Condition	NoEXO	EXO	Repeated measures ANOVA
Left AntDel 10th % MVC	4.6 kg 100–170 cm	1.4 ± 2.3%	1.1 ± 1.4%	$F(1,14) = 3.000$, $p = .111$, $\eta^2 = .214$
	4.6 kg 15–100 cm	0.9 ± 1.2%	0.7 ± 0.8%	**$F(1,14) = 5.366$, $p = .037$, $\eta^2 = .338$**
	17.6 kg 100–170 cm	1.5 ± 1.9%	0.9 ± 1.0%	**$F(1,14) = 6.109$, $p = .027$, $\eta^2 = .403$**
	17.6 kg 15–100 cm	0.8 ± 1.1%	0.6 ± 0.7%	**$F(1,14) = 12.900$, $p = .003$, $\eta^2 = .575$**
Right AntDel 10th % MVC	4.6 kg 100–170 cm	1.4 ± 1.9%	0.9 ± 0.8%	$F(1,13) = 1.307$, $p = .277$, $\eta^2 = .106$
	4.6 kg 15–100 cm	0.6 ± 0.5%	0.5 ± 0.4%	$F(1,13) = 4.360$, $p = .061$, $\eta^2 = .284$
	17.6 kg 100–170 cm	1.4 ± 1.7%	0.9 ± 0.9%	**$F(1,14) = 6.768$, $p = .021$, $\eta^2 = .428$**
	17.6 kg 15–100 cm	0.6 ± 0.6%	0.4 ± 0.3%	**$F(1,14) = 7.489$, $p = .016$, $\eta^2 = .424$**
Left AntDel 90th % MVC	4.6 kg 100–170 cm	30.9 ± 12.5%	25.7 ± 11.3%	**$F(1,14) = 19.496$, $p < .001$, $\eta^2 = .639$**
	4.6 kg 15–100 cm	14.5 ± 9.0%	11.9 ± 7.2%	**$F(1,14) = 6.445$, $p = .024$, $\eta^2 = .384$**
	17.6 kg 100–170 cm	48.9 ± 16.0%	42.0 ± 12.2%	**$F(1,13) = 24.411$, $p < .001$, $\eta^2 = .709$**
	17.6 kg 15–100 cm	24.6 ± 15.9%	20.3 ± 11.7%	$F(1,13) = 3.240$, $p = .099$, $\eta^2 = .228$
Right AntDel 90th % MVC	4.6 kg 100–170 cm	33.3 ± 12.6%	27.9 ± 13.1%	**$F(1,14) = 23.176$, $p < .001$, $\eta^2 = .678$**
	4.6 kg 15–100 cm	15.2 ± 9.1%	12.3 ± 9.0%	**$F(1,14) = 5.839$, $p = .030$, $\eta^2 = .362$**
	17.6 kg 100–170 cm	51.5 ± 15.9%	44.6 ± 12.2%	**$F(1,13) = 26.508$, $p < .001$, $\eta^2 = .726$**
	17.6 kg 15–100 cm	21.4 ± 11.5%	17.4 ± 10.4%	**$F(1,13) = 13.818$, $p = .003$, $\eta^2 = .574$**
Left UppTrap 10th % MVC	4.6 kg 100–170 cm	1.5 ± 1.3%	1.2 ± 1.1%	**$F(1,14) = 7.549$, $p = .016$, $\eta^2 = .423$**
	4.6 kg 15–100 cm	1.3 ± 1.1%	1.0 ± 0.9%	**$F(1,14) = 20.803$, $p < .001$, $\eta^2 = .654$**
	17.6 kg 100–170 cm	1.7 ± 1.3%	1.3 ± 1.0%	**$F(1,14) = 4.699$, $p = .048$, $\eta^2 = .338$**
	17.6 kg 15–100 cm	1.3 ± 0.9%	1.0 ± 0.8%	**$F(1,14) = 10.724$, $p = .006$, $\eta^2 = .516$**
Right UppTrap 10th % MVC	4.6 kg 100–170 cm	1.2 ± 0.8%	0.9 ± 0.6%	**$F(1,14) = 6.714$, $p = .022$, $\eta^2 = .393$**
	4.6 kg 15–100 cm	0.9 ± 0.9%	0.6 ± 0.5%	**$F(1,14) = 6.042$, $p = .028$, $\eta^2 = .369$**
	17.6 kg 100–170 cm	1.3 ± 1.0%	1.1 ± 1,2%	**$F(1,14) = 8.161$, $p = .013$, $\eta^2 = .473$**
	17.6 kg 15–100 cm	0.9 ± 0.6%	0.6 ± 0.5%	**$F(1,14) = 7.519$, $p = .016$, $\eta^2 = .436$**
Left UppTrap 90th % MVC	4.6 kg 100–170 cm	16.4 ± 9.6%	18.1 ± 15.4%	$F(1,14) = .029$, $p = .869$, $\eta^2 = .003$
	4.6 kg 15–100 cm	6.3 ± 5.4%	5.4 ± 4.7%	$F(1,14) = 2.556$, $p = . 138$, $\eta^2 = .189$
	17.6 kg 100–170 cm	26.2 ± 13.6%	28.6 ± 17.6%	$F(1,14) = 1.272$, $p = .286$, $\eta^2 = .113$
	17.6 kg 15–100 cm	12.0 ± 9.2%	11.4 ± 10.8%	$F(1,14) = 3.034$, $p = .109$, $\eta^2 = .216$
Right UppTrap 90th % MVC	4.6 kg 100–170 cm	15.5 ± 6.8%	17.2 ± 9.9%	$F(1,14) = .651$, $p = .437$, $\eta^2 = .056$
	4.6 kg 15–100 cm	5.6 ± 4.3%	5.1 ± 4.0%	$F(1,14) = 1.139$, $p = .309$, $\eta^2 = .094$
	17.6 kg 100–170 cm	25.0 ± 10.4%	31.2 ± 19.6%	$F(1,14) = 2.424$, $p = .151$, $\eta^2 = .195$
	17.6 kg 15–100 cm	12.7 ± 7.4%	10.6 ± 7.2%	**$F(1,14) = 5.008$, $p = .042$, $\eta^2 = .324$**
Left ErecSpin 10th % MVC	4.6 kg 100–170 cm	2.2 ± 3.2%	1.8 ± 0.9%	$F(1,14) = .645$, $p = .439$, $\eta^2 = .055$
	4.6 kg 15–100 cm	2.8 ± 1.6%	2.8 ± 1.9%	$F(1,14) = .211$, $p = .655$, $\eta^2 = .019$

(continued on next page)

Table 3 (*continued*)

Variable	Condition	NoEXO	EXO	Repeated measures ANOVA
	17.6 kg 100–170 cm	1.7 ± 0.7%	1.8 ± 0.8%	$F(1,14) = .317$, $p = .586$, $\eta^2 = .031$
	17.6 kg 15–100 cm	2.5 ± 1.3%	3.0 ± 1.8%	$F(1,14) = 2.862$, $p = .119$, $\eta^2 = .206$
Right ErecSpin 10th % MVC	4.6 kg 100–170 cm	2.3 ± 1.3%	2.6 ± 1.8%	$F(1,14) = 1.706$, $p = .218$, $\eta^2 = .134$
	4.6 kg 15–100 cm	3.3 ± 2.3%	3.4 ± 2.1%	$F(1,14) = 1.341$, $p = .271$, $\eta^2 = .109$
	17.6 kg 100–170 cm	2.5 ± 1.7%	2.3 ± 1.1%	$F(1,14) = 2.587$, $p = .139$, $\eta^2 = .206$
	17.6 kg 15–100 cm	3.4 ± 2.3%	3.5 ± 1.9%	$F(1,14) = 2.961$, $p = .113$, $\eta^2 = .212$
Left ErecSpin 90th % MVC	4.6 kg 100–170 cm	11.1 ± 8.9%	11.4 ± 6.6%	$F(1,14) = 1.416$, $p = .259$, $\eta^2 = .114$
	4.6 kg 15–100 cm	27.5 ± 16.3%	22.6 ± 8.6%	$F(1,14) = 2.376$, $p = .151$, $\eta^2 = .178$
	17.6 kg 100–170 cm	17.5 ± 7.7%	18.2 ± 8.9%	$F(1,14) = 1.997$, $p = .188$, $\eta^2 = .166$
	17.6 kg 15–100 cm	39.5 ± 19.3%	32.8 ± 11.6%	$F(1,14) = 1.029$, $p = .332$, $\eta^2 = .086$
Right ErecSpin 90th % MVC	4.6 kg 100–170 cm	9.0 ± 4.1%	10.5 ± 5.9%	$F(1,14) = 3.662$, $p = .082$, $\eta^2 = .250$
	4.6 kg 15–100 cm	26.3 ± 11.2%	24.1 ± 10.8%	**$F(1,14) = 5.488$, $p = .034$, $\eta^2 = .347$**
	17.6 kg 100-170	15.4 ± 5.7%	15.3 ± 6.9%	$F(1,14) = .613$, $p = .452$, $\eta^2 = .058$
	17.6 kg 15–100 cm	35.4 ± 13.8%	34.5 ± 13.8%	$F(1,14) = 1.541$, $p = .240$, $\eta^2 = .123$

the sEMG amplitude of the right erector spinae at the 4.6 kg 15–100 cm work task for EXO compared with NoEXO ($p = .034$). No further effects of the PSE were found at the erector spinae muscles. (Fig. 2).

3.1.2. Kinematics

Mean values ± SD of the kinematics and results of the statistical analysis are reported in Table 4. The 2RM-ANOVA revealed significant increases in the 10th percentile of shoulder flexion for EXO compared with NoEXO at three work tasks for the left joint (4.6 kg 100–170 cm, 4.6 kg 15–100 cm, 17.6 kg 100–170 cm; $p < .009$) and at all four work tasks for the right joint ($p < .010$). Additionally, significant increases were seen in the 90th percentile of shoulder flexion for EXO compared with NoEXO for the left joint at the 4.6 kg 100–170 cm and 17.6 kg 100–170 cm condition ($p < .028$), and for the right joint at the 4.6 kg 100–170 cm condition ($p = .040$). Significant increases were detected for all work tasks in the 10th percentile of the shoulder abduction for EXO compared with NoEXO for the left ($p < .002$) and the right joint ($p < .010$). Additionally, significant increases were found for all work tasks in the 90th percentile of shoulder abduction for EXO compared with NoEXO for the left ($p < .005$) and the right joint ($p < .039$). Finally, there were significant increases in the 10th percentile of the back flexion (L5-S1) for EXO compared with NoEXO at the 4.6 kg 100–170 cm and the 17.6 kg 100–170 cm condition ($p < .018$). Additionally, significant decreases were seen in the 90th percentile of the back flexion (L5-S1) for EXO compared with NoEXO at the 4.6 kg 15–100 cm, 17.6 kg 100–170 cm, and 17.6 kg 15–100 cm condition ($p < .013$) (Fig. 3).

3.1.3. Perceived effort

The 2RM-ANOVA revealed significant decreases in the ratings of perceived effort at the 4.6 kg 100–170 cm ($F_{1,16} = 12.053$, $p = .003$) and the 17.6 kg 100–170 cm condition ($F_{1,16} = 27.268$, $p < .001$) for EXO compared with NoEXO (Fig. 4).

3.2. Effects of familiarization

The participants showed a low adherence at 22.4 ± 13.7% of the

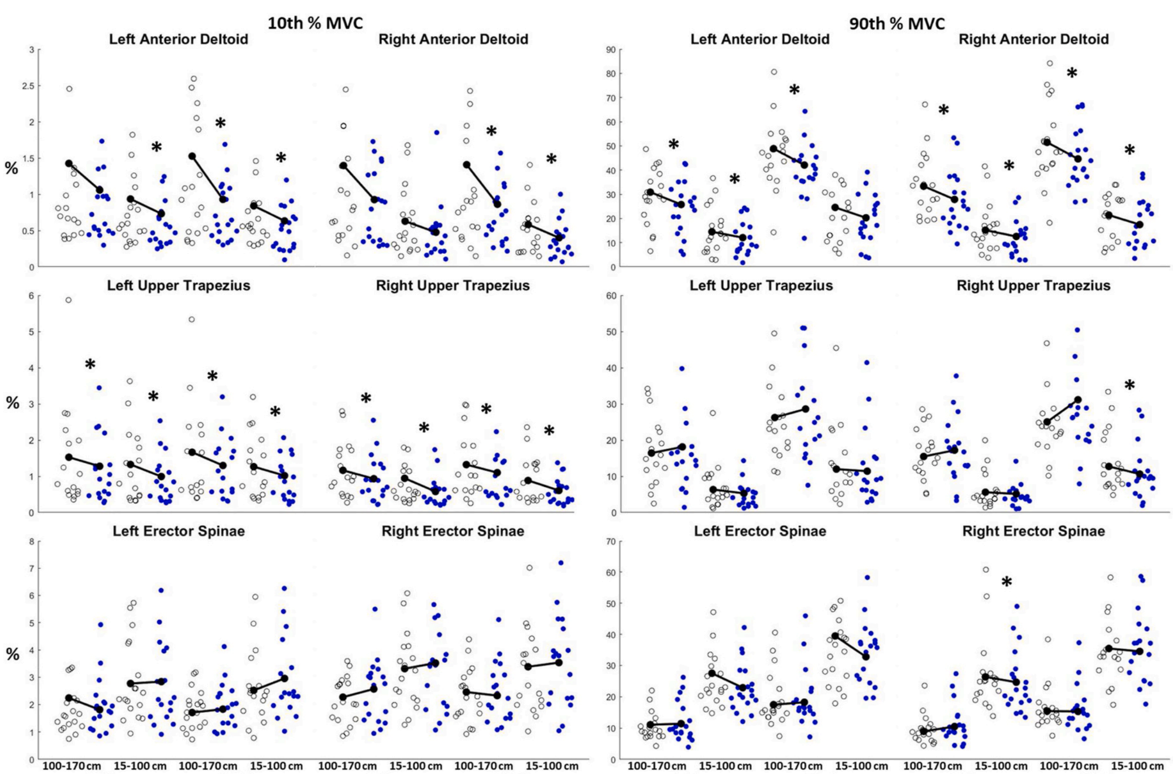

Fig. 2. Scatterplots reporting the mean (black dots) and individual distributions of the 10th (left) and 90th (right) percentile normalized average rectified sEMG values of left and right anterior deltoid, upper trapezius, and erector spinae during box lifting without (black circles) and with (blue filled circles) the passive shoulder exoskeleton. Note that measured values from pre- and post-tests of control and intervention group are included. * Indicates significant differences ($\alpha \leq .05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
The effects of the passive shoulder exoskeleton use on kinematics. The table includes mean ± SD of 10th and 90th percentiles of the joint angles for NoEXO and EXO conditions of left and right shoulder flexion, shoulder abduction, and back flexion (L5-S1). Additionally, the results of the repeated measures ANOVA are reported, including the f-values, p-values, and eta partial squared (η^2) effect sizes.

Variable	Condition	NoEXO	EXO	Statistics
Left shoulder Flex 10th % joint angle	4.6 kg 100–170 cm	−1.2 ± 8.4	9.9 ± 12.5	**$F(1,13) = 9.467, p = .009, \eta^2 = .707$**
	4.6 kg 15–100 cm	0.1 ± 7.5	5.6 ± 11.4	**$F(1,12) = 9.978, p = .008, \eta^2 = .454$**
	17.6 kg 100–170 cm	−0.1 ± 6.3	6.0 ± 8.7	**$F(1,13) = 25.364, p < .001, \eta^2 = .717$**
	17.6 kg 15–100 cm	1.4 ± 7.4	8.1 ± ± 12.9	$F(1,13) = 4.655, p = .054, \eta^2 = .297$
Right shoulder Flex 10th % joint angle	4.6 kg 100–170 cm	0.3 ± 9.1	8.0 ± 10.2	**$F(1,13) = 34.066, p < .001, \eta^2 = .850$**
	4.6 kg 15–100 cm	1.2 ± 6.4	6.8 ± 11.4	**$F(1,12) = 9.292, p = .010, \eta^2 = .436$**
	17.6 kg 100–170 cm	−0.7 ± 7.0	4.1 ± 9.1	**$F(1,13) = 13.713, p = .003, \eta^2 = .611$**
	17.6 kg 15–100 cm	0.6 ± 9.1	7.5 ± 10.8	**$F(1,12) = 28.722, p < .001, \eta^2 = .723$**
Left shoulder Flex 90th % joint angle	4.6 kg 100–170 cm	90.1 ± 15.8	99.8 ± 19.0	**$F(1,13) = 6.154, p = .028, \eta^2 = .579$**
	4.6 kg 15–100 cm	62.8 ± 12.3	64.3 ± 16.6	$F(1,13) = .214, p = .653, \eta^2 = .019$
	17.6 kg 100–170 cm	85.4 ± 14.4	96.1 ± 16.4	**$F(1,13) = 12.333, p = .004, \eta^2 = .614$**
	17.6 kg 15–100 cm	59.3 ± 13.7	61.4 ± 14.4	$F(1,13) = .472, p = .507, \eta^2 = .045$
Right shoulder Flex 90th % joint angle	4.6 kg 100–170 cm	89.7 ± 14.0	95.7 ± 17.9	**$F(1,13) = 5.222, p = .040, \eta^2 = .532$**
	4.6 kg 15–100 cm	62.2 ± 10.9	60.0 ± 14.0	$F(1,13) = .143, p = .713, \eta^2 = .013$
	17.6 kg 100–170 cm	85.4 ± 16.1	88.9 ± 18.7	$F(1,13) = 2.998, p = .117, \eta^2 = .250$
	17.6 kg 15–100 cm	59.6 ± 13.8	58.4 ± 15.1	$F(1,13) = 1.048, p = .330, \eta^2 = .095$
Left shoulder Abd 10th % joint angle	4.6 kg 100–170 cm	12.1 ± 4.6	20.4 ± 7.4	**$F(1,13) = 49.702, p < .001, \eta^2 = .892$**
	4.6 kg 15–100 cm	11.3 ± 4.1	19.0 ± 6.8	**$F(1,12) = 58.138, p < .001, \eta^2 = .829$**
	17.6 kg 100–170 cm	12.5 ± 4.1	20.3 ± 7.3	**$F(1,13) = 34.519, p < .001, \eta^2 = .775$**
	17.6 kg 15–100 cm	10.1 ± 5.3	17.9 ± 6.9	**$F(1,12) = 15.547, p = .002, \eta^2 = .586$**
Right shoulder Abd 10th % joint angle	4.6 kg 100–170 cm	12.8 ± 3.0	22.5 ± 6.3	**$F(1,13) = 48.413, p < .001, \eta^2 = .890$**
	4.6 kg 15–100 cm	10.9 ± 3.6	19.3 ± 6.7	**$F(1,12) = 43.837, p < .001, \eta^2 = .785$**
	17.6 kg 100–170 cm	13.1 ± 3.9	19.9 ± 6.7	**$F(1,13) = 9.071, p = .010, \eta^2 = .502$**
	17.6 kg 15–100 cm	9.9 ± 4.0	15.9 ± 5.5	**$F(1,12) = 18.105, p = .001, \eta^2 = .635$**
Left shoulder Abd 90th % joint angle	4.6 kg 100–170 cm	31.4 ± 6.5	40.3 ± 9.7	**$F(1,13) = 11.481, p = .005, \eta^2 = .759$**
	4.6 kg 15–100 cm	27.6 ± 5.4	38.5 ± 10.1	**$F(1,12) = 60.967, p < .001, \eta^2 = .847$**
	17.6 kg 100–170 cm	34.2 ± 6.8	39.8 ± 9.2	**$F(1,13) = 13.617, p = .003, \eta^2 = .649$**
	17.6 kg 15–100 cm	28.2 ± 6.4	37.5 ± 11.0	**$F(1,12) = 12.061, p = .005, \eta^2 = .561$**
Right shoulder Abd 90th % joint angle	4.6 kg 100–170 cm	33.9 ± 5.5	41.8 ± 9.7	**$F(1,13) = 6.798, p = .022, \eta^2 = .610$**
	4.6 kg 15–100 cm	28.5 ± 6.6	36.5 ± 11.6	**$F(1,12) = 15.287, p = .002, \eta^2 = .611$**
	17.6 kg 100–170 cm	36.6 ± 8.2	41.0 ± 10.3	**$F(1,13) = 5.250, p = .039, \eta^2 = .394$**
	17.6 kg 15–100 cm	27.7 ± 5.7	34.8 ± 12.4	**$F(1,12) = 6.899, p = .020, \eta^2 = .432$**
Back Flexion 10th % joint angle	4.6 kg 100–170 cm	−2.3 ± 1.3	−1.7 ± 0.9	**$F(1,13) = 10.269, p = .007, \eta^2 = .726$**
	4.6 kg 15–100 cm	−1.6 ± 1.5	−1.7 ± 1.2	$F(1,13) = .670, p = .429, \eta^2 = .053$
	17.6 kg 100–170 cm	−2.8 ± 1.7	−2.0 ± 1.2	**$F(1,13) = 7.361, p = .018, \eta^2 = .443$**
	17.6 kg 15–100 cm	−2.0 ± 1.7	−1.3 ± 1.0	$F(1,13) = 1.431, p = .257, \eta^2 = .115$
Back Flexion 90th % joint angle	4.6 kg 100.170 cm	1.5 ± 0.8	0.9 ± 0.8	$F(1,13) = 3.298, p = .119, \eta^2 = .355$
	4.6 kg 15–100 cm	1.9 ± 1.5	1.0 ± 1.1	**$F(1,12) = 29.347, p < .001, \eta^2 = .727$**
	17.6 kg 100–170 cm	1.8 ± 1.4	1.1 ± 0.9	**$F(1,13) = 8.343, p = .013, \eta^2 = .512$**
	17.6 kg 15–100 cm	1.8 ± 1.3	1.5 ± 1.3	**$F(1,12) = 12.140, p = .005, \eta^2 = .568$**

total time included in the protocol, yielding a total average of approx. 25 h of PSE use per worker (the familiarization protocol scheduled a total of 112 h). The individual and average progression of the reported PSE use among the workers of the intervention group is shown in Fig. 5. Additionally, the workers were divided into two groups: a group with moderate adherence ($n = 3$) and a group of low adherence ($n = 7$). Visual inspections on differences between the two groups were made on the muscle activity of anterior deltoid and upper trapezius, and joint angle of shoulder flexion and abduction. Of note, no statistical analysis was conducted due to the low sample size. No tendencies of effect of PSE use on muscle activity of the anterior deltoid and upper trapezius muscles were seen between the group of workers with moderate and low adherence to the familiarization protocol. The picture differed for the kinematics as the group with moderate adherence seemed to exhibit signs of reductions in shoulder flexion and abduction from pre to post test. The visual inspections and figures are included as supplementary material (Online Appendix 2).

3.2.1. Muscle activity and kinematics

The 2RM-ANOVA revealed no significant interaction between within- and between-subject factors in the 10th and 90th percentile of the sEMG amplitude or joint angles among any of the lifting tasks. Figures including pre- and post-test changes are included in the supplementary material (Online Appendix 3 and 4).

3.2.2. Perceived effort

No significant effects of the familiarization and interaction were

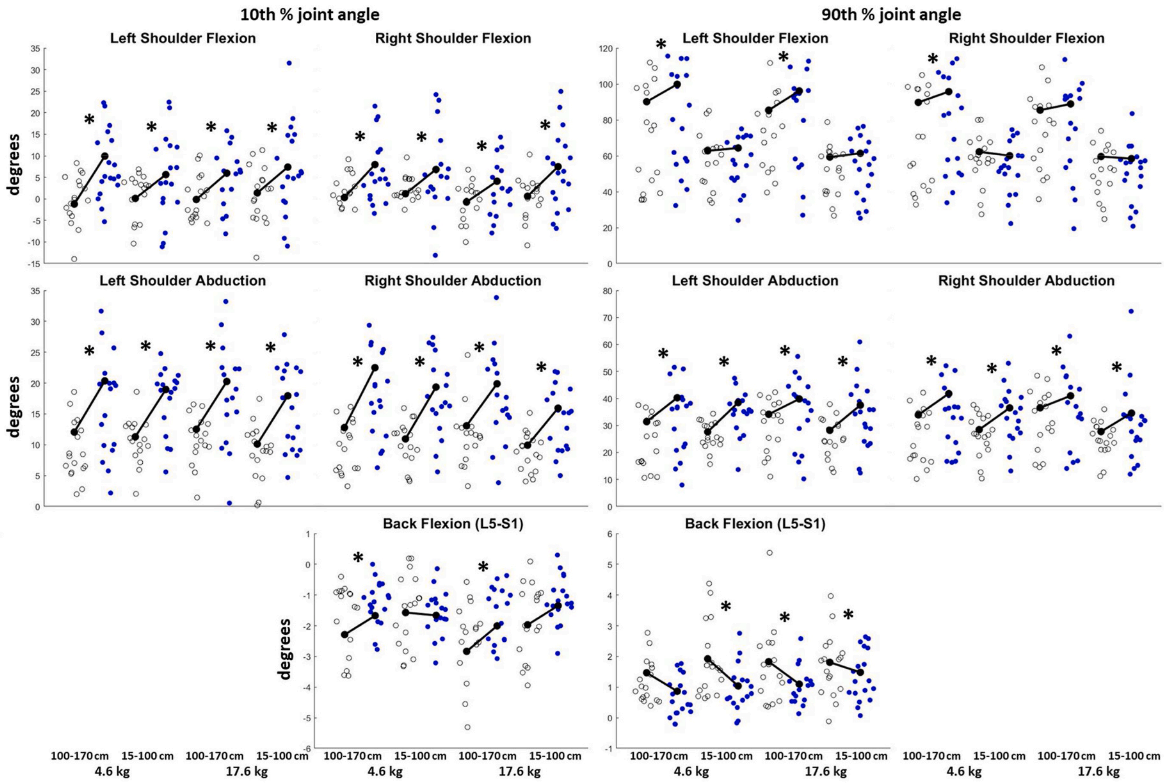

Fig. 3. Scatterplots reporting the mean (black dots) and individual distributions of the 10th (left) and 90th (right) percentile joint angle of left and right shoulder flexion and abduction, and back flexion (L5-S1) during box lifting without (black circles) and with (blue filled circles) the PSE. Note that measured values from pre- and post-tests of control and intervention group are included. * Indicates significant differences (α≤.05). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

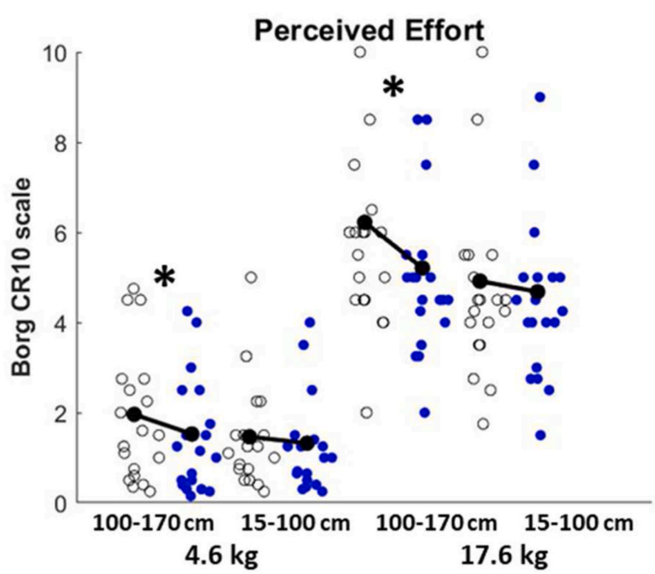

Fig. 4. Scatterplots reporting the mean (black dots) and individual distributions of the Borg CR10 scale rating of the box lifting without (black circles) and with (blue filled circles) the PSE. Note that measured values from pre- and post-tests of control and intervention group are included. * Indicates significant differences (α≤.05). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

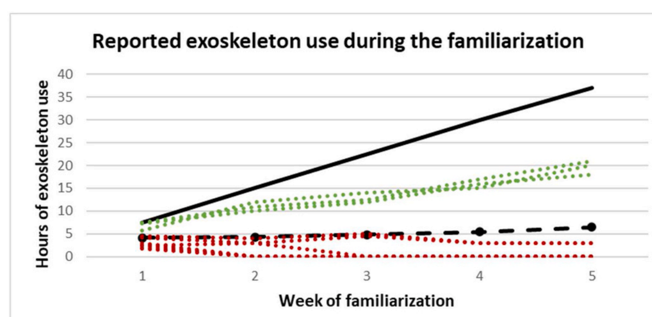

Fig. 5. Week-by-week reported exoskeleton use by the intervention group during the 5-week familiarization. The reported use is presented in weekly mean (black dashed line) and individual distribution (red/green dashed lines) of the ten workers of the intervention group. The red lines represent the seven workers with low adherence, while the green lines represent the three workers with moderate adherence. The line represents the scheduled exoskeleton use during the 5-week familiarization. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

revealed on the perceived effort ratings (Fig. 6).

3.2.3. *Subjective evaluation of the exoskeletons*

The 2RM-ANOVA revealed significant decreases for the two groups combined from pre-to post-test in perceived usefulness ($F_{1,16} = 25.780$, $p < .001$), emotions ($F_{1,16} = 32.493$, $p < .001$), attitude ($F_{1,16} = 27.004$, $p < .001$), and comfort ($F_{1,16} = 10.764$, $p = .005$) meaning that the ratings decreased regardless of whether the subjects underwent the intervention or not. Additionally, a significant interaction between

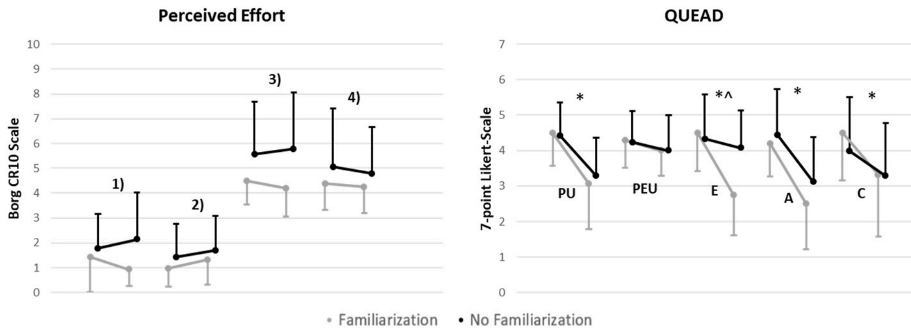

Fig. 6. Left: Mean and standard deviation of the Borg CR10 scale ratings of the lifts during exoskeleton use pre and post familiarization. The four lifts: 1: 4.6 kg from 100 to 170 cm, 2: 4.6 kg from 15 to 100 cm, 3: 17.6 kg from 100 to 170 cm, and 4: 17.6 kg from 15 to 100 cm are presented left to right. The grey lines represent the intervention group and the black lines represent the control group.
Right: Mean and standard deviation of the Questionnaire for the Evaluation of Physical Assistive Devices (QUEAD) likert-scale ratings pre and post familiarization. The ratings of perceived usefulness (PU), perceived ease of use (PEU), emotions (E), attitude (A), and comfort (C), are presented left to right. The grey lines represent the intervention group and the black lines represent the control group. * Indicates significant differences pre and post familiarization and ˆ indicates a significant interaction between familiarization and groups (α = .05).

familiarization and group was found for emotions ($F_{1,16} = 17.902$, $p = .001$) meaning that the intervention reinforced the decrease of the ratings (Fig. 6).

4. Discussion

The present field study investigated the changes in the level of muscular activity, kinematics, perceived effort, and subjective evaluation before and after an established familiarization of the PSE used for MMH. Decreases in the muscle activity of the shoulder, perceived effort, and modifications of the kinematics were found when using the PSE. Additionally, the subjective rating of the PSE decreased after the familiarization period. We could neither confirm nor infirm our hypotheses due to the low adherence to the familiarization protocol.

4.1. Immediate impact of a passive shoulder exoskeleton on the biomechanics of the shoulder girdle and the lower back

Passive shoulder exoskeletons have previously been examined in various industrial sectors, e.g., mechanics, manufacturing, and construction (van der Have et al., 2022; Jorgensen et al., 2022). Yet, in-field investigations on the use of PSEs in the logistics sector have not been conducted. This contributes to the novelty of the present study.

In agreement with findings made in manufacturing (Jorgensen et al., 2022), the use of the PSE reduced the 90th percentile of the sEMG amplitude of the anterior deltoid representing a decrease in the *peak* level of muscle activation (Szeto et al., 2009) across all work tasks. Additionally, decreases in the *low* measure of the sEMG amplitude (10th percentile) were found across all work tasks at the anterior deltoid and the upper trapezius as an effect of the PSE use (Fig. 2). This indicates that the PSE provides a reduction in the muscular load of the neck/shoulder region when performing common MMH tasks within the logistics sector. No effects were found on the muscle activity of the erector spinae, except for a decrease in the 90th percentile of the sEMG amplitude in the 4.6 kg 15–100 cm work task. In line with the sEMG findings, the use of the PSE resulted in decreased ratings of perceived effort in the high dimension work tasks (100–170 cm). No changes in perceived effort were found in the low dimension work tasks (15–100 cm), even though significant reductions in muscle activity were revealed for the anterior deltoid. This could be explained by the level of muscle activity and perceived effort, which showed that the low dimension tasks were conducted with less effort. Thus, this implies that the PSE mostly did not decrease the perceived effort of the task.

Besides the abovementioned effects, the use of the PSE also resulted in modifications of the kinematics in the form of increased shoulder flexion and abduction in both the 10th and 90th percentile of the joint angles. This indicates that the PSE alters the kinematics, and the muscular loads as increased flexion and abduction are reported in addition to lowered sEMG amplitude of the anterior deltoid muscles. Looking at the low measure of shoulder flexion and abduction, the PSE use increased the joint angles resulting in an offset of the motion to what would occur to differ from the normal for the resting position (Fig. 3). These results underline that the PSE modifies the shoulder movement of the workers, not only when the support is active but also when it is disengaged. This could be a factor contributing to the higher level of discomfort reported by the users (Fig. 6). The PSE caused small yet significant increases in the low measure of back flexion and decreases in the high measure of back flexion at two and three of the work tasks, respectively (Fig. 3). This indicated a reduced range of motion of the back that could be caused by the waist belt and the rigid frame of the PSE. Further, the reduction in range of motion explains the decrease in the level of activity of the erector spinae (Fig. 2).

These results show that the ShoulderX reduces the muscle activity of the neck/shoulder muscles and that the perceived effort of the users during the work tasks representative of logistics MMH without extensively affecting the back. Yet, use of the PSE modifies the kinematics not only when the support was required, which could explain the low perceived comfort. At the present stage, it is difficult to conclude whether these modifications of the neutral posture can be detrimental in the long-term. However, previous literature has reported less neutral arm posture among workers suffering from neck/shoulder pain (Madeleine et al., 1999).

4.2. Effects of a passive shoulder exoskeleton on the biomechanics of the shoulder girdle and the lower back after a five-week familiarization program

The weekly use of the PSE in the intervention group did not increase as planned. Fig. 5 indicates that some workers stopped using the PSE (7 out of 10), whilst other workers increased their use of the PSE (3 out of 10) reaching a moderate level of PSE use. This indicates that preferences for using the PSE or not took place at an individual level in the intervention group. However, given the fact that only 22% of the familiarization protocol was executed, it is not possible to draw any conclusions on the effect of the familiarization on the PSE use on neither muscle activity, kinematics, perceived effort, nor acceptance. The lack of adherence was concomitant to decreases in the subjective evaluations of the PSE, i.e., perceived usability, emotions, attitude, and comfort after the 5-week period. Additionally, the intervention group reported a larger decrease in ratings of emotions (related to the feeling of liking the use of the PSE) compared with the controls (Fig. 6). Interestingly, there were also reductions in the ratings of the control group which could be the result of negative talk and attitude towards the PSE among the workers at the warehouse.

Different potential reasons for the lack of adherence to the familiarization protocol were identified. Firstly, a laboratory study has shown that the PSE used in the present study has side effects when used for tasks beneath shoulder height (van der Have et al., 2022). Even though it is not supported by the sEMG results of the present study (Fig. 2), previous studies have shown PSEs are mostly beneficial for occupational tasks above shoulder height, especially static overhead work (van der Have et al., 2022; Van Engelhoven et al., 2018; Crea et al., 2021). Still the ShoulderX was chosen for the present study 1) due to a high prevalence of neck/shoulder pain within the company and 2) because in-field use of a PSE has not been investigated within manual logistics. Secondly, considering that the tasks conducted by the workers mainly consisted of stacking a truck from a height of 15 cm to a maximum allowed stack height of 170 cm, it appears that using the PSE for these tasks was not perceived as beneficial as expected. Crea et al. (2021) specifically pointed out the importance of matching the work task with the right model of occupational exoskeleton; thus, emphasizing this issue. Thirdly, the extra layer of the PSE might have caused heat issues and restricted movements of the workers as most work is conducted in confined spaces between the shelfs and the truck. These issues have previously been identified as negative parameters of exoskeleton use (Gutierrez et al., 2023; Nussbaum et al., 2019). Fourthly, the latter also emphasized the modifications of kinematics earlier mentioned, which could be a potential reason for the low ratings of comfort. Yet, the visual inspection (Online appendix 2), showed signs that the modifications of the shoulder movement could be reduced by familiarization. Future longitudinal studies focusing on the long-term effects on the shoulder biomechanics of exoskeleton use are needed. Based on the overall findings, it is questionable if the exoskeleton used matched the product line within the logistics sector. Thus, other assistive devices maybe more suitable for work tasks performed in logistics, e.g, exoskeletons supporting the lower back, could result in other conclusions as this sector require manual load handling involving both elevation of the arms and flexion/extension of the trunk. This emphasizes the need for more research on practical issues related to the use of exoskeletons in specific field work scenarios. Future studies combining the progressive use of exoskeletons at work after a thorough work task and biomechanical analysis are warranted.

4.3. Limitations

Firstly, the present study only analyzed the acute effects of one PSE used in four standardized real work tasks selected as representative of MMH within the logistics sector. Furthermore, a total blinding of the workers participating in the study was not possible due to the easy visual appearance of the PSE, which could affect the ratings of the perceived effort of the tasks in both groups. Secondly, the low adherence to the familiarization protocol makes it difficult to conclude whether familiarization influences the different parameters of the PSE use (see section 4.2). Thirdly, the choice of IMU-based motion capture and sEMG for measurements of kinematics and muscle activity, respectively, implies some methodological considerations on potential drawbacks. However, these assessments enable field recordings (Skals et al., 2021a,b).

4.4. Conclusion

The findings of the present study show that the tested PSE successfully reduced the muscle activity of the neck/shoulder musculature without affecting the back, which is additionally corroborated by decreases in perceived effort supporting the findings in other industrial sectors. This indicates that the PSE beneficially reduced the biomechanical load in logistics MMH. Yet, due to low adherence to the PSE use, it was not possible to draw any conclusions on the effects of the familiarization of the PSE. Based on the findings, literature, and assessments of the daily work tasks, it is questionable whether this PSE is suitable for the product line of the logistics sector. The implementation of exoskeletons for industrial use remains a challenging process. To achieve a wide acceptance of the use of exoskeletons, models more suitable for the complexity of MMH within the logistics sector are recommended.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2023.104104.

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