Passive Shoulder Exoskeletons: More Effective in the Lab Than in the Field?

Sander De Bock, Jo Ghillebert, Renée Govaerts, Shirley A. Elprama, Uros Marusic, Ben Serrien, An Jacobs, Joost Geeroms, Romain Meeusen, and Kevin De Pauw

Abstract*—Shoulder exoskeletons potentially reduce overuse injuries in industrial settings including overhead work or lifting tasks. Previous studies evaluated these devices primarily in laboratory setting, but evidence of their effectiveness outside the lab is lacking. The present study aimed to evaluate the effectiveness of two passive shoulder exoskeletons and explore the transfer of laboratory-based results to the field. Four industrial workers performed controlled and in-field evaluations without and with two exoskeletons, ShoulderX and Skelex in a randomized order. The exoskeletons decreased upper trapezius activity (up to 46%) and heart rate in isolated tasks. In the field, the effects of both exoskeletons were less prominent (up to 26% upper trapezius activity reduction) while lifting windscreens weighing 13.1 and 17.0 kg. ShoulderX received high discomfort scores in the shoulder region and usability of both exoskeletons was moderate. Overall, both exoskeletons positively affected the isolated tasks, but in the field the support of both exoskeletons was limited. Skelex, which performed worse in the isolated tasks compared to ShoulderX, seemed to provide the most support during the in-field situations. Exoskeleton interface improvements are required to improve comfort and usability. Laboratory-based evaluations of exoskeletons should be interpreted with caution, since the effect of an exoskeleton is task specific and not all in-field situations with high-level lifting will equally benefit from the use of an exoskeleton. Before considering passive exoskeleton implementation, we recommend analyzing joint angles in the field, because the support is inherently dependent on these angles, and to perform in-field pilot tests. This paper is the first thorough evaluation of two shoulder exoskeletons in a controlled and in-field situation.

***Index Terms*—Assistive devices, ergonomics, industrial plants, system validation.**

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I. Introduction

FORTY percent of European workers suffer from neck, shoulder or low back pain and 60% of all permanent work incapacity results from work-related musculoskeletal disorders [1]. In the European Union, the total cost of productivity losses due to work-related musculoskeletal disorders rises up to 2.5% of the gross domestic product [2]. These high numbers reflect the frequent exposure of employees in industrial environments to high physical workloads [3]. For shoulder injuries specifically, overhead work has been defined as a risk factor because of the exposure to complex and concurrent stresses and strains on tissues in the upper extremity [1], [4]. Given the relationship between occurrence of work-related musculoskeletal disorders and lifting intensity (odds ratio 1.09, $95\%CI$ $(1.03-1.15)$) and frequency (odds ratio 1.11, $95\%CI$ $(1.05-1.18)$) [5], reduced physical workload might reduce the prevalence of musculoskeletal disorders. Despite efforts to improve the working conditions, workers are still exposed to high physical workloads [1], [3]. Moreover, preventive strategies are preferred since evidence to advocate the use of exercise and ergonomic interventions in the treatment of work-related musculoskeletal disorders is limited [6].

Exoskeletons are considered to be one of the strategies to reduce the load on the operator [7]. An exoskeleton, a wearable device working in tandem with the user, augments, reinforces or restores human performance while being worn on the user's body [7], [8]. Active systems contain actuators to provide energy, whereas passive systems store and release energy by means of their elastic components [7], [9]. de Looze *et al.* (2016) highlighted the potential of exoskeletons in industrial settings. The correlation between absenteeism and exposure to physical workloads stresses the potential benefits of exoskeletons for workers, companies and societal healthcare burdens [10].

Supported by technological advancements, industrial exoskeletons reached higher technology readiness levels and start-ups began to originate. In general, previous passive shoulder exoskeleton evaluations demonstrated that exoskeletons reduced muscle activity facilitating shoulder flexion or abduction, and reduced cardiovascular and metabolic load during overhead work [11]. Mixed effects of shoulder exoskeletons on work performance have been reported [12]–[15]. Despite reduced activity of muscles responsible for lifting, shoulder exoskeletons potentially yield increased activation of other muscles, such as triceps brachii or erector spinae [16], [17].

Most commercially available exoskeletons have only been tested in a laboratory environment. In-field experiments were rarely performed or reported and therefore, the effect of exoskeletons in real-life situations remains to be determined and the value of laboratory evaluations with regard to real-life situations remains unclear [7]. Moyon *et al.* (2018) evaluated a shoulder exoskeleton when performing an in-field work routine which included overhead sanding. In the exoskeleton condition, indications of reduced cardiovascular load were observed compared to working without exoskeleton. In the automotive industry, increased working performance was observed [14] and a long-term evaluation of three months indicated decreased self-reported musculoskeletal discomfort [18]. Comparing multiple exoskeletons from different studies remains challenging because of the large variety of exoskeleton evaluation protocols that were used. The urge for standardized effectiveness studies of industrial exoskeletons in the workplace was highlighted in recent review papers [11], [19].

This study aims to investigate the effectiveness of two shoulder exoskeletons by assessing the physical load on the human operator during real-life working situations. In order to facilitate comparison of results with previous research, isolated tasks were added to the protocol. Furthermore, this study explores the results of exoskeleton evaluations in controlled settings and in the field.

II. Methods

A. Participants

Four healthy male industrial workers (33.4 ± 5.7 years, 80.9 ± 5.8 kg, 1.79 ± 0.02 m) working for 9.3 ± 6.4 years in the European distribution center of Carglass (Bilzen, Belgium) voluntarily participated in this study with a randomized within-subject design. Participants signed the written informed consent form describing the study protocol, which was approved by the local medical ethics commission of Vrije Universiteit Brussel and Universitair Ziekenhuis Brussel (B.U.N. 143201837251). Carglass cooperated by recruiting qualified volunteers, and providing opportunities and infrastructure to test on the work cite. Participants were excluded when suffering from musculoskeletal disorders or when experiencing pain that could affect daily life activities. Between two trials at least 24 h was scheduled.

B. Exoskeletons

In this experiment, two commercially available passive shoulder exoskeletons were tested (Figure 1). The first exoskeleton model was ShoulderX (V2, SuitX, Emeryville, United States) with a weight of 5.3 kg. Skelex (V2, Skelex, Rotterdam, The Netherlands), the second exoskeleton, weighs 4.0 kg. Both exoskeleton types claim to reduce load on the shoulders during work at shoulder height or higher and, as a result, reduce the risk of shoulder injuries. Furthermore, it is claimed that exoskeletons could improve workplace productivity.

(a) (b)

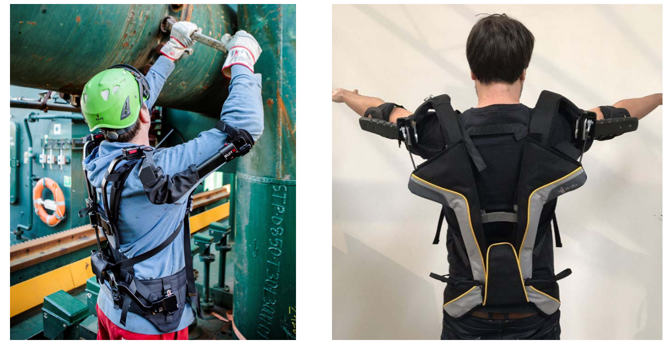

Fig. 1. The shoulder exoskeletons evaluated during this study were (a) ShoulderX V2 (SuitX, Emeryville,United States) and (b) Skelex V2 (Skelex, Rotterdam, The Netherlands). Both exoskeletons are attached to the pelvis and the upper arms. Shoulder straps ensure a stable location of the devices on the operator's body. SuitX and Skelex gave consent to illustrate both exoskeletons with pictures.

The exoskeletons are spring systems providing support by applying force to the upper arms, creating a flexion or abduction moment in the shoulder joint. These moments were already reported in previous studies [17], [20]. In order to transmit these moments, the exoskeletons are similarly interfaced with the operator, i.e. through a pelvis belt, shoulder straps and upper arm interfaces (Figure 1). As a result, a reduced muscle activity and decreased physical effort during work at or above shoulder height is expected. Based on the preference of the operators, assistance levels were set at the maximum for both exoskeletons. The maximal peak assistive torque of ShoulderX (15 Nm) was higher than the support of the Skelex (6 Nm) and therefore a superior assistive effect of the ShoulderX was expected.

C. Procedure

The experimental procedure was illustrated in Figure 2. Prior to the start of the experiment, relevant workstations were selected, and the exoskeletons and evaluation protocol were introduced in the company. The mechanism behind the devices was briefly explained and the instruction brochure was read in detail. All participants wore each exoskeleton for five blocks of two hours in a two-week time span prior to the evaluation, with a maximal frequency of one block per day.

Before a trial started, electromyographic (EMG) and measurement devices were attached to the body. Skin preparation and EMG sensor placement (Neuroline 710, Ambu, Copenhagen, Denmark) were executed according to the SENIAM guidelines [21]. Since not all potential side effects can be captured, analysis of the overall task intensity is required. The

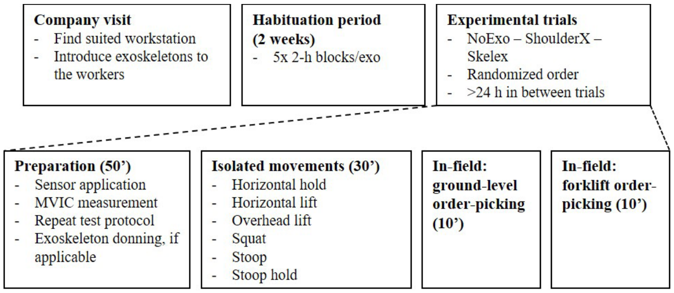

Fig. 2. A graphical representation of the experimental procedure is displayed.

current study opted for collecting heart rate data because this did not hinder the in-field work, allows accurate monitoring of task intensity [22] and it has already been used in exoskeleton evaluations [23]–[25]. Therefore, electrocardiographic (ECG) electrodes (BlueSensor L, Ambu, Copenhagen, Denmark) were placed bilaterally on the second intercostal space and on the left side below the twelfth rib.

Three maximal voluntary isometric contractions (MVIC) of the upper part of the trapezius muscle (TR), the lumbar erector spinae longissimus muscle (ES), the vastus medialis (VM) and the biceps femoris (BF) were performed. While many muscles contribute to the complex shoulder motions (e.g. deltoids, serratus anterior, trapezius), only TR activity was measured to quantify the support of the exoskeleton in the shoulder region. TR activity was selected because of its synergic contribution in shoulder flexion and abduction [26] and its relation to occupational shoulder-neck complaints [27]. Furthermore, previous research indicated reduced TR activity during overhead work with a passive shoulder exoskeleton [17], [28]. Accelerometers were attached to the right hand, and the right trochanter major. EMG, ECG and accelerations were synchronously captured at 500 Hz, i.e. the maximal sampling rate of the measurement device (LiveAmp with Trigger and Sensor extension, BrainProducts, Gilching, Germany). Habitual working and safety equipment was worn during all experimental trials. At the end of each trial participants filled out the body part discomfort scale and the NASA-TLX questionnaire [29]. The system usability scale was only filled out when wearing an exoskeleton [30], [31].

Six isolated tasks based on frequent movements in an industrial environment and previous passive shoulder exoskeleton evaluations [14], [17], [32] were executed separated by three minutes of rest [33]. Each repetition started in the neutral standing position with the weight of 5 kg in the participants' hands. Horizontal lifting required the participants to lift the weight with extended arms until horizontal (Figure 3a). Overhead lifting aimed to move the weight to the maximal height above the head of the participant (Figure 3b). Squatting was performed until the participants' buttocks reached the chair positioned behind the participant (Figure 3c). During the stoop lift, participants tried to place the weight on the ground in front the feet and returned to their starting position (Figure 3d). Each of these tasks was repeated 10 times, intercepted by three seconds of rest. In the first static task, the weight was

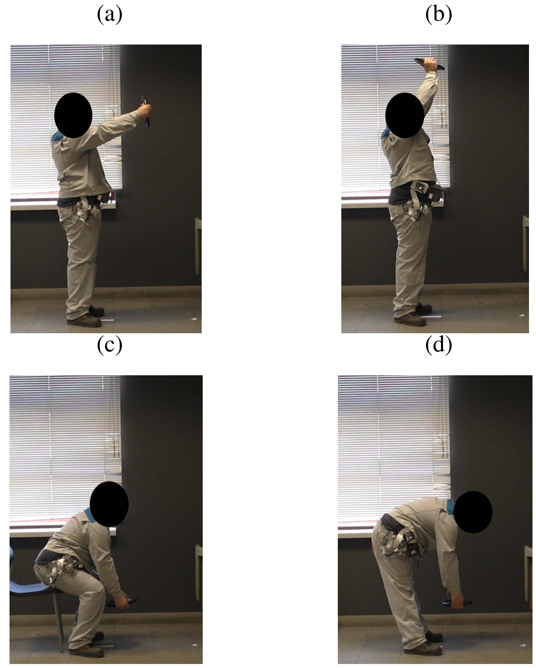

Fig. 3. Six isolated tasks were performed in a controlled environment. (a) Horizontal lift, (b) overhead lift, (c) squat and (d) stoop lift were performed ten times during the isolated tests. Furthermore, static (a) horizontal hold and (d) stoop hold positions were obtained for 60 seconds.

lifted for 60 seconds with the extended arms in a horizontal position (Figure 3a). The final isolated task was to hold a static stoop position for 60 seconds (Figure 3d). After each task the rating of perceived exertion (RPE) was collected through the Borg scale (scale: 6-20) [34].

After completion of the isolated tasks, the participant walked to the test location on the work floor and rested for 3 minutes. Ten windscreens, five large (dimensions: 1.50 x 1.13 m, weight: 17.0 kg) and five smaller windscreens (dimensions: 1.45 x 0.99 m, weight: 13.1 kg), served as standardized loads. All in-field tests were filmed with a video camera (GoPro, San Mateo, United States)(1080p, 100 Hz). Prior to the assessment, the participant faced the camera and clapped its hands to facilitate data synchronization during data analysis.

During the first in-field test, participants transferred windscreens from a trailer into a storage rack (height:1.53 m) and subsequently placed all windscreens back onto the trailer (Figure 4a). The same procedure was repeated a second time, but on a lower rack (height: 0.12 m). To perform the second in-field test, participants were standing on a platform of a forklift (dimensions 1.79 x 1.84 m) (Figure 4b). First, all 10 windscreens were lifted from the forklift into the storage rack on the right side. Next, all windscreens were again collected in the forklift. Subsequently, the same procedure was executed on the left side. Each windscreen needed to be lifted over a safety bar with a height of 0.98 m, which was aligned with the height of the shelve of the storage rack and the distance from the forklift platform to the storage rack was 0.58 m. Additional video documentation is available in appendix A.

(a)

(b)

Fig. 4. In-field assessments were performed at the European Carglass distribution facility. (a) First, an order picking task was performed on ground level. (b) Next, an order picking task was performed while standing on a forklift platform.

D. Data Analysis

Data was processed with the Python programming language (Anaconda Inc., Austin, TX, United States). Raw EMG signals were high pass filtered (20 Hz), full-wave rectified, low pass filtered (6 Hz) and normalized to MVIC. Acceleration signals from the hand and hip, assisted in determining each repetition of the dynamic isolated movements. The peak muscle activity of each repetition was determined. During static tasks, the average activity was computed. Data and video synchronization during the in-field tests was accomplished by a hand signal, a clap, triggering an acceleration peak at the beginning of the task. This allowed to determine the time frame of windscreen lifting. In each time frame, peak muscle activity was obtained. The average relative differences in TR activity per participant were determined between working with ShoulderX or Skelex and working without exoskeleton to compare the influence of the exoskeleton during isolated and in-field tasks. For this comparison, three isolated tasks; horizontal holding, horizontal lifting and overhead lifting, were selected because these provoke shoulder flexion. The average change in TR activity per exoskeleton was calculated per movement in the in-field tasks. Subsequently, the average effect was calculated for the order picking activity on ground level and on the forklift platform separately.

Heart rate was computed via the distance between R peaks in the recorded ECG data using the BioSPPy Python package [35]. Local discomfort scores were calculated for each body part and a general usability score was calculated from the SUS questionnaires according to Brooke *et al.* (1996) [30]. The NASA-TLX questionnaire provides a score for five different subcategories of workload; mental demand, physical demand, temporal demand, effort and frustration [29].

E. Statistical Analysis

Custom-made Python scripts (Anaconda Inc., Austin, TX, United States) were used for statistical data analysis. Muscle activity was modeled with linear mixed effects models. Random effects included subject-specific intercepts to account for repeated measures on participants. Fixed effects included exoskeleton for the four dynamic isolated tasks and exoskeleton, level or side, movement and all two-way and three-way interactions for the in-field tasks. If no interaction effects were found, the main effect of the exoskeleton condition was evaluated. Post hoc analyses were performed when applicable, focusing only on the effect of the exoskeletons to avoid abundant analyses. Friedman analyses were performed to investigate the effect of the exoskeleton condition on the heart rate, RPE and the static muscle activities of the isolated tasks. Significant effects were assessed in detail through Wilcoxon signed rank tests. Significance level in this study was set at 0.05, but trends towards significance were also considered ($p < 0.1$) given the small sample size. Effect sizes of ANOVA analyses were reported as partial eta squared (η_p^2), where large (> 0.13), medium (> 0.06) and small (> 0.01) effect sizes were distinguished. Rank-biserial correlation (r_{rb}) was used as the effect size of ranked tests. Values over 0.5 were considered large effects, values over 0.3 were considered medium and small effects reached higher than 0.1. Data is presented as the average and the standard deviation.

III. Results

A. Isolated Movements

Post-hoc tests were performed when a significant repeated measures ANOVA or Friedman analysis was observed (Table I). Also, trends towards significance were considered. A trend of reduced TR activity was observed during one-minute horizontal holding with ShoulderX (9.4±3.6% MVIC) compared to Skelex ($12.2 \pm 3.8\%$ MVIC, $p = 0.068$, $r_{rb} = 0.143$) and NoExo ($17.1 \pm 2.9\%$ MVIC, $p = 0.068$, $r_{rb} = 0.571$). Compared to NoExo, Skelex tended to reduce TR activity ($p = 0.068$, $r_{rb} = 0.429$) during this task. During horizontal lifting, TR activity reduced with ShoulderX ($13.6 \pm 6.2\%$) compared to Skelex ($20.4 \pm 6.1\%$ MVIC, $p = 0.045$, $\eta_p^2 = 0.290$) and a trend towards reduced TR activity was observed with ShoulderX compared to NoExo ($25.5 \pm 6.7\%$, $p = 0.076$, $\eta_p^2 = 0.209$). Overhead lifting without exoskeleton elicited higher TR activities ($44.2 \pm 12.3\%$ MVIC) compared to Skelex ($31.9 \pm 9.5\%$ MVIC, $p = 0.009$, $\eta_p^2 = 0.568$)

TABLE I
FRIEDMAN TESTS AND REPEATED MEASURES ANOVAS ASSESSING THE DIFFERENCES IN UPPER TRAPEZIUS (TR), ERECTOR SPINAE (ES), BICEPS FEMORIS (BF) AND VASTUS MEDIALIS (VM) ACTIVITY DURING THE ISOLATED MOVEMENTS

	Effect of Exoskeleton condition on:			
	TR activity	ES activity	BF activity	VM activity
H. Hold.	$\chi^2 = 8.00,\ p = 0.018^{**}$	$\chi^2 = 0.50,\ p = 0.779$	$\chi^2 < 0.01,\ p = 1.000$	$\chi^2 = 0.50,\ p = 0.779$
H. Lift	$F = 6.04,\ p = 0.037^{**}$	$F = 0.23,\ p = 0.799$	$F = 0.77,\ p = 0.502$	$F = 0.03,\ p = 0.969$
O. Lift	$F = 9.01,\ p = 0.016^{**}$	$F = 1.92,\ p = 0.226$	$F = 2.90,\ p = 0.132$	$F = 0.14,\ p = 0.868$
Squat	$F = 7.16,\ p = 0.026^{**}$	$F = 7.97,\ p = 0.020^{**}$	$F = 1.70,\ p = 0.260$	$F = 0.29,\ p = 0.758$
Stoop	$F = 2.42,\ p = 0.170$	$F = 1.35,\ p = 0.328$	$F = 2.33,\ p = 0.179$	$F = 0.22,\ p = 0.810$
Stoop Hold	$\chi^2 = 1.50,\ p = 0.472$	$\chi^2 = 0.50,\ p = 0.779$	$\chi^2 = 6.00,\ p = 0.050^{*}$	$\chi^2 = 3.50,\ p = 0.174$

* indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05, H. = Horizontal, O. = Overhead.

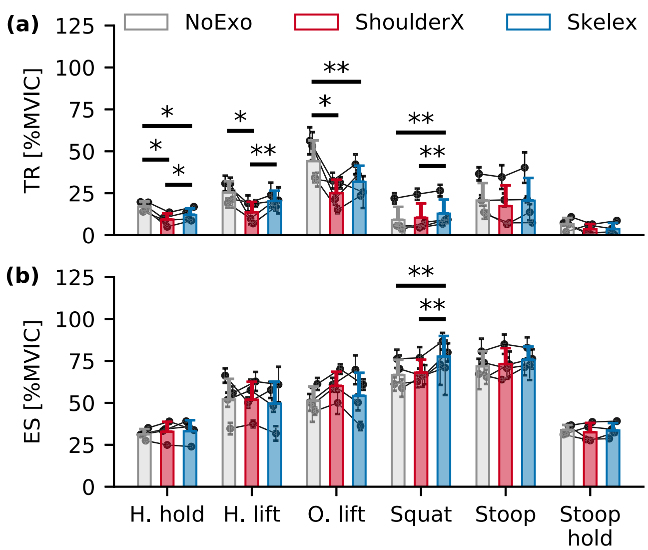

Fig. 5. The average and standard deviation of peak (a) upper trapezius (TR) and (b) erector spinae (ES) activity are illustrated per isolated movement. Line plots indicate individual activation levels. If multiple repetitions of the movement were performed, standard deviations were displayed. H. = horizontal, O. = overhead. * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

and ShoulderX (25.1 $\pm$ 8.0% MVIC, $p = 0.056$, $\eta_p^2 = 0.255$). TR activity increased when squatting with Skelex (12.9 $\pm$ 8.3% MVIC) in comparison to NoExo (9.17 $\pm$ 7.7%, $p = 0.037$, $\eta_p^2 = 0.324$) and similar trend was found in the comparison between NoExo and ShoulderX (10.4 $\pm$ 8.5% MVIC, $p = 0.014$, $\eta_p^2 = 0.496$)(Figure 5a). Skelex increased ES activity during squatting (77.7 $\pm$ 12.2% MVIC) compared to ShoulderX (68.1 $\pm$ 7.6%, $p = 0.012$, $\eta_p^2 = 0.526$) and a trend towards the same effect was found when comparing to NoExo (66.6 $\pm$ 9.1% MVIC, $p = 0.079$, $\eta_p^2 = 0.203$) (Figure 5b). Effects of exoskeletons on the muscle activity of VM and BF during isolated movements yielded insufficient evidence (Appendix B).

RPE was not significantly influenced by the exoskeleton conditions. ShoulderX tended to reduce heart rates during horizontal holding (82$\pm$13 bpm) compared to NoExo (100$\pm$16 bpm, $p = 0.068$, $r_{rb} = 0.278$) and Skelex (94 $\pm$ 14 bpm, $p = 0.068$, $r_{rb} = 0.278$). Overhead lifting with ShoulderX yielded trends towards lower heart rates (78 $\pm$ 10 bpm) compared to NoExo (87 $\pm$ 10 bpm, $p = 0.068$, $r_{rb} = 0.278$) and Skelex (84 $\pm$ 13 bpm, $p = 0.068$, $r_{rb} = 0.222$). Holding a stooped position for one minute with the ShoulderX resulted in a trend towards reduced heart rate (81 $\pm$ 11 bpm) compared to NoExo (90 $\pm$ 10 bpm, $p = 0.068$, $r_{rb} = 0.222$) and Skelex (91 $\pm$ 9 bpm, $p = 0.068$, $r_{rb} = 0.222$).

B. In-Field Order Picking on Ground Level

No significant triple interactions (Exoskeleton x Level x Movement) for the muscle activities occurred during in-field order picking task on ground level. Furthermore, no significant two-way interactions were observed for TR, ES, VM or BF activity (Appendix C). While moving small windscreens into and out of the lowest rack, Skelex tended to reduce RPE scores (in: 8.25 $\pm$ 1.7, out: 8.0 $\pm$ 1.6) compared to NoExo (in: 9.5 $\pm$ 1.3, $p = 0.092$, $r_{rb} = 0.143$; out: 9.5 $\pm$ 1.3, $p = 0.063$, $r_{rb} = 0.250$). No significant differences were observed compared to the ShoulderX condition (9.0 $\pm$ 1.8). During this in-field task, a tendency towards lower heart rates in the ShoulderX condition (102 $\pm$ 4 bpm) was observed compared to Skelex (107 $\pm$ 3 bpm, $p = 0.068$) and NoExo (105 $\pm$ 3 bpm, $p = 0.068$, $r_{rb} = 0.429$).

C. In-Field Order Picking on Forklift Platform

No three-way interactions were observed for the muscle activities during the second in-field test. Two-way interaction effects of the exoskeleton condition and the performed movement were detected for TR ($p = 0.081$, $\eta_p^2 = 0.101$), ES ($p = 0.031$, $\eta_p^2 = 0.128$) and BF activity ($p = 0.037$, $\eta_p^2 = 0.122$) (Table II) and no significant effects were observed in VM activity (Appendix D).

When lifting small windscreens into the storage rack, a trend towards reduced reduced TR activities with Skelex (33.1 $\pm$ 17.7% MVIC) compared to NoExo (61.5 $\pm$ 16.7% MVIC; $p = 0.084$, $\eta_p^2 = 0.350$) was observed (Figure 6a). ShoulderX increased ES activities when lifting windscreens back onto the forklift (small: 71.6 $\pm$ 24.5% MVIC; large: 76.3 $\pm$ 15.0 MVIC) condition compared to NoExo (small: 42.5 $\pm$ 26.4% MVIC, $p = 0.042$, $\eta_p^2 = 0.495$; large: 52.9 $\pm$ 25.7% MVIC, $p = 0.003$, $\eta_p^2 = 0.856$) (Figure 6b). When lifting large windscreens onto the forklift, ShoulderX also increased ES activity compared to Skelex (45.0$\pm$25.7% MVIC, $p = 0.014$, $\eta_p^2 = 0.694$). This effect was not observed when lifting small windscreens back onto the forklift. ShoulderX consistently

TABLE II

POST HOC REPEATED MEASURES ANOVA ASSESSING THE DIFFERENCES IN UPPER TRAPEZIUS (TR), ERECTOR SPINAE (ES) AND BICEPS FEMORIS (BF) ACTIVITY DURING THE ORDER PICKING TASK ON THE FORKLIFT PLATFORM BETWEEN EXOSKELETON CONDITIONS. LIFTING WINDSCREENS FROM THE FORKLIFT INTO THE RACK WAS CALLED 'IN', 'OUT' SYMBOLIZES LIFTING WINDSCREENS FROM THE RACK ONTO THE FORKLIFT PLATFORM

Fixed factor: Movement	Effect of Exoskeleton condition on:		
	TR activity	ES activity	BF activity
Large windscreen - In	$F = 2.22,\ p = 0.190$	$F = 0.91,\ p = 0.453$	$F = 55.07,\ p \leq 0.001^{**}$
Large windscreen - Out	$F = 1.60,\ p = 0.277$	$F = 14.46,\ p = 0.005^{**}$	$F = 13.94,\ p = 0.006^{**}$
Small windscreen - In	$F = 5.28,\ p = 0.048^{**}$	$F = 1.78,\ p = 0.248$	$F = 7.78,\ p = 0.022^{**}$
Small windscreen - Out	$F = 2.42,\ p = 0.169$	$F = 3.75,\ p = 0.088^{*}$	$F = 15.92,\ p = 0.004^{**}$

* indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

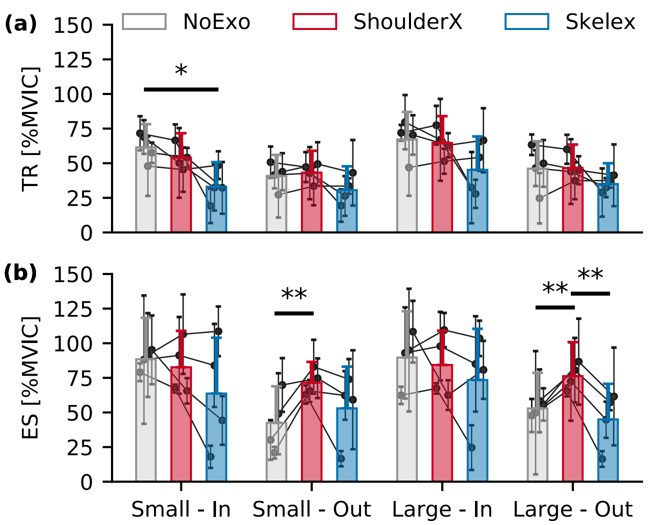

Fig. 6. The average and standard deviation of peak (a) upper trapezius (TR) and (b) erector spinae (ES) activity during the order picking task on the forklift platform were illustrated per movement in this figure. Line plots indicate the individual activation levels with intrapersonal standard deviation. * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

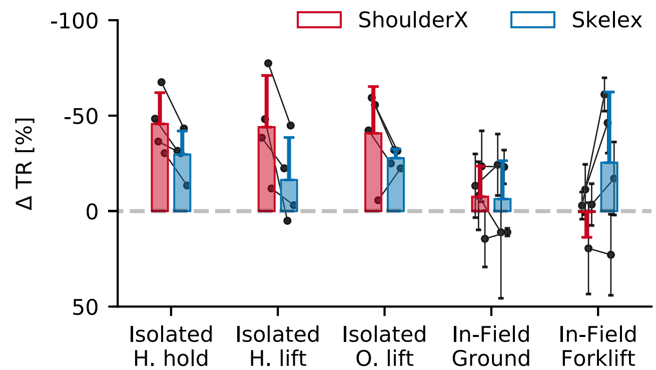

Fig. 7. The average relative change in upper trapezius (TR) activity with each exoskeleton was illustrated for the isolated movements in which support of the exoskeleton was expected. Furthermore the average relative change in TR activity during the in-field evaluations was illustrated. This figure allows to compare the efficacy of the exoskeleton in TR reduction between isolated tests and in-field evaluations. H. = horizontal, O. = overhead.

increased BF activity when lifting windscreens compared to NoExo and Skelex ($p \leq 0.030$, $\eta_p^2 \leq 0.460$) (Appendix D). Skelex reduced BF activity while lifting large windscreens into the storage rack ($20.4 \pm 8.7\%$ MVIC) compared to NoExo ($25.5 \pm 7.6\%$ MVIC, $p = 0.033$, $\eta_p^2 = 0.542$).

On the forklift platform, ShoulderX tended to reduce RPE scores compared to NoExo ($p \leq 0.068$, $\eta_p^2 \leq 0.429$), with exception of lifting the large windscreen into the storage rack on the right side ($p = 0.180$, $\eta_p^2 = 0.071$). Compared to NoExo lifting, trends towards a reduced RPE with Skelex were observed in half of the movements, but no systematic effect was observed. The effect of exoskeleton conditions on heart rates at this workpost did not reach statistical significance.

D. Transfer From Isolated Tasks to In-Field Situations

Compared to NoExo, ShoulderX reduced TR activity during horizontal holding ($-46 \pm 16\%$), horizontal lifting ($-44 \pm 27\%$) and overhead lifting ($-40.74 \pm 24.50\%$). Skelex reduced TR activity to a smaller extent during horizontal holding ($-30 \pm 12\%$), horizontal lifting ($-16 \pm 22\%$) and overhead lifting ($-28 \pm 5\%$) (Figure 7). This phenomenon was observed unanimously, with exception of one participant, where Skelex elicited the largest TR activity reduction during overhead lifting. The effect of the exoskeletons on TR activity in the field was not consistent, which is illustrated by the low average relative TR activity changes of ShoulderX ($-8 \pm 16\%$) and Skelex ($-6 \pm 20\%$) compared to NoExo (Figure 7). Only working on the forklift platform with an exoskeleton tended to reduce TR activities. Here, Skelex reduced the TR activity with $25 \pm 37\%$ compared to NoExo, while wearing the ShoulderX did not affect TR activity significantly ($+5 \pm 13\%$). On the forklift platform, ShoulderX and Skelex reduced TR activities in three out of the four participants. In one participant, the effect of the exoskeletons deviated strongly from the other participants.

E. Subjective Evaluation

Most categories of the NASA-TLX were not influenced by the exoskeletons (Figure 8), but a trend of reduced temporal workload was found in ShoulderX and Skelex compared to NoExo ($-21 \pm 10\%$, $p = 0.059$, $r_{rb} = 0.361$; $-26 \pm 10\%$, $p = 0.066$, $r_{rb} = -0.444$, respectively). ShoulderX increased the sensation of frustration compared to NoExo ($+416 \pm 413\%$, $p = 0.068$, $r_{rb} = 0.429$), while Skelex did not. Overall, more discomfort was present in the ShoulderX condition compared to NoExo. On average, ShoulderX and Skelex scored 1.6 ± 0.6

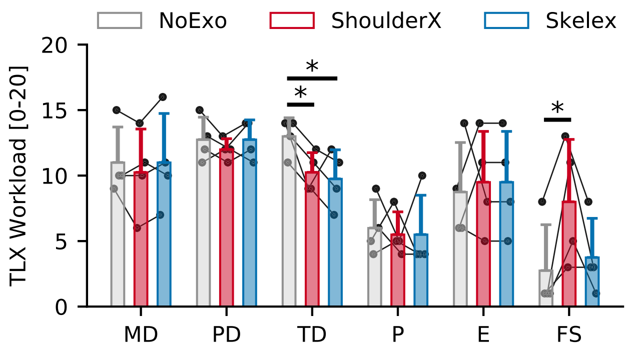

Fig. 8. The average score for each NASA-TLX subcategory (mental demand (MD), physical demand (PD), temporal demand (TD), performance (P), effort (E), frustration (FS). was displayed in a bar graph with the standard deviation illustrated by the error bars. * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

and 1.2 ± 0.4 out of 5 for discomfort. The score of all body parts incorporated in the local discomfort scale is illustrated via a color scale in Figure 9. The increased discomfort is most remarkable with the ShoulderX and mainly focused in the upper body. In the shoulder region, the least comfortable region when wearing the ShoulderX, three out of four participants indicated an increased discomfort while wearing the ShoulderX ($+1.5 \pm 1.3$). Shoulder discomfort increased while wearing the Skelex in only one participant ($+0.25 \pm 0.5$). The usability of ShoulderX (61.3 ± 12.3) and Skelex (68.8 ± 8.3) were not significantly different.

IV. Discussion

To our knowledge, this study was the first to thoroughly evaluate two commercially available passive shoulder exoskeletons during both isolated and in-field tasks. The physical effort and subjective experience were evaluated in a healthy working population that is daily exposed to high physical workloads. The main finding of this study included reduced TR activities up to 46% with ShoulderX and 30% with Skelex compared to NoExo during isolated tasks. These differences were less pronounced during in-field work, where reductions up to 8% and 26% were observed with ShoulderX and Skelex, respectively. Subjective data demonstrated that the operators experienced a reduced temporal workload, but scored the usability moderate when working with a passive shoulder exoskeleton. Additionally, increased upper body discomfort and frustration were present, especially with ShoulderX.

The difference in peak assistive torque between ShoulderX (15 Nm) [17] and Skelex (6 Nm) [20] led to higher TR activity reductions with ShoulderX during isolated movements. ShoulderX reduced TR activity with 46% during horizontal holding, 44% during horizontal lifting and 41% during overhead lifting compared to NoExo, which aligns with the results of a recent ShoulderX evaluation [17].

Literature and the current study evidenced that shoulder exoskeletons reduce the physical load during standardized isolated movements [11]. However, the question remains whether these supportive characteristics of shoulder exoskeletons are still present in field conditions. The combination of isolated and in-field tasks with and without exoskeletons is novel. The current study found no effect of shoulder exoskeletons on TR activity during the in-field task on ground level and the assistive function of the exoskeletons while working on the forklift platform was negligible. The lack of support of the shoulder exoskeletons might be due to the selected working tasks. However, the working situations were selected, because operators work at, or close to shoulder height. With a rack height of 1.53 m and windscreens of approximately 1.00 m high, overhead working situations were expected during the in-field evaluation on ground level. Although exoskeleton support during these movements was hypothesized, expectations were not met.

A large variability in muscle activity levels exists during both in-field tasks, which illustrates different intra-individual and inter-individual lifting techniques. During picking on the forklift platform, only Skelex affected TR activity, which indicates a possible supportive effect of the Skelex during this particular task. Additionally, both exoskeletons did not affect TR activity during the picking task on ground level. The difference between both workstations might be related to the dimensions of available space surrounding the operator. In contrast to working on ground level, the space on the forklift platform is limited and the windscreens must be placed outside of the cage, forcing the operators to work with higher shoulder elevation. The resultant lifting technique allowed the exoskeletons to provide more support compared to the in-field assessment on ground level. Overall, only Skelex reduced TR activity with 25% during in-field testing, whereas ShoulderX and Skelex reduced TR activity during isolated tasks up to 45% and 30%, respectively. While the difference between the effect of both exoskeletons during the isolated tests was justified through the torque-angle profile of each exoskeleton, the discrepancy observed when comparing the isolated with the in-field results was not hypothesized. The torque-angle profile of the Skelex exoskeleton remains unchanged when the abduction angle in the shoulder changes [20], a phenomenon that was not specified in previous ShoulderX evaluations. It is remarkable that the higher support of the ShoulderX results in a superior effect on TR activity when lifting a load with the arms in front of the body, while in the field the reverse result was observed in the field when lifting a large object, forcing the operators to lift with large shoulder abduction angles. Future research could investigate the effect of shoulder abduction angles on different shoulder exoskeletons.

Other assistive devices have been evaluated in the past, e.g. an exoskeleton with mechanical arm. The latter device increased muscle activity at the low back, while the load on the upper-extremities was reduced [16]. The current study did not reveal increased ES activation while supporting the upper extremities during isolated tasks. However, other compensatory muscle activities have been found, such as subtle increments in TR activity during the squat task with Skelex compared to NoExo. Involuntary lumbar flexion possibly elongated the spine during the lift [36], and the increased the tension of the shoulder straps provoked this increased TR activity. In contrast to Skelex, ShoulderX has a rigid spinal structure which might limit this lumbar flexion and thus no increased TR activity was detected.

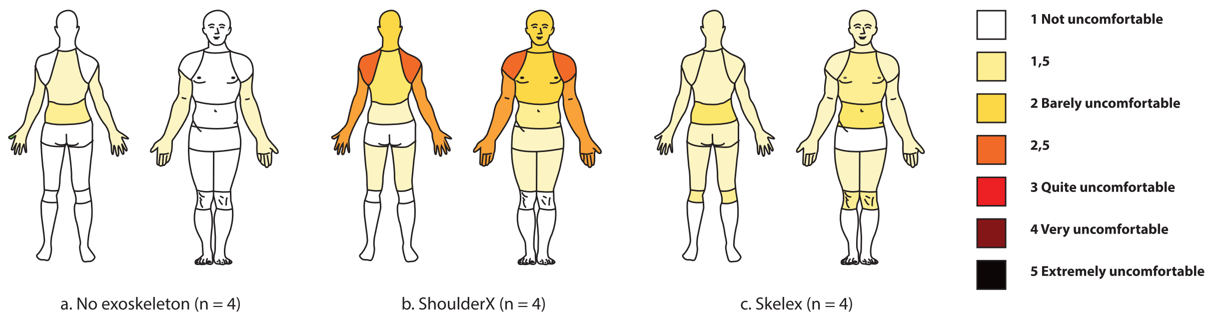

Fig. 9. Discomfort scores are illustrated as color scales on silhouettes. The average discomfort score is determined per body part for (a) NoExo, (b) ShoulderX, (c) Skelex.

Similarly, ES activity increased while squatting with Skelex in comparison to the other conditions. Again, this is possibly related to the tension on the shoulder straps and the soft structure around the lumbar zone. In field conditions, ShoulderX also increased ES activity when lifting windscreens from the rack onto the forklift platform. Additionally, BF activity was consistently higher while working on the forklift platform with the ShoulderX compared to the other conditions, while no increased BF activity was observed during the isolated tasks. Possibly, the exoskeletons changed the operators' preferred lifting technique, a phenomenon that was already reported in passive low back exoskeletons [37], [38]. The rigid spinal module of the ShoulderX could limit the lumbar range of motion forcing additional leg flexion to compensate for this restriction. An altered lifting technique indicates that caution is warranted when squatting with exoskeletal devices designed for shoulder support when the neutral position of the trunk cannot be preserved, especially with rigid structures surrounding the trunk.

Another assistive device that has been evaluated during continuous overhead work in a laboratory setting is the passive Paexo Shoulder exoskeleton [23], [24]. It was shown the heart rate decreased up to 19%, which is consistent with the results of the current study, i.e. reductions of $17 \pm 8\%$ during the isolated horizontal holding task and $11 \pm 7\%$ when lifting overhead using the ShoulderX. The combined effects of reduced heart rate and larger TR activity reduction during isolated work indicates the superior assistance of ShoulderX compared to Skelex.

RPE was not affected by the exoskeletons during the isolated movements, despite reduced heart rates and muscle activity. We assume that the participants did not perceive the effect of the exoskeletons because these tasks lasted too short to provoke a steady state in breathing frequency [39], which is strongly associated with RPE [40]. This contrasts the evaluation of Van Engelhoven *et al.* (2019), where ShoulderX reduced the perceived effort of overhead work [17]. While working on ground level, the exoskeletons did not reduce RPE, which corresponds to the muscle activity results. Both exoskeletons reduced RPE on the forklift platform. The reduced RPE with Skelex confirms the reduced muscle activity, but RPE scores and muscle activation levels were not congruent with ShoulderX.

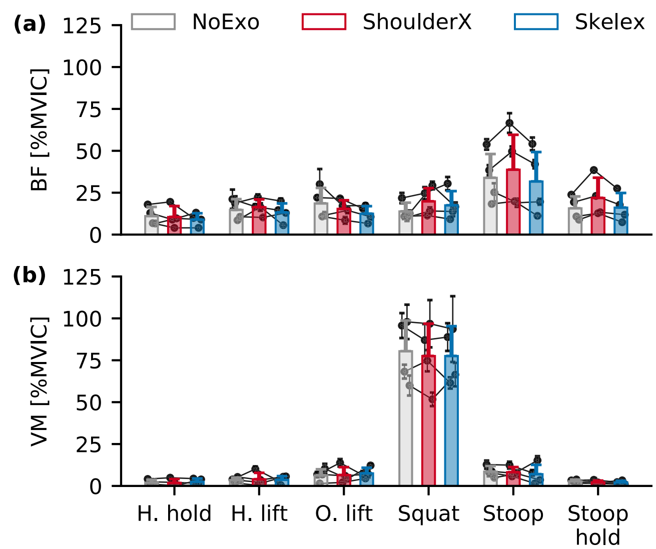

Fig. 10. The average and standard deviation of peak (a) biceps femoris (BF) and (b) vastus medialis (VM) activity are illustrated per isolated movement. Line plots indicate individual activation levels. If multiple repetitions of the movement were performed, standard deviations were displayed. H. = horizontal, O. = overhead. * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

Ease-of-use, usefulness and comfort are important determinants for the intention-to-use [41], [42]. Therefore, subjective evaluations of exoskeletons are valuable for exoskeleton designers and companies who are considering exoskeleton implementation. Apart from changes in discomfort score and an increased feeling of frustration, temporal workload reduced while working with the exoskeletons. The combination of these findings could explain the similar, moderate, SUS score for both exoskeletons. This indicates a margin for usability improvements for these specific in-field situations. Exoskeleton interfaces could be improved in future exoskeleton devices which may lead to enhanced usability. The highest discomfort was observed with ShoulderX in areas where the exoskeleton and the user's body interacted, or body parts onto which the exoskeletons where attached. The rigid frame of the ShoulderX caused this discomfort, while this effect was less prominent with the softer structure of the Skelex.

TABLE III

THE AVERAGE AND STANDARD DEVIATION OF MAXIMAL ACTIVATION OF THE UPPER TRAPEZIUS (TR), ERECTOR SPINAE (ES), BICEPS FEMORIS (BF) AND VASTUS MEDIALIS (VM) ACTIVITY DURING THE ORDER PICKING TASK ON GROUND LEVEL ARE DISPLAYED IN THIS TABLE. LIFTING WINDSCREENS INTO THE RACK WAS CALLED 'IN', 'OUT' SYMBOLIZES LIFTING WINDSCREENS FROM THE RACK ONTO THE FORKLIFT PLATFORM

	Movement	NoExo [% MVIC]	ShoulderX [% MVIC]	Skelex [% MVIC]
TR Activity [%MVIC]]	Large windscreen - In	51.31 ± 21.40	52.26 ± 21.29	50.41 ± 21.10
	Large windscreen - Out	42.92 ± 15.12	40.24 ± 16.84	39.94 ± 16.00
	Small windscreen - In	42.97 ± 23.16	38.77 ± 19.57	40.06 ± 19.01
	Small windscreen - Out	41.36 ± 19.75	32.39 ± 13.68	30.33 ± 12.97
ES Activity [%MVIC]]	Large windscreen - In	94.66 ± 44.16	77.79 ± 32.01	85.36 ± 20.79
	Large windscreen - Out	66.02 ± 22.07	61.34 ± 24.55	64.25 ± 16.16
	Small windscreen - In	97.30 ± 48.77	77.95 ± 23.07	87.24 ± 31.80
	Small windscreen - Out	65.54 ± 21.65	69.11 ± 18.87	67.33 ± 26.19
BF Activity [%MVIC]]	Large windscreen - In	27.52 ± 10.83	37.16 ± 16.29	26.22 ± 8.49
	Large windscreen - Out	25.54 ± 7.71	35.71 ± 12.29	23.04 ± 9.16
	Small windscreen - In	30.74 ± 8.38	35.27 ± 18.37	25.15 ± 8.56
	Small windscreen - Out	31.42 ± 12.99	32.13 ± 10.97	27.03 ± 8.44
VM Activity [%MVIC]	Large windscreen - In	25.18 ± 17.03	27.59 ± 18.67	21.80 ± 14.69
	Large windscreen - Out	21.95 ± 14.53	21.23 ± 8.99	23.03 ± 18.70
	Small windscreen - In	16.83 ± 7.24	22.30 ± 10.08	18.58 ± 12.05
	Small windscreen - Out	24.68 ± 19.25	19.23 ± 10.33	18.36 ± 9.78

Compared to NoExo, * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.
† indicates p-values ≤ 0.1, †† indicates p-values ≤ 0.05 between ShoulderX and Skelex.

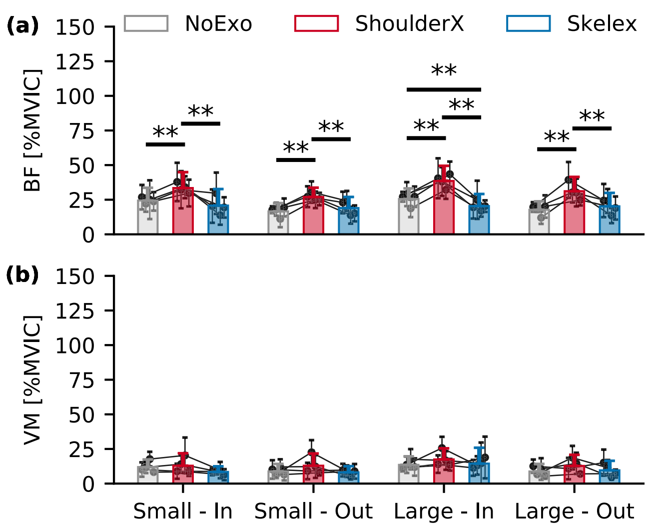

Fig. 11. The average and standard deviation of peak (a) biceps femoris (BF) and (b) vastus medialis (VM) activity during the order picking task on the forklift platform were illustrated per movement in this figure. Line plots indicate the individual activation levels with intrapersonal standard deviation. * indicates p-values ≤ 0.1, ** indicates p-values ≤ 0.05.

This in-field study has some limitations. First, due to practical issues, we reached a sample size of four participants. Furthermore, all participants were male. Future research should also focus on female participants in order to validate the efficacy and to solve challenges posed by the different body dimensions and composition of female operators. Due to synchronized acceleration, ECG and EMG data capturing, the sampling rate of the muscle activity measurements in this study was limited to 500 Hz. EMG data is most often captured at frequencies above 1000 Hz and bandpass filtering between 20 and 400 Hz is a common practice. The current EMG analyses were performed on activity between 20 and 249 Hz, which includes the majority of the relevant EMG frequency spectrum [43]. Furthermore, the amount of synchronized measurement channels was finite, limiting the EMG signals to four muscles on the right side of the body. Even though the asymmetric in-field tasks on the forklift platform were executed on both sides of the body, a bilateral EMG analysis is recommended in future studies as it may indicate uneven loading or support on the worker's body. Additionally, the lifting tasks required a combination of movements in the glenohumeral, sterno-clavicular, clavico-humeral and scapula-thoracic joints. Therefore, activity of other muscles contributing to the work, among which the serratus anterior, the deltiod muscles and the pectoralis major, should be incorporated in the evaluation to provide a complete evaluation of the load on the shoulder. To verify our suggestion regarding altered lifting techniques in the field, future studies should include three-dimensional movement analysis to link the exoskeletons efficacy to the kinematic posture of the participants. An altered lifting technique might have resulted in changes in muscle fibre length, which can influence the EMG signal [44], [45]. Quantification of the three-dimensional movement pattern could facilitate interpretation of the EMG signals. Additionally, the peripheral effects of passive shoulder exoskeletons might influence the central nervous system, which advocates for future research incorporating the neuroergonomic and cognitive aspect of passive shoulder exoskeletons implementation. In this study the adaptation period to the exoskeletons was limited to ten hours. Until now, no clear evidence is present to indicate the duration and the nature of this adaptation period. We suggest a gradual implementation of exoskeletons in order to optimally deal with unexpected challenges in the field, but further research in this area is required.

V. CONCLUSION

To conclude, the ShoulderX and Skelex showed reduced TR muscle activity during isolated tasks, whereas these results were not obvious during in-field work. Beneficial effects in the field were more pronounced when wearing Skelex, while better assistance of the ShoulderX was reported during isolated tasks. Despite reduced muscle activity and heart rate when wearing an exoskeleton, the RPE was not always altered. This is probably due to the combination of the exoskeleton support and negative subjective feelings, such as discomfort, frustration and limited usability. The current study emphasizes that caution is needed when interpreting laboratory-based exoskeleton evaluations because these results cannot be transferred to all in-field conditions.

Acknowledgment

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Appendix A

Videos documentation of the in-field testing environment can be found at https://sanderdeb.github.io/TNSRE_PassiveShoulderExoskeletonsInTheField/.

Appendix B

Figure of biceps femoris and vastus medialis activity during isolated tasks (Figure 10).

Appendix C

This table contains muscle activity during in-field picking on ground level (Table III).

Appendix D

Figure of biceps femoris and vastus medialis activity during in-field picking on the forklift platform (Figure 11).

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