Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: www.tandfonline.com/journals/terg20

Arm-support exoskeleton reduces shoulder muscle activity in ceiling construction

S. J. Baltrusch, F. Krause, A. W. de Vries & M. P. de Looze

To cite this article: S. J. Baltrusch, F. Krause, A. W. de Vries & M. P. de Looze (2024) Arm-support exoskeleton reduces shoulder muscle activity in ceiling construction, Ergonomics, 67:8, 1051-1063, DOI: 10.1080/00140139.2023.2280443

To link to this article: https://doi.org/10.1080/00140139.2023.2280443

Published online: 10 Nov 2023.

ERGONOMICS
2024, VOL. 67, NO. 8, 1051–1063
https://doi.org/10.1080/00140139.2023.2280443

Taylor & Francis
Taylor & Francis Group

Arm-support exoskeleton reduces shoulder muscle activity in ceiling construction

S. J. Baltrusch, F. Krause, A. W. de Vries and M. P. de Looze

TNO, Leiden, The Netherlands

ABSTRACT

The objective of this study was to assess the efficacy and user's impression of an arm-support exoskeleton in complex and realistic ceiling construction tasks. 11 construction workers performed 9 tasks. We determined objective and subjective efficacy of the exoskeleton by measuring shoulder muscle activity and perceived exertion. User's impression was assessed by questionnaires on expected support, perceived support, perceived hindrance and future intention to use the exoskeleton. Wearing the exoskeleton yielded persistent reductions in shoulder muscle activity of up to 58% and decreased perceived exertion. Participants reported limited perceived hindrance by the exoskeleton, as also indicated by no increase in antagonistic muscle activity. The findings demonstrate the high potential of an arm-support exoskeleton for unloading the shoulder muscles when used in the dynamic and versatile working environment of a ceiling construction worker, which is in line with the consistent intention of the workers to use the exoskeleton in the future.

Practitioner Summary: The majority of research focuses on the effect of using an arm-support exoskeleton during isolated postures and prescribed movements. We investigated the efficacy of an exoskeleton during a complex and realistic work, namely ceiling construction. Shoulder muscle activity was lower in almost all tasks when wearing the exoskeleton.

ARTICLE HISTORY
Received 14 April 2022
Accepted 2 November 2023

KEYWORDS
Exoskeleton; muscle activity; musculoskeletal disorders; construction; perceived exertion

1. Introduction

Work-related shoulder pain and shoulder disorders are widespread in the occupational population. Associated high rates of sick leave, work disability and early retirement put a high burden on our society and affect workers' quality of life. The construction sector is one of the main sectors where many workers are constantly exposed to multiple physical risk factors. The 1-year prevalence of musculoskeletal symptoms (MSS) of the shoulder among construction workers has been shown to be as high as 32.4% (Umer et al. 2018). Physical risk factors, such as working above shoulder level (Wærsted, Koch, and Veiersted 2020), repetitive movements (Mayer, Kraus, and Ochsmann 2012) and high-level of hand force (Van Rijn et al. 2010) are associated with mechanical loading of the shoulder and the occurrence of shoulder disorders.

A relatively new mechanical intervention to address the challenge of reducing mechanical loading of the shoulder in the work environment is a passive arm-support exoskeleton., This body-worn assistive device supports users during arm-elevated work. It is intended to reduce mechanical load on the shoulder by decreasing muscular activity in the shoulder muscles, needed to counteract external moments caused by inertial and external forces. Previous research has shown that this concept of providing an assisting external flexion moment can be effective in reducing shoulder muscle activity (Alabdulkarim and Nussbaum 2019; de Vries, Krause, and de Looze 2021; Huysamen et al. 2018; Kim et al. 2018; Rashedi et al. 2014; Van Engelhoven et al. 2018; de Vries and de Looze 2019), perceived exertion (de Vries, Krause, and de Looze 2021; Huysamen et al. 2018) and perceived discomfort in the shoulder (Alabdulkarim and Nussbaum 2019; Rashedi et al. 2014).

While most of the earlier studies in the domain of industrial exoskeletons were conducted in the lab, more recently, an increasing number of field-based studies have been published (e.g. Kim et al. 2021; Kim, Nussbaum, and Smets 2022; Iranzo et al. 2020; de Vries, Baltrusch, and Looze 2023). These studies address various outcome measures like mechanical support, usability, acceptance, actual use and health

CONTACT Saskia Baltrusch saskia.baltrusch@tno.nl TNO, Leiden, The Netherlands.

effects in different work settings but mainly car assembly. Results vary across studies. Given the spring-based exoskeleton design, the work and particularly the time profiles of postures and movements largely effect the mechanical support the exoskeleton may provide and thereby influence the other outcome measures. A more diverse and variable movement pattern is likely to lower the exoskeleton's efficacy.

Ceiling construction work encompasses complex tasks and multiple movements. The work is characterised by prolonged overhead work with different types of movements and postures. It comprises of movements into different directions, quasi-static work vs. large movements, different angles in arm elevation and the use of working tools. Given this high variety of movements in this use-case, an exoskeleton would be supportive when arms are elevated in static work (60° to 120°), but might be hindering during pick up of material or other movements with smaller arm angles (<30°) (de Vries et al. 2019). Besides, ceiling construction workers perform not only symmetric, but also asymmetric working tasks, in which the dominant arm mainly performs quasi-static work, whereas the non-dominant arm performs larger movements, such as handling material and tools. This difference in arm elevation and task behaviour between dominant and non-dominant side might lead to differences in muscle activity and the effect of using an arm-support exoskeleton between both arms. The non-dominant arm might need less support than the dominant arm, as the force applied by the exoskeleton during large movements might be rather hindering, than helping. Muscle activity in the non-dominant arm might therefore be less affected by the exoskeleton than muscle activity in the dominant arm.

The aim of this study was therefore to determine the potential of wearing an arm-support exoskeleton to support ceiling construction. The potential was assessed with the following research questions:

1. What is the objective and subjective efficacy of the exoskeleton when used in ceiling construction?
2. What is the ceiling construction worker's expectation and impression on the use of an arm-support exoskeleton?

For evaluating objective and subjective efficacy of the exoskeleton, we measured shoulder muscle activity and perceived exertion, respectively. User's impressions were assessed by evaluating user's expectations, perceived support and hindrance and the intention to use the exoskeleton in the future. In order to check for differences in the effect of the exoskeleton on muscle activity between the dominant and non-dominant arm, muscle activity was measured bilaterally.

2. Methods

2.1. Passive arm support exoskeleton

The device tested in this study was the passive exoskeleton 'Skelex 360' (Rotterdam, The Netherlands), which is currently available on the market and used in various companies. The Skelex 360 is a non-powered exoskeleton that supports the weight of the arms against gravity. It is worn on the shoulders and consists of two carbon-fibre springs that run along the back of the trunk. The springs are connected to the arm cuffs that are worn around the upper arms. By creating a flexion moment around the shoulders, the exoskeleton supports the user at arm elevation angles between 30 and 120 degrees (A. de Vries et al. 2019). The force adjustors can be used to adjust the supporting force for each arm individually. In this study the support setting was set at about half way and was not adjusted between subjects or tasks (Figure 1).

2.2. Participants

We recruited 11 male employees, working as ceiling construction workers in Germany, who had experience with building ceilings at work. The age, height and body mass of these participants were mean (sd): 47 years (11.8 years), 179 cm (5.6 cm), and 81 kg (10.8 kg).

The participants received an information letter prior to the experiment and signed an informed consent form on the measurement day. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee (TNO, Leiden, The

Figure 1. Skelex 360 (Rotterdam, The Netherlands).
A picture of Skelex 360, the passive arm support exoskeleton that was used in the study.

Netherlands, 2021-081) and with the 1964 Helsinki declaration and its later amendments .

2.3. Instrumentation

2.3.1. Muscle activity

Muscle activity was recorded at a sample rate of 4000 Hz, using surface Electromyography (Porti, SAGA 32+/64+, Oldenzaal, The Netherlands). Bipolar surface electrodes were placed bilaterally at 4 sites on the skin after abrasion and cleaning with alcohol (Ag-AgCl electrodes; interelectrode distance, 20 mm). The recording sites were: m. deltoideus anterior, m. deltoideus medial, m. trapezius descendens and m.pectoralis major, of which the last one was chosen as antagonist muscle to check for counterproductive muscle activity due to hindrance of the exoskeleton. Electrode locations and procedures for obtaining muscular voluntary contractions (MVCs) were chosen according to guidelines by Hermens et al., n.d.; Konrad 2005. In order to investigate the effect of wearing an exoskeleton on both, mean muscle activity and limits of muscle activity during high loading, we decided to determine the 50th percentile and the 90th percentile, respectively.

2.3.2. Perceived exertion

To assess perceived exertion of each task a Rate of Perceived Exertion (RPE) Chart was used. Participants could grade the effort on a Borg scale between minimum 6 (=no effort) and maximum 20 (= not possible).

2.3.3. User's impression

User's impression was assessed in two questionnaires. The first questionnaire consisted of questions on expected support of the exoskeleton, desired body regions to be unloaded and working tasks that need assistance by the use of an exoskeleton. The second questionnaire included questions on perceived hindrance and support by the exoskeleton and the intention to use the exoskeleton in the future.

2.4. Experimental procedure

At the start of the measurement, participants were asked to fill in the first questionnaire on their expectations regarding the exoskeleton. Subsequently, the exoskeleton was fitted and adjusted to the participants and they got familiarised with the exoskeleton by moving around and trying out some tasks. Participants were then instrumented with EMG equipment and maximum voluntary isometric contractions (MVCs) were performed. During MVC contractions, participants had to maximally activate the recorded muscles against manual resistance for 5s. The maximum values across 3 repetitions were later used to normalise EMG data of the subsequent trials.

During the actual experiment participants had to construct a ceiling in the size of 200x125cm. This work was divided in nine tasks (Figure 2). The participants started with drilling holes in a cement beam and hammering nails into the holes (Task 1). After that they had to place upper and lower metal hangers (Task 2) in order to mount the longitudinal profiles (Task 3) of the ceiling. Subsequently, they placed cross connectors (Task 4), on which they mounted the transverse profiles (Task 5). In task 6 they placed a plasterboard and screwed it onto the profiles. After filling the screwing joints with plaster (Task 7), they sanded the ceiling manually (Task 8) and with the machine (Task 9).

Participants were free to perform these tasks in their personal working method. Differences between participants in movements or usage of tools were not elaborated on, as we aimed to keep the work as realistic as possible. The tasks were performed while standing on a platform which was adjusted in height once, at the start of the experiment, according to the wishes of the participant. Each task lasted about 3–4 mins. The last two tasks, sanding manually and sanding with the machine, were stopped after 3 minutes to prevent fatigue. Every participant had to perform these tasks in two conditions: without (NoExo) and with the arm support exoskeleton (Exo). The condition order was randomised and counterbalanced between participants. A break of 15 mins was given between conditions to prevent from fatigue effects. Muscle activity was recorded over the whole duration of each task. After each task participants were asked to indicate the perceived exertion for the dominant and non-dominant arm. Dominant and non-dominant arms were defined by the handedness of the participants. At the end of the experiment participants were requested to fill in the questionnaire on how they experienced the use of the exoskeleton (users' impression). This questionnaire included questions on perceived hindrance and perceived support by the exoskeleton. Furthermore participants were asked to weigh perceived benefits and drawbacks of the exoskeleton to estimate their intention to use the exoskeleton in the future.

The venue for the experiment was a facility for testing materials and methods for ceiling construction work. Part of the facility was put in order to enable

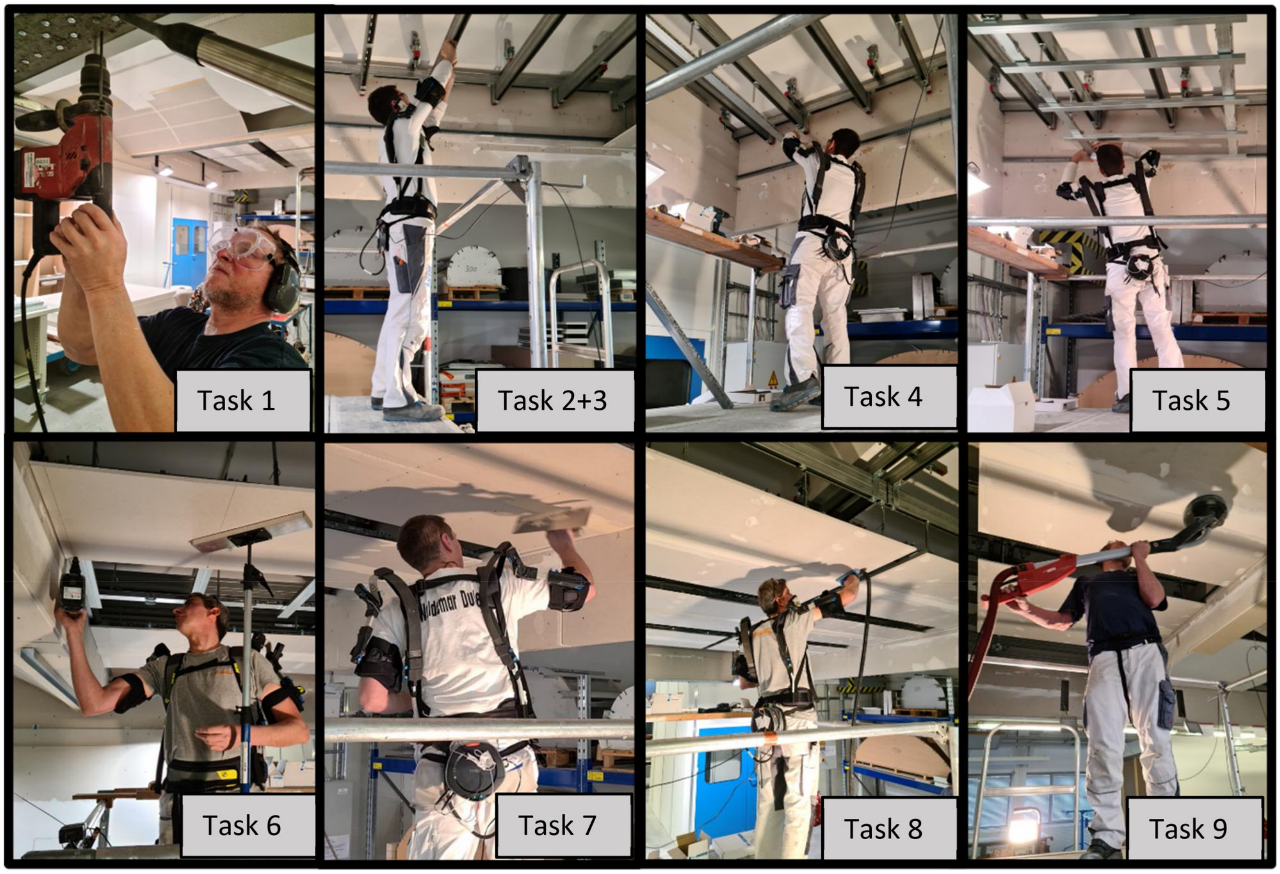

Figure 2. Overview of the nine tasks that the participants had to perform in the experiment to construct a ceiling in the size of 200 × 125cm. Task 1: Drilling holes; Task 2: Placing upper and lower metal hangers; Task 3: Mounting longitudinal profiles; Task 4: Placing cross connectors; Task 5: Mounting transverse profiles; Task 6: Placing plasterboard; Task 7: Filling screwing joints; Task 8: Sanding manually; Task 9: Sanding with the machine.
In eight panels photographs are showing several participants performing task 1–9. Task 2 and 3 are presented in one panel.

the fulfilment of the experimental procedure and the realistic execution of the nine tasks.

2.5. Data analysis

Data collected in this study were processed using MATLAB (R2020b, The MathWorks, Inc., Natick, Massachusetts, United States). EMG data were filtered using a 4th order Butterworth band pass filter between of 25–500 Hz (De Luca et al. 2010). Subsequently, the data were rectified and smoothed using MOVAG with a window size of 200 ms. Next, we normalised muscle activity for each muscle to the maximum of the linear envelope obtained in the MVC trials. The normalised data were averaged over task time. Median (P50) and peak (P90) load levels of EMG were calculated. For the muscle activity of the upper trapezius we had to exclude three participants, as the MVC values were considered as not reliable after visual inspection.

2.6. Statistics

To test for the effect of exoskeleton use on the dependent variables, we conducted GEE (Generalised Estimating Equations) analyses. For muscle activity, we conducted a GEE analysis to test for main effects of exoskeleton condition (Exo, NoExo) and interaction effects of exoskeleton condition and task on p50 and p90 for each muscle. In case of an interaction effect, Bonferroni post-hoc tests were conducted to determine differences between exoskeleton conditions. To test for statistically significant differences in perceived exertion, a GEE was conducted to test for main and interaction effects of exoskeleton condition and task on RPE. As this data is ordinal, we conducted post-hoc Wilcoxon signed rank tests, if an interaction effect was found. The critical level of significance was an alpha of 0.05. Users' impression is presented descriptively, as this parameter was not compared between conditions. All statistical analyses were performed using SPSS for Windows (IBM, SPSS 25.0, USA).

3. Results

3.1. Main effect on muscle activity

A main effect of exoskeleton condition ($p < 0.001$) and an interaction effect (task* exoskeleton condition; $p < 0.001$) on p50 and p90 muscle activity was found for each muscle, dominant and non-dominant side. An exception was the antagonistic pectoralis major (p90), which did not reach significance when testing for the main effect of exoskeleton condition.

3.2. Muscle activity p50

When wearing the exoskeleton, the p50 muscle activity of the *anterior deltoid* significantly decreased on the dominant side for each task. The highest decrease was found during placing the cross connectors (−58%) and mounting the transverse profiles (−57%, Figure 3). Sanding with the machine showed the lowest decrease in muscle activity (−15%). On the non-dominant side the p50 muscle activity of the *anterior deltoid* significantly decreased in 5 out of the 9 tasks.

Muscle activity of the dominant *medial deltoid* significantly decreased when wearing the exoskeleton in 6 out of the 9 tasks. Drilling, screwing the plasterboard and sanding with the machine did not show an effect of the exoskeleton. The biggest decrease in muscle activity was found during sanding manually (−55%, Figure 4). On the non-dominant side the p50 muscle activity of the *medial deltoid* significantly decreased in 4 tasks, during drilling, placing the hangers and mounting the profiles.

The p50 muscle activity of the dominant *upper trapezius* decreased when wearing an exoskeleton in 3 of the 9 tasks, with the biggest effect of the exoskeleton on muscle activity during placing cross connectors (−16%) and mounting transverse profiles (−17%, Figure 3). During sanding with the machine, muscle activity of the *upper trapezius* increased (+18%). On the non-dominant side the muscle activity showed a significant decrease in 6 out of the 9 tasks, with the biggest decrease during mounting transverse profiles (−23%). Placing hangers, placing cross connectors and sanding with the machine did not get affected by wearing the exoskeleton.

When wearing the exoskeleton, the p50 mean muscle activity of the antagonistic *pectoralis major* was not higher than 7%max. On the dominant and the non-dominant side, significant lower muscle activity was found for 5 out of the 9 tasks, with the biggest decrease during screwing the plasterboard (−22%) for the dominant side and during sanding with the machine (−28%) for the non-dominant side. An overview of the p50 muscle activity of all muscles is shown in Table 1.

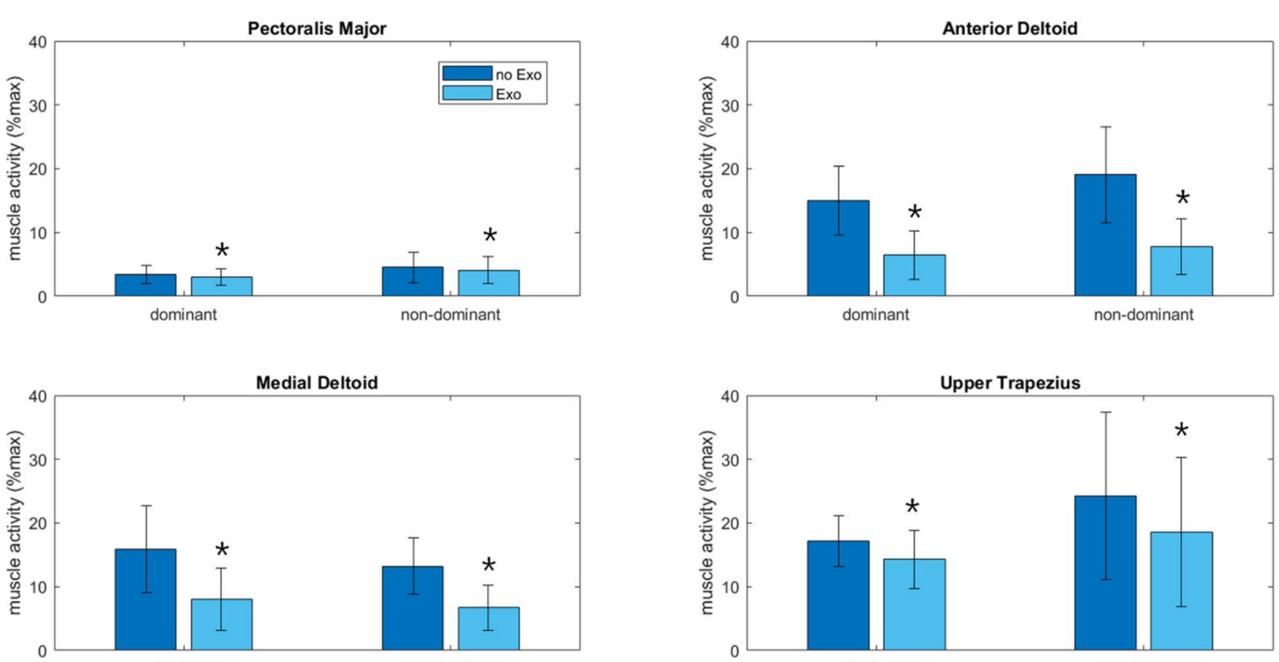

Figure 3. P50 muscle activity of the dominant and non-dominant antagonist and the three shoulder muscles during the task 'Mounting transverse profiles'. * Significant difference ($p = 0.005$) between Exo and NoExo condition. Error bars indicate standard deviations.
Four panels show the P50-muscle activity of the pectoralis major, anterior deltoid, medial deltoid, and upper trapezius muscles. For dominant and non-dominant sides the figure shows the differences between 'exo' vs. 'no exo' conditions during the task 'Mounting transverse profiles'.

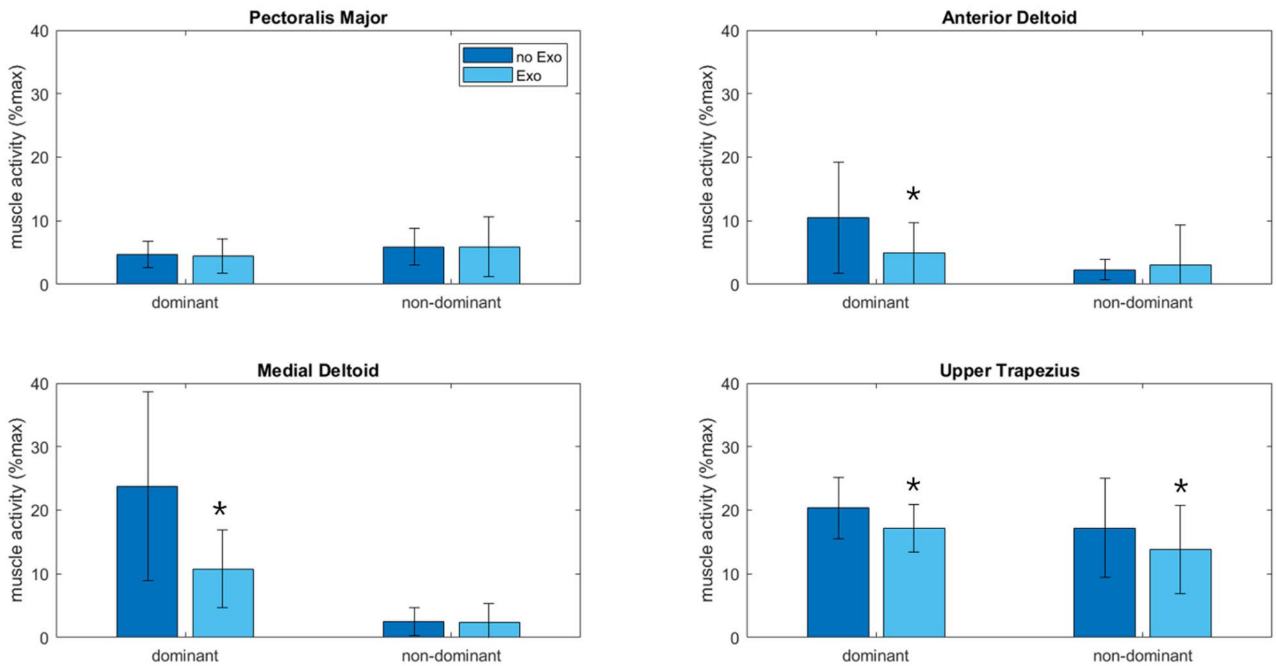

Figure 4. P50 muscle activity of the dominant and non-dominant antagonist and the three shoulder muscles during the task 'Sanding manually'. * Significant difference ($p = 0.005$) between Exo and NoExo condition. Error bars indicate standard deviations. Four panels show the P50-muscle activity of the pectoralis major, anterior deltoid, medial deltoid, and upper trapezius muscles. For dominant and non-dominant sides the figure shows the differences between 'exo' vs. 'no exo' conditions during the task 'Sanding manually'.

Table 1. P50 muscle activity(%max) and the standard deviation of the measured shoulder muscles per task, comparing Exo and NoExo conditions, for dominant and non-dominant side.

P50		Anterior Deltoid		Medial Deltoid		Upper Trapezius		Pectoralis Major	
		NoExo	Exo	NoExo	Exo	NoExo	Exo	NoExo	Exo
drill and hammer	d	12.54 (5.2)	**9.83 (4.6)**	11.53 (5.5)	9.97 (3.8)	16.82 (5.7)	16.36 (5.0)	4.31 (1.8)	**3.79 (1.5)***
	nd	17.15 (7.6)	**9.98 (7.2)***	9.35 (6.4)	**6.63 (5.5)***	20.29 (8.4)	**17.26 (8.1)**	4.67 (2.6)	**4.20 (2.0)**
place hangers	d	16.70 (7.5)	**9.20 (5.6)***	17.07 (9.8)	**9.65 (5.1)***	18.19 (6.0)	17.01 (5.0)	3.22 (1.3)	3.06 (1.1)
	nd	19.64 (9.2)	**12.48 (6.6)**	15.43 (6.6)	**10.59 (5.1)***	25.22 (12.4)	24.19 (13.0)	4.05 (2.1)	3.89 (1.8)
mount horizontal profiles	d	12.50 (4.6)	**5.80 (3.2)***	15.33 (10.1)	**7.86 (4.3)***	15.47 (4.79)	14.09 (5.0)	3.03 (1.5)	**2.71 (1.1)**
	nd	17.06 (7.3)	**8.00 (4.2)***	12.31 (4.9)	**6.36 (3.2)***	21.90 (14.9)	**18.89 (12.1)**	3.96 (2.5)	3.46 (1.9)
place cross connectors	d	8.17 (4.1)	**3.44 (2.5)***	9.22 (5.7)	**4.68 (3.5)***	11.17 (4.5)	**9.41 (3.4)***	2.72 (1.5)	2.41 (1.2)
	nd	7.59 (6.9)	4.74 (3.5)	4.26 (4.1)	2.60 (1.8)	13.81 (6.9)	11.37 (6.1)	3.72 (2.9)	2.96 (1.9)
mount transverse profiles	d	14.95 (5.3)	**6.46 (3.8)***	15.84 (6.8)	**8.06 (4.9)***	17.17 (3.9)	**14.28 (4.5)***	3.37 (1.4)	**3.02 (1.2)***
	nd	19.06 (7.5)	**7.81 (4.4)***	13.24 (4.4)	**6.73 (3.5)***	24.27 (13.2)	**18.58 (11.7)***	4.54 (2.4)	**4.15 (2.1)***
place plasterboard	d	6.18 (4.0)	**4.64 (3.3)**	3.48 (2.5)	3.09 (2.2)	8.72 (4.1)	8.62 (1.9)	4.08 (2.1)	**3.19 (1.5)***
	nd	8.37 (3.8)	**4.74 (2.7)***	4.75 (3.4)	3.41 (2.9)	15.15 (8.1)	**12.27 (6.9)**	4.51 (2.80)	**3.89 (2.3)***
screw plasterboard	d	11.41 (7.1)	**6.18 (4.2)***	9.83 (6.5)	**6.44 (4.7)***	13.61 (6.1)	12.77 (3.1)	3.27 (1.43)	**2.68 (1.1)***
	nd	1.48 (1.1)	1.12 (0.8)	1.98 (2.0)	1.39 (1.3)	11.27 (5.3)	**9.14 (4.5)***	3.58 (2.01)	**3.02 (1.9)***
sand manually	d	10.51 (8.8)	**4.94 (4.8)***	23.79 (14.9)	**10.75 (6.1)***	20.35 (4.8)	**17.16 (3.7)**	4.69 (2.09)	4.45 (2.7)
	nd	2.31 (1.6)	3.00 (6.4)	2.53 (2.2)	2.40 (2.92)	17.19 (7.8)	**13.86 (6.9)***	5.92 (2.92)	5.90 (4.7)
sand with machine	d	5.54 (7.5)	**4.72 (5.4)**	3.33 (3.4)	6.72 (12.5)	10.44 (5.7)	**12.36 (6.8)**	7.42 (5.48)	6.68 (4.3)
	nd	13.07 (9.7)	12.45 (10.0)	4.75 (3.6)	4.69 (4.0)	14.00 (7.9)	15.94 (6.0)	9.49 (5.99)	**6.86 (3.9)**

Statistically significant differences ($p \leq 0.05$) between Exo and NoExo condition are shown in bold. Highly statistically significant differences ($p \leq 0.005$) are marked with a *. Significant decrease in muscle activity is marked in green. Significant increase in muscle activity is marked in red.
d = dominant; nd = non-dominant.

3.3. Muscle activity p90

The p90 muscle activity of the *anterior deltoid* significantly decreased when wearing the exoskeleton for almost every task. On the dominant side there was no effect for drilling and sanding with the machine, on the non-dominant side only sanding with the machine did not show an effect. The biggest decrease in muscle activity was found during mounting transverse profiles (−52%; −55%) and manual sanding (−51%; −50%, Figure 5) on the dominant an non-dominant side, respectively.

Wearing the exoskeleton yielded a significant decrease in p90 muscle activity of the *medial deltoid* in each task, except sanding with the machine. Manual sanding (−52%; −43%, Figure 5) and placing cross connectors (−43%; −42%) showed the biggest

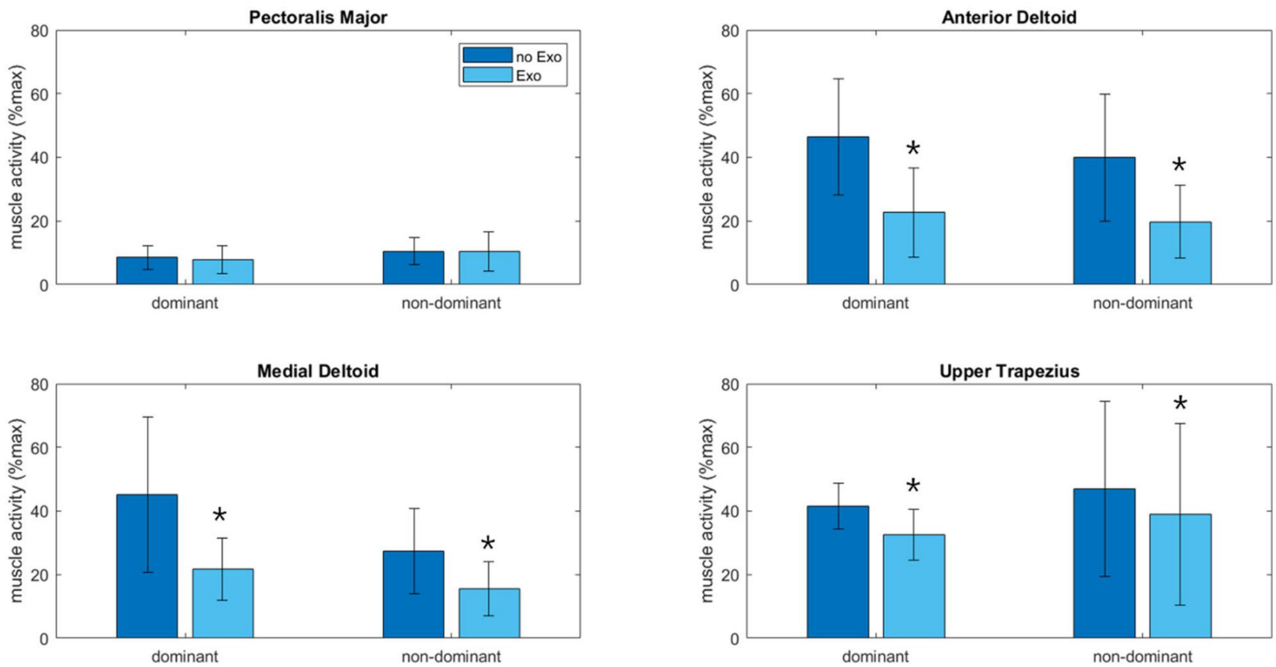

Figure 5. P90 muslce activity of the dominant and non-dominant antagonist and the three shoulder muscles during the task 'Sanding manually'. * Significant difference ($p = 0.005$) between Exo and NoExo condition. Error bars indicate standard deviations. Four panels show the P90-muscle activity of the pectoralis major, anterior deltoid, medial deltoid, and upper trapezius muscles. For dominant and non-dominant sides the figure shows the differences between 'exo' vs. 'no exo' conditions during the task 'Sanding manually'.

Table 2. P90 muscle activity(%max) and the standard deviation of the measured shoulder muscles per task, comparing Exo and NoExo conditions, for dominant and non-dominant side.

P90		Anterior Deltoid		Medial Deltoid		Upper Trapezius		Pectoralis Major	
		no exo	exo	no exo	exo	no exo	exo	no exo	exo
drill and hammer	d	53.18 (20.3)	45.30 (23.4)	36.60 (17.9)	**30.60 (16.7)***	32.63 (6.5)	**28.99 (6.7)**	9.04 (5.4)	**7.59 (4.4)**
	nd	43.84 (19.5)	**28.46 (16.9)**	28.76 (12.2)	**18.85 (11.0)**	39.51 (18.2)	**33.21 (12.8)**	8.33 (4.3)	8.43 (3.8)
place hangers	d	33.84 (13.7)	**20.04 (11.3)***	31.97 (18.4)	**22.71 (11.2)***	31.85 (10.2)	**26.85 (7.9)***	5.47 (2.5)	5.18 (1.7)
	nd	36.34 (17.2)	**24.04 (13.7)***	26.85 (10.1)	**21.26 (8.7)**	45.53 (34.4)	40.87 (28.8)	7.49 (3.6)	7.62 (3.4)
mount horizontal profiles	d	25.30 (8.6)	**13.36 (7.6)***	27.82 (17.0)	**17.92 (10.3)***	24.88 (6.3)	22.50 (7.5)	5.24 (2.6)	4.88 (1.9)
	nd	35.44 (15.3)	**18.24 (9.7)***	22.98 (7.5)	**14.92 (6.9)***	37.04 (27.9)	30.88 (20.9)	7.96 (4.1)	8.39 (4.2)
place connectors	d	22.41 (8.2)	**11.64 (7.1)***	24.22 (12.1)	**13.91 (10.0)***	21.51 (3.9)	**16.66 (5.7)***	6.14 (4.6)	5.45 (3.1)
	nd	25.21 (14.1)	**14.06 (8.9)***	13.75 (8.5)	**7.96 (4.5)**	25.64 (11.6)	20.94 (11.6)	8.67 (6.7)	8.18 (4.7)
mount transverse profiles	d	28.92 (9.9)	**13.80 (7.5)***	29.36 (14.4)	**17.10 (10.0)***	28.08 (6.7)	**23.83 (7.5)***	6.02 (2.4)	5.77 (2.6)
	nd	38.36 (17.3)	**17.21 (8.9)***	24.79 (6.9)	**14.66 (6.5)***	42.13 (29.5)	**34.32 (26.7)***	8.84 (4.4)	9.20 (4.5)
place plasterboard	d	36.16 (9.9)	**26.24 (12.7)***	22.45 (8.8)	**18.40 (10.4)***	26.86 (6.10)	25.80 (6.4)	9.64 (5.1)	**6.89 (2.9)***
	nd	38.84 (14.4)	**20.42 (12.5)***	22.26 (9.4)	**13.95 (5.9)***	37.01 (18.5)	**30.12 (14.2)***	9.69 (5.1)	8.77 (4.5)
screw plasterboard	d	35.45 (15.6)	**18.85 (12.3)***	27.09 (14.9)	**17.56 (9.4)***	32.07 (7.3)	**27.89 (8.0)**	6.62 (2.8)	**5.27 (2.0)***
	nd	14.67 (18.7)	**7.56 (10.1)**	8.98 (10.0)	**5.63 (6.2)**	20.97 (7.7)	**16.20 (7.5)***	8.07 (4.0)	7.68 (4.3)
sand manually	d	46.31 (18.3)	**22.66 (14.1)***	45.10 (24.5)	**21.70 (9.7)***	41.59 (7.3)	**32.65 (7.9)***	8.60 (3.7)	7.85 (4.3)
	nd	39.90 (19.9)	**19.80 (11.5)***	27.37 (13.5)	**15.53 (8.6)***	47.03 (27.5)	**39.06 (28.6)**	10.53 (4.3)	10.44 (6.2)
sand with machine	d	10.67 (12.2)	13.82 (13.7)	6.43 (4.8)	13.64 (24.9)	16.92 (7.9)	19.70 (8.5)	13.36 (8.3)	11.78 (7.3)
	nd	27.64 (12.1)	26.52 (14.4)	11.68 (7.5)	13.81 (9.0)	27.36 (13.1)	32.03 (15.6)	15.62 (8.8)	13.52 (6.6)

Statistically significant differences ($p \leq 0.05$) between Exo and NoExo condition are shown in bold. Highly statistically significant differences ($p \leq 0.005$) are marked with a *. Significant decrease in muscle activity is marked in green.
d = dominant; nd = non-dominant.

effect of the exoskeleton on the dominant an non-dominant side, respectively.

Muscle activity of the dominant *upper trapezius* significantly decreased in 6 out of the 9 tasks when wearing the exoskeleton, with the biggest effect during placing cross connectors (−23%) and manual sanding (−22%). On the non-dominant side, wearing the exoskeleton yielded a significant decrease in muscle activity in 5 out of the 9 tasks. The biggest decrease was found during filling joints (−22%) and screwing the plasterboard (−19%).

The antagonistic *pectoralis major* only showed a decrease in p90 muscle activity on the dominant side during drilling (−16%), screwing the plasterboard (−29%) and filling the joints (−20%). The non-dominant side did not show any effects when using the exoskeleton (Table 2).

3.4. Rate of perceived exertion

Perceived exertion in the dominant arm significantly decreased ($p < 0.05$) compared to the control condition (Figure 6), when wearing the exoskeleton for placing hangers, placing cross connectors, screwing the plasterboard, filling the joints and manual sanding. The tasks mounting longitudinal profiles and mounting transverse profiles showed a trend towards lower RPE when wearing the exoskeleton ($p = 0.054$ and $p = 0.057$, respectively). For the non-dominant side a significant decrease in perceived exertion when wearing the exoskeleton was found for manual sanding ($p = 0.005$) and machine sanding ($p = 0.03$, Figure 7). The RPE in the remaining tasks were not significantly affected by the use of the exoskeleton.

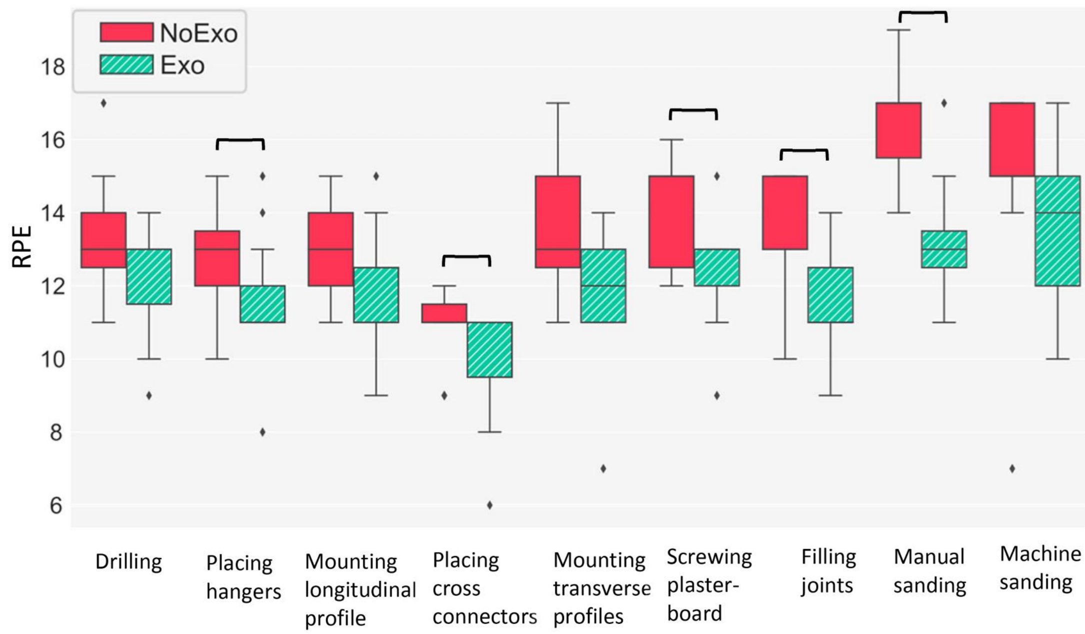

Figure 6. Boxplots of perceived exertion in the dominant arm. The horizontal black line represents the sample median, the distances between the tops and the bottoms are the interquartile ranges. Whiskers show the min and max values; outliers are presented as ◆. A bracket above a boxplot pair indicates a significant difference between the exoskeleton condition (Exo) and the control condition (NoExo).
For the dominant arm, red and green boxplots show the ratings of perceived exertion in the 'no eoskeleton' and 'exoskeleton' condition, respectively, for each of the nine tasks.

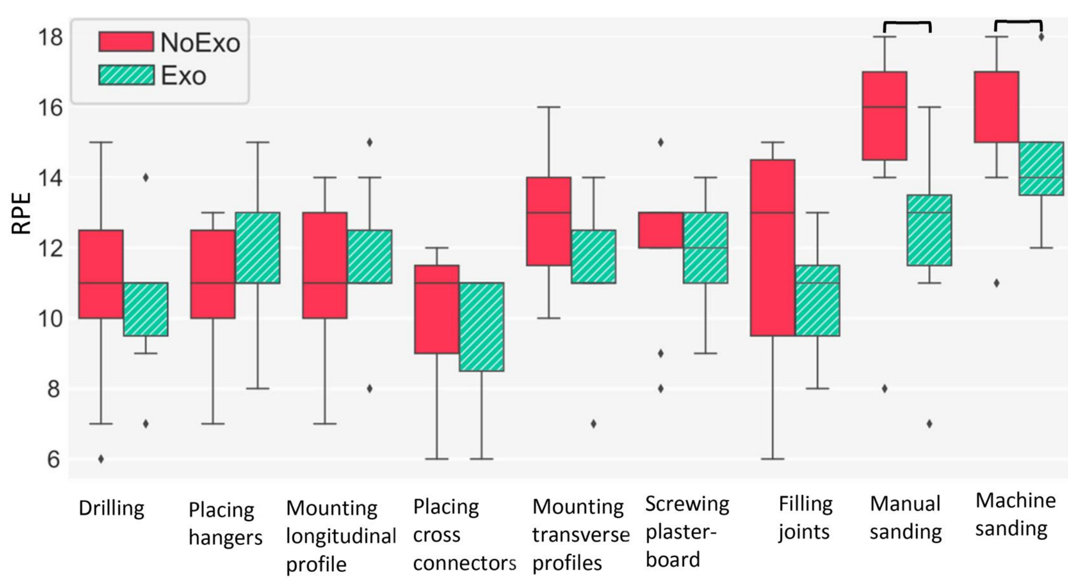

Figure 7. Boxplots of perceived exertion in the **non-dominant arm**. Brackets indicate significant differences between the exoskeleton condition (Exo) and the control condition (NoExo).
For the non-dominant arm, red and green boxplots show the ratings of perceived exertion in the 'no eoskeleton' and 'exoskeleton' condition, respectively, for each of the nine tasks.

3.5. Users' impression

Main body regions that require support during ceiling construction, based on the participants' answers, were shoulders (n = 9) and the upper back (n = 8). When asking for main tasks that would need assistance by an exoskeleton, all participants (n = 11) named 'sanding with the machine' and 'screwing the plaster-board'. 8 out of the 11 participants mentioned 'drilling' and 'mounting transversal profiles'. Expected level of support by the exoskeleton was mainly answered with 'a little bit' (Figure 8).

The results of the second questionnaire on the intention to use the exoskeleton in the future and perceived hindrance and support by the exoskeleton are shown in Figure 9.

Figure 10 shows the results of a question about the participant's intention to use the exoskeleton in the future, based on a weighing of benefits and drawbacks. Participants place an x on a line showing 'intention to use' on the right (>0) and 'intention to not use' (<0) on the left.

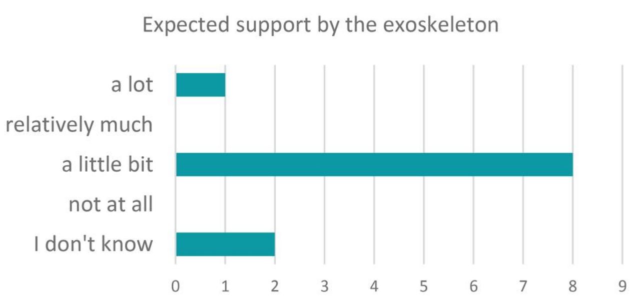

Figure 8. Expected support by the exoskeleton, shown as number of answers per category.
Horizontal bars show the numbers of subjects rating the expected support as 'a lot', 'relatively much', 'a little bit', 'not at all', and 'I don't know'.

4. Discussion

The aim of this paper was to determine the potential of using an arm-support exoskeleton to support ceiling construction. Specifically, we assessed the objective and subjective efficacy of the exoskeleton and the workers' impression of using an arm-support exoskeleton in a real and complex working task.

4.1. Muscle activity

Muscle activity in the three shoulder muscles significantly decreased in almost all tasks, with up to 58%, indicating that an exoskeleton effectively supports ceiling construction workers in their arm-elevated work, by unloading the shoulder muscles. The biggest effects were found for the tasks 'Placing cross connectors', 'Mounting transverse profiles', and 'Sanding manually'. This can be explained by the fact that the task 'Sanding manually' was the most demanding task, as seen in the results of the perceived exertion. The other two tasks required prolonged arm elevation without resting moments during the whole task. This positive effect was more pronounced in the peak load levels (p90) than in the median load levels (p50), which indicates that the exoskeleton especially supports when the shoulder muscles are profoundly

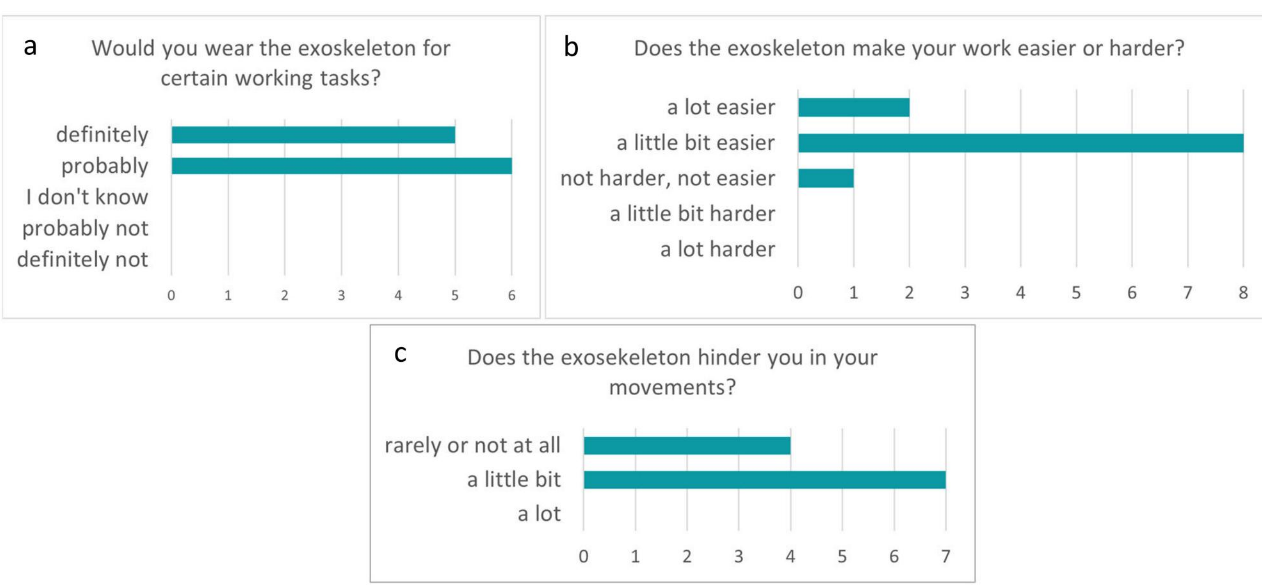

Figure 9. The intention to use the exoskeleton (a), perceived support (b) and perceived hindrance (c) by the exoskeleton, as reported by the participants (n = 11) after the whole measurement. The x-axis shows the number of answers per category.
Horizontal bars in three diagrams show the numbers of subjects with their answers to three questions: 'Would you wear the exoskeleton for certain working tasks?', 'Does the exoskeleton make your work easier?', and 'Does the exoskeleton hinder you in your movements?'.

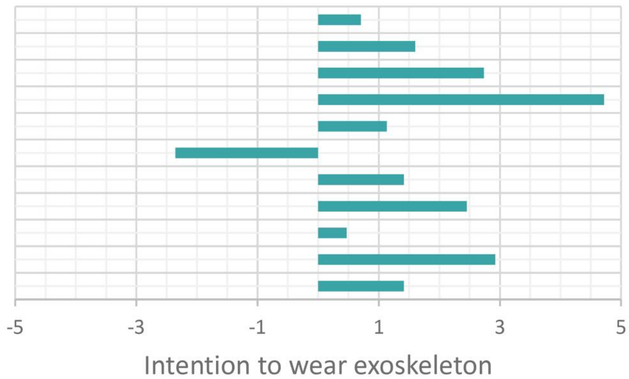

Figure 10. Participant's intention to wear the exoskeleton in the future when weighing benefits and drawbacks. The higher the values, the higher the intention; the lower the values, the lower the intention. Each horizontal line represents the answer of a single participant.
Horizontal bars show the intention to use the exoskeleton in the future of each participant on a scale from −5 to 5.

loaded, as the 90th percentile represents the moments of high loading. Sanding with the machine (Task 9) did not yield reductions in muscle activity when using the exoskeleton. The muscle activity in the upper trapezius even increased by 18% in this task. This lack of effect can be explained by the fact that the participants worked at a low ceiling height during machine sanding, which did not allow for an optimal support of the exoskeleton, as the arms were not elevated higher than 30 degrees. When asking participants on their personal opinion, they indicated that sanding with the machine at a higher ceiling height would probably yield an effective support of the exoskeleton.

The reductions in muscle activity are similar to reductions found in previous research on simulated working tasks above shoulder height, such as drilling tasks, simulated assembly tasks and plastering (Alabdulkarim and Nussbaum 2019; Huysamen et al. 2018; Kim et al. 2018; Rashedi et al. 2014; Van Engelhoven et al. 2018, Iranzo et al. 2020, de Vries, Krause, and de Looze 2021). Studies in automotive assembly have found reductions in muscle activity of 18% and 34% of the deltoid and the trapezius (Iranzo et al. 2020) and even up to 40% reduction at the shoulder area Claramunt-Molet et al. 2019). These relatively large reductions might be due to the amount of time that the arms remain in elevated postures. The ceiling construction workers in the present study were free on how to move through the different tasks having some periods without arm elevation. Their work involved a variety of different postures and also required picking up tools and materials. During tasks involving various movements, passive exoskeletons typically are not as effective as during less varied tasks (de Vries and de Looze 2019; Looze et al. 2016). Yet, comparable reductions in muscle activity for the three shoulder muscles were found for almost all tasks, emphasising the high efficacy of the exoskeleton in this complex use-case. de Vries, Krause, and de Looze (2021) found similar muscle reductions upon exoskeleton use in plastering tasks compared to the present study. Task duration was higher in some plastering tasks (up to 7 minutes) studies, but the freedom in task performance was comparable.

In general, differences in muscle activity reductions upon using an exoskeleton can be traced back to multiple factors. The design of the exoskeleton is only one of them. As most arm support exoskeleton have a similar working mechanism (a spring stretched in arm elevation provides mechanical support), the type of exoskeleton used might not be the main one, although the adjustment of the level of support in each type will be of importance. The task that is studied is a factor that can highly affect the level of muscle activity reduction. The adopted posture, the movements, the external loads (carried weights) and particularly the time profiles within tasks will all have their effect on muscle activity and the reduction that could be achieved when using an exoskeleton.

4.2. Dominant versus non-dominant side

Differences between the dominant and the non-dominant side were mainly dependent on task execution, the use of tools and the preferred arm position. Tasks such as manual sanding, placing cross connectors or filling the joints, were often performed one-handed and therefore might have not yield positive effects of using the exoskeleton on the non-dominant side. When holding tools, such as the drilling machine, the decrease in muscle activity was only found in the non-dominant arm, as this arm was holding the drilling machine with an arm elevation >30 degrees, whereas the arm that was actually drilling was not elevated enough to receive support by the exoskeleton (<30 degrees). This points out the need for researchers to assess both arms, as both of them might be the 'dominant' arm depending on task execution and the use of tools. Besides, the non-dominant arm, picking up tools and materials, has a rather dynamic movement behaviour, increasing the likelihood that the exoskeleton could be more of a hindrance than an actual support. Our findings, however, reveal that the muscle activity of the non-dominant arm did not increase in any of the tasks, indicating that the non-dominant side did not get hindered by the exoskeleton. We also measured muscle activity of the antagonist (Pectoralis major) to check for an increase in muscle activity, which would also indicate hindrance by the exoskeleton. However, an increase in muscle activity was not found, implying that the exoskeleton did not hinder the participants in their work.

A previous study assessed the effect of an arm-support exoskeleton on bilateral muscle activity in a simulated drilling task (Alabdulkarim and Nussbaum 2019) and found that the design of an arm exoskeleton can lead to different demands on the dominant and non-dominant arm. Exoskeletons that include a mechanical arm to support a tool by transferring loads to the hips, increase the demand on the non-dominant arm as users are not able to put the tool down between holes. An exoskeleton, as used in the present study, allows for this countermovement. This suggests that, especially when used in a real working environment, an exoskeleton should allow for a free movement pattern to obtain optimal support for dominant and non-dominant arm without hindering the user.

4.3. Subjective experience

Perceived exertion in the dominant arm showed statistically significant reductions in 7 out of the 9 tasks, which is in line with the reductions found in muscle activity. Manual sanding showed the biggest effect and was perceived as less strenuous on the dominant and non-dominant side. This is in line with the objective efficacy, which showed highest reductions in muscle activity in the same task. A previous study, assessing the change of perceived exertion when wearing the same arm-support exoskeleton during plastering activities, found reduced exertion in all tasks, with slightly bigger effects (de Vries, Krause, and de Looze 2021). A potential explanation is that the plastering tasks demanded prolonged arm elevation during all tasks, whereas the ceiling construction workers also performed tasks, in which they lowered their arms for instance for picking up tools. Thus, allowing for 'rest moments' during some tasks might have influenced the effect of the exoskeleton on perceived exertion.

The results of the user impression questionnaire indicate that participants felt supported by the exoskeleton, which is in line with the persistent decrease of muscle activity in the shoulder muscles. Besides, participants reported limited hindrance of movement, confirming our assumption that the exoskeleton did not hinder the participants movement, as an increase in muscle activity in the antagonist was not found. In various studies hindrance has been mentioned as related to the use of an exoskeleton (e.g. de Vries, Baltrusch, and Looze 2023, Gillette and Stephenson 2019). Obviously, it is depending on the work place and tasks whether hindrance my occur or not. The level of perceived support and perceived hindrance by the exoskeleton may influence user acceptance (Baltrusch et al. 2018). Indeed, all participants reported that they intend to use the exoskeleton in the future, for some of the tasks performed. When asking them to weigh benefits and drawbacks of the exoskeleton to estimate their intention-to-use, only one participant weighed the drawbacks higher than the benefits, which is in line with the perceived limited hindrance by the exoskeleton. Intention-to-use has been used as an indicator of exoskeleton acceptance before. Schwerha et al. (2022) identified major factors contributing to exoskeleton-use-intention, such as perceived comfort, task-technology fit, perceived safety, and perceived usefulness.

4.4. Practical relevance and limitations

Even though the study was not performed in a ceiling construction worker's real working environment, the results are of high relevance for this use-case. As participants were constructing a small ceiling (200x125cm), the duration of the different tasks was limited to ∼3mins. In a real working environment, ceilings are generally much larger and tasks can therefore last much longer, potentially leading to even bigger effects on muscle activity and perceived support. Also, due to division of labour, certain tasks will be performed by certain construction workers, providing an opportunity to use the exoskeleton as a work tool along with other tools necessary for a specific task, rather than wearing the exoskeleton the whole working day.

Perceived exertion was only evaluated in the arms. A common assertion is that strain from the arms might have also be transferred to other regions as the upper back or lower limbs. However, numerous studies have indicated that shoulder exoskeletons may actually provide beneficial effects on other body regions, including the neck and the back (Smets 2019; Gillette and Stephenson 2019; Hefferle, Snell, and Kluth 2021; Kim et al. 2018).

The results of this study should be interpreted in the light of some limitations. First, due to the different designs of the various arm-support exoskeletons that are currently assessed in research or available on the market, we cannot generalise our outcome to other assistive devices, since effects are dependent on the design of the exoskeleton. Furthermore, as the duration of the different tasks was limited to ∼3mins, the results cannot be directly generalised to a normal working environment. As mentioned above, we believe, however, that the beneficial effect of wearing an arm-support exoskeleton will be even more pronounced in a real work setting.

5. Conclusion

The findings presented in this study demonstrate the high potential of using an arm-support exoskeleton for unloading the shoulder muscles and decreasing perceived exertion during ceiling construction. Objective and subjective efficacy showed clear benefits of wearing an arm-support exoskeleton. Persistent reductions in shoulder muscle activity are in line with exoskeleton user's perceived support by the exoskeleton. Different effects in muscle activity between dominant and non-dominant arms result from the variety in task execution and the use of tools, instead of being associated to hindrance by the exoskeleton. Summing up, an arm-support exoskeleton is most likely effective in unloading the shoulder muscles when used in the dynamic and versatile working environment of a ceiling construction worker, which is in line with the consistent intention of the workers to use the exoskeleton in the future.

Acknowledgements

The authors would like to acknowledge the support of Knauf Gips KG for making this study possible.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Knauf Gips KG.

ORCID

S. J. Baltrusch http://orcid.org/0000-0002-9464-6894
A. W. de Vries http://orcid.org/0000-0001-9547-2702

References

Alabdulkarim, S., and M. A. Nussbaum. 2019. "Influences of Different Exoskeleton Designs and Tool Mass on Physical Demands and Performance in a Simulated Overhead Drilling Task." *Applied Ergonomics 74* (February 2018): 55–66. doi:10.1016/j.apergo.2018.08.004.

Baltrusch, S. J., J. H. van Dieën, C. A. M. van Bennekom, and H. Houdijk. 2018. "The Effect of a Passive Trunk Exoskeleton on Functional Performance in Healthy Individuals." *Applied Ergonomics 72*: 94–106. doi:10.1016/j.apergo.2018.04.007.

Claramunt-Molet, M., B. Domingo-Mateu, J. Danús-Jaume, A. Ugartemendia-Etxarri, La De, I. Maza, V. Enriquez-Carrera, O. Muñoz-Fernandez, S. Domingo, F. Miralles, JM. Font-Llagunes, and S. Idelsohn-Zielonka. 2019. "Biomechanical Evaluation of Upper Limb Exoskeletons in Automotive Assembly Using EMG.". In *Reunión Del Capítulo Español De La Sociedad Europea De Biomecánica*. Barcelona: Grupo de Investigación de Biomateriales y Biomecánica, 25–26.

De Luca, C. J., L. Donald Gilmore, M. Kuznetsov, and S. H. Roy. 2010. "Filtering the Surface EMG Signal: Movement Artifact and Baseline Noise Contamination." *Journal of Biomechanics 43* (8): 1573–1579. doi:10.1016/j.jbiomech.2010.01.027.

de Vries, A., M. Murphy, R. Könemann, I. Kingma, and M. de Looze. 2019. "The Amount of Support Provided by a Passive Arm Support Exoskeleton in a Range of Elevated Arm Postures." *IISE Transactions on Occupational Ergonomics and Human Factors 7* (3–4): 311–321. doi:10.1080/24725838.2019.1669736.

de Vries, Aijse W., and M. P. de Looze. 2019. "The Effect of Arm Support Exoskeletons in Realistic Work Activities : A Review Study." *J Ergonomics 9* (4): 1–9. doi:10.35248/2165-7556.19.9.255.

de Vries, Aijse Willem, F. Krause, and M. P. de Looze. 2021. "The Effectivity of a Passive Arm Support Exoskeleton in Reducing Muscle Activation and Perceived Exertion during Plastering Activities." *Ergonomics 64* (6): 712–721. doi:10.1080/00140139.2020.1868581.

de Vries, A., S. Baltrusch, and MP de Looze. 2023. "Field Study on Use and Acceptance of an Arm Support Exoskeleton in Plastering." *Ergonomics* 66 (10): 1622–1632. doi:10.1080/00140139.2022.2159067.

Gillette, J. C., and M. L. Stephenson. 2019. "Electromyographic Assessment of a Shoulder Support Exoskeleton during on-Site Job Tasks." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 302–310. doi: 10.1080/24725838.2019.1665596.

Hefferle, M., M. Snell, and K. Kluth. 2021. "Influence of Two Industrial Overhead Exoskeletons on Perceived Strain – A Field Study in the Automotive Industry.". In: Zallio, M. (eds) *Advances in Human Factors in Robots, Drones and Unmanned Systems. AHFE 2020. Advances in Intelligent Systems and Computing*, vol 1210. Springer, Cham. doi:10.1007/978-3-030-51758-8_13.

Huysamen, Kirsten, Tim Bosch, Michiel de Looze, Konrad S. Stadler, Eveline Graf, and Leonard W. O'Sullivan. 2018. "Evaluation of a Passive Exoskeleton for Static Upper Limb Activities." *Applied Ergonomics 70* (August 2017): 148–155. doi:10.1016/j.apergo.2018.02.009.

Iranzo, S., A. Piedrabuena, D. Iordanov, U. Martinez-Iranzo, and J. M. Belda-Lois. 2020. "Ergonomics Assessment of Passive Upper-Limb Exoskeletons in an Automotive Assembly Plant." *Applied Ergonomics* 87: 103120. doi:10.1016/j.apergo.2020.103120.

Kim, S., M. A. Nussbaum, M. I. Mokhlespour Esfahani, M. M. Alemi, S. Alabdulkarim, and E. Rashedi. 2018. "Assessing the Influence of a Passive, Upper Extremity Exoskeletal Vest for Tasks Requiring Arm Elevation: Part I – "Expected" Effects on Discomfort, Shoulder Muscle Activity, and Work Task Performance." *Applied Ergonomics 70* (September 2017): 315–322. doi:10.1016/j.apergo.2018.02.025.

Kim, S., M.A. Nussbaum, M. Smets, and S. Ranganathan. 2021. "Effects of an Arm-Support Exoskeleton on Perceived Work Intensity and Musculoskeletal Discomfort: An 18-Month Field Study in Automotive Assembly." *American Journal of Industrial Medicine* 64 (11): 905–914. doi:10.1002/ajim.23282.

Kim, S., M.A. Nussbaum, and M. Smets. 2022. "Usability, User Acceptance, and Health Outcomes of Arm-Support Exoskeleton Use in Automotive Assembly: An 18-Month Field Study in." *Journal of Occupational and Environmental Medicine* 64 (3): 202–211. 2022. doi:10.1097/JOM.0000000000002438.

Konrad, P. 2005. "The Abc of Emg." *A Practical Introduction to Kinesiological Electromyography* 1: 30–35.

Looze, M. P. De., T. Bosch, F. Krause, K. S. Stadler, W. O. Sullivan, M. P. De Looze, T. Bosch, F. Krause, and K. S. Stadler. 2016. "Exoskeletons for Industrial Application and Their Potential Effects on Physical Work Load." *Ergonomics 59* (5): 671–681. doi:10.1080/00140139.2015.1081988.

Mayer, J., T. Kraus, and E. Ochsmann. 2012. "Longitudinal Evidence for the Association between Work-Related Physical Exposures and Neck and/or Shoulder Complaints: A Systematic Review." *International Archives of Occupational and Environmental Health 85* (6): 587–603. doi:10.1007/s00420-011-0701-0.

Rashedi, E., S. Kim, M. A. Nussbaum, and M. J. Agnew. 2014. "Ergonomic Evaluation of a Wearable Assistive Device for Overhead Work." *Ergonomics 57* (12): 1864–1874. doi:10.1080/00140139.2014.952682.

Schwerha, D., N. McNamara, S. Kim, and MA. Nussbaum. 2022. "Exploratory Field Testing of Passive Exoskeletons in Several Manufacturing Environments: Perceived Usability and User Acceptance." *IISE Transactions on Occupational Ergonomics and Human Factors* 2022 -Jun10 (2): 71–82. doi:10.1080/24725838.2022.2059594.

Smets, M. 2019. "A Field Evaluation of Arm-Support Exoskeletons for Overhead Work Applications in Automotive Assembly." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 192–198. Oct doi:10.1080/24725838.2018.1563010.

Umer, W., M. F. Antwi-Afari, H. Li, G. P. Y. Szeto, and A. Y. L. Wong. 2018. "The Prevalence of Musculoskeletal Symptoms in the Construction Industry: A Systematic Review and Meta-Analysis." *International Archives of Occupational and Environmental Health* 91 (2): 125–144. doi:10.1007/s00420-017-1273-4.

Van Engelhoven, Logan, Nathan Poon, Homayoon Kazerooni, Alan Barr, David Rempel, and Carisa Harris-Adamson. 2018. "Evaluation of an Adjustable Support Shoulder Exoskeleton on Static and Dynamic Overhead Tasks." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 62 (1): 804–808. doi:10.1177/1541931218621184.

Van Rijn, R. M., B. M. Huisstede, B. W. Koes, and A. Burdorf. 2010. "Associations between Work-Related Factors and Specific Disorders of the shoulder - A Systematic Review of the Literature." *Scandinavian Journal of Work, Environment & Health* 36 (3): 189–201. doi:10.5271/sjweh.2895.

Wærsted, Morten, Markus Koch, and Kaj Bo Veiersted. 2020. "Work above Shoulder Level and Shoulder Complaints: A Systematic Review." *International Archives of Occupational and Environmental Health* 93 (8): 925–954. doi:10.1007/s00420-020-01551-4.