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Influence of an upper limb exoskeleton on muscle activity during various construction and manufacturing tasks ☆

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ABSTRACT

Musculoskeletal disorders (MSDs) significantly impact workers in the manufacturing and construction sectors. One solution that has gained interest to reduce MSDs incidence is the use of exoskeletons. In this study, the influence of an upper limb exoskeleton on muscle activity was investigated experimentally for three commonly performed tasks in the manufacturing and construction sectors. The tasks tested were overhead assembly, bricklaying, and box moving tasks. Eighteen males participated in the tests. The results showed a reduction in shoulder flexor muscle activation during all three tasks (up to -45.46 $\pm$ 4.52% for the anterior deltoid), but increased extensor activation (up to 15.47 $\pm$ 8.01% for the latissimus dorsi) was observed when the task was not primarily performed above shoulder level. The results revealed the dependence of the upper-body exoskeleton on tasks and arm posture, which should be considered for both in-field applications and designing new exoskeletons for performance enhancement.

1. Introduction

According to the latest report from the European Agency for Safety and Health at Work, musculoskeletal disorders (MSDs) are common among European workers, with 60% reporting being affected by MSDs (Kok et al. (2020)). MSDs are damage to the human body tissues and structures such as muscles, tendons, ligaments, nerves, cartilage, bones, and joints (Kok et al. (2020); Pizam (2010)). Different strategies have been adopted to mitigate the incidence of MSDs in the workplace, including ergonomic modifications of workstations, physical exercises, and the use of tools like brace and belts (Skamagki et al. (2018); Patel et al. (2022)).

In recent years exoskeletons have gained increasing attention as a potential solution for addressing MSDs. Exoskeletons are wearable devices that support and enhance human capabilities (Lowe et al. (2019)). Exoskeletons can be classified based on the body parts they assist, such as shoulder and upper limb, back, or lower limb exoskeletons (Kok et al. (2020)). Focusing particularly on exoskeletons for shoulder support, the literature shows a growing number of devices on the market or prototypes in development (Gull et al. (2020); Voilqué et al. (2019); Hyun et al. (2019); Bock et al. (2022b); Balser et al. (2022)). Some available exoskeletons include the Skelex 360-XFR (Skelex, Rotterdam, The Netherlands), the MATE-XT (Comau, Turin, Italy), the Ottobock Shoulder (Ottobock, Duderstadt, Germany), the EVO (Ekso Bionics, San Rafael, CA, USA), and the Airframe (Levitate Technologies, San Diego, CA, USA).

While previous studies have reported positive effects in reducing muscle activity around the shoulder region, the efficacy of these devices in reducing MSDs incidence has not yet been fully verified, as epidemiological studies are not yet available (Bock et al. (2022a)). The studies to date have focused on evaluating the effects of exoskeletons on parameters related to the onset of MSDs. Specifically, commercially available exoskeletons for shoulder support have shown the ability to decrease the electromyographic (EMG) activity of shoulder agonist muscles, such as the three deltoid heads, pectoralis major, and trapezius, during tasks performed at or above shoulder level, including drilling (Kim et al. (2018); Alabdulkarim et al. (2019); Schmalz et al. (2019); Maurice et al. (2020); Engelhoven et al. (2019)), wiring (Kim et al. (2018); Bock et al. (2022b)), or plastering tasks (de Vries et al. (2021)). Reductions in muscle recruitment (measured using surface EMG) are highly relevant for preventing MSDs, as higher levels of fatigue may be delayed and/or avoided and there is a potential reduction in joint loading due to muscle recruitment. Both aspects, muscular fatigue and load, are linked with the MSDs insurgence (Sa-Ngiamsak (2016); Gallagher

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and Heberger (2013)). In the study by Weston et al. (2021), differences in fatigue onset during drilling tasks when using upper limb exoskeletons were directly assessed by evaluating muscle tissue oxygenation, but significant differences were found in only one condition. More systemic analyses were also conducted by evaluating the change in metabolic cost while using an exoskeleton, by observing the heart rate (Moyon et al. (2019); Maurice et al. (2020); Schmalz et al. (2019)), or the oxygen consumption (Schmalz et al. (2019); Maurice et al. (2020)). Finally, subjective measures, including joint perceived discomfort and perceived effort, were also collected (Weston et al. (2021); Maurice et al. (2020); de Vries et al. (2021); Engelhoven et al. (2019); Moyon et al. (2019)).

From our literature review, we have found that previous studies primarily focus on evaluating upper limb exoskeletons during tasks requiring working with a shoulder flexion angle of 90°, while there are limited researches on tasks involving arm positions below the shoulder. Working above shoulder level is indeed a risk factor for the onset of MSDs (Wærsted et al. (2020)), and upper limb exoskeletons are mostly designed to provide the maximum support at that angle. However, previous studies have shown that shoulder MSDs could already occur when working with shoulder flexion angles greater than 60° (Anderson et al. (1997)). Furthermore, working with a shoulder flexion angles below 60° but above 20° for extended periods or in a repetitive manner is not without risk of developing MSDs, and changes may be required (McAtamney and Corlett (1993)), particularly if a tool or another external load is handled. The relation between the number of repetitions of a task, the load carried, and the onset of MSDs is reported by (Gallagher and Heberger (2013)).

In this study, we aim to assess the impact of an upper limb exoskeleton on muscle activity during common tasks in the construction and manufacturing sectors. We tested the device on three tasks to analyze its performance over different ranges of motion. To perform a more comprehensive analysis of the influence of an upper limb exoskeleton on human muscle activity and evaluate its applicability also for tasks for which it is not primarily designed. The first task we examined was an overhead assembly task, selected due to the evidence of a relation between MSDs and overhead work (Wærsted et al. (2020)). The second task was a bricklaying task. Within bricklayers, shoulder and upper arm MSDs are among those with the highest incidence (Boschman et al. (2012); Holmström and Engholm (2003), even though they work mainly with an arm elevation below 60° (Luijsterburg et al. (2005). The third task studied was a box-moving task from the ground to a table. Relations between shoulder MSDs and lifting tasks were found by Harkness et al. (2003).

The paper is organized as follows: Section 2 describes the methods followed for the study: the exoskeleton used, tasks performed, data collection procedures, and analysis methodology. Results are presented in Section 3 and discussed in Section 4. Finally, the limitations of the study procedure are stated in Section 5 and the conclusions in Section 6.

2. Methods

2.1. Participants

Eighteen healthy males (Table 1) took part in the study. The exclusion criteria for the study included shoulder or back pain, muscle soreness in these areas, and the inability to comfortably fit the exoskeleton. No participants were excluded based on the latter criteria. All participants provided written informed consent before participation. The research protocol was approved by the Scientific Ethics Committee for Region North Jutland (Denmark).

Table 1
Subjects' physiological characteristics.

Variable	Mean (n = 18)	SD
Age (y)	27.11	3.71
Weight (kg)	78.67	10.87
Height (cm)	179.50	6.96
Dominant side	18 R | 0 L	\

2.2. Exoskeleton

The exoskeleton used in the study was the Skelex 360 (Skelex, Rotterdam, The Netherlands, Fig. 1). It is a passive device with an adjustable support level ranging from 0.5 to 3.5 kg. The support level can be changed by modifying the distance between the center of rotation of the exoskeleton shoulder and the attachment point of the cable on the exoskeleton's shoulder element. Changing this distance adjusts the pretension of the spring system that generates the support. This spring system consists of a leaf spring and a tension cable. The system, in addition to generating the support force, serves as a structural element of the device's back. The total weight of the exoskeleton is 2.7 kg.

Fig. 1. The Skelex 360 exoskeleton.

2.3. Experimental design and procedures

The study was performed in one session, beginning with the adjustment of the exoskeleton to ensure a comfortable fit for each participant. The support force level of the device was then set to the gravity compensation level. Participants were asked to extend their arms in front of them with a shoulder flexion angle of 90°. The support force was set at a level that allowed them to lower their arms from that position without effort. A familiarization phase was performed once the exoskeleton was adjusted on the participants. During this phase, participants were required to catch and toss a foam ball back to an operator. The operator made sure to toss the ball to the participants at different heights and direction to familiarize them with the device. Minor adjustments to the device fit were made during this phase. The familiarization phase lasted, on average, for 10 minutes.

Following the familiarization phase, EMG sensors were placed on the participants to assess muscle activity. Participants did not wear the device during this process. Eight muscles were targeted during the experiment on both sides: anterior (AD), middle (MD), and posterior (PD) deltoids, biceps brachii (BB), brachioradialis (BRA), pectoralis major (PM), latissimus dorsi (LD), and erector spinae longissimus (ERL). These muscles were selected due to their roles in shoulder movements or, as for the brachioradialis and erector spinae longissimus, might be influenced by the presence of the exoskeleton. The device could alter the normal recruitment of these muscles during the tasks redistributing the load to or stabilizing the corresponding body regions. The FREEEMG1000 (BTS S.p.A., Garbagnate Milanese, Italy) system equipped with Ag/AgCl ECG electrodes Kendall™ H124SG (CardinalHealth™, Dublin, Ohio, USA) was used for the EMG assessment. A sample frequency of 1000 Hz was used. The SENIAM recommendations (Hermens et al. (2000)) were followed for sensor placement. Prior to EMG placement, the participants' skin was prepared by shaving and cleaning it with alcohol wipes. After EMG

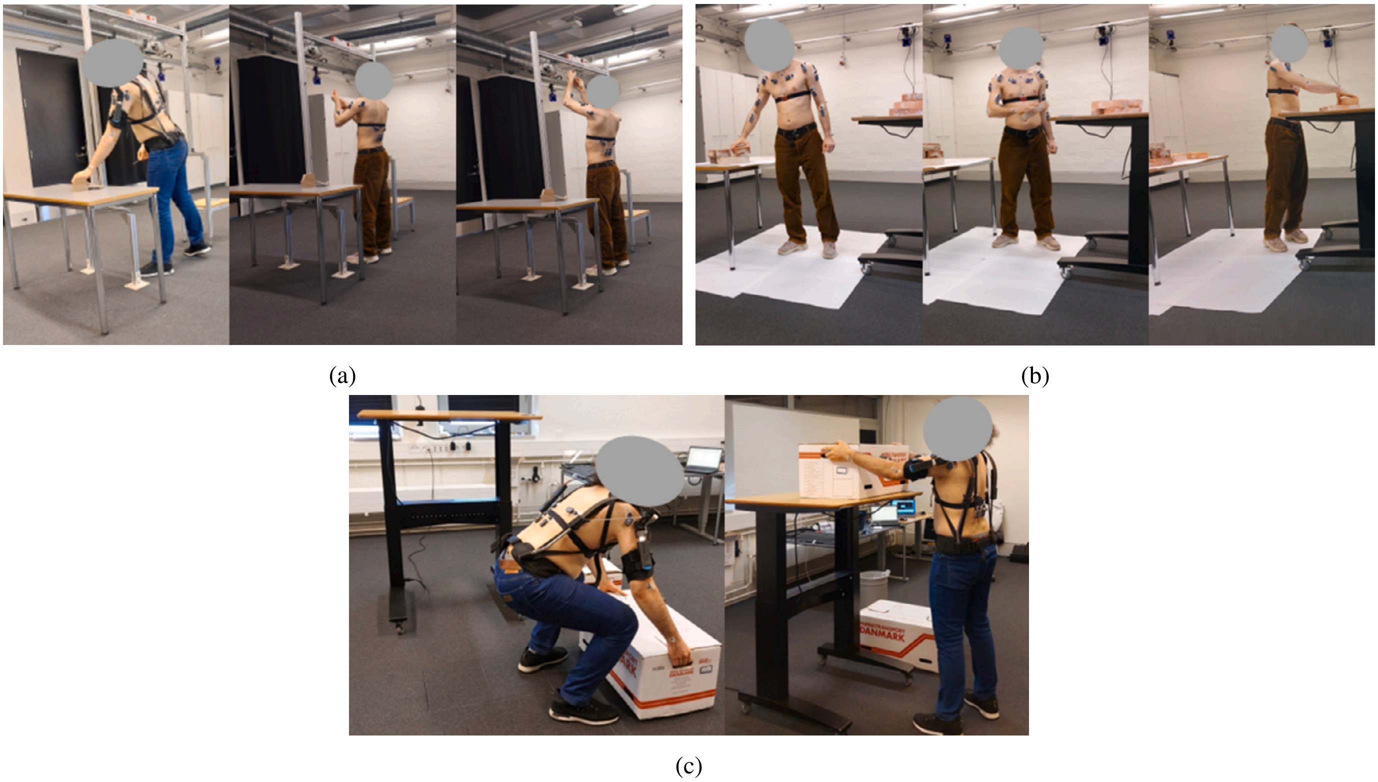

Fig. 2. The three tasks tested in the study. (a) Overhead assembly, (b) brick laying, and (c) box moving.

placement, the maximal voluntary contraction (MVC) of the muscles was recorded. For this purpose, the tasks proposed by Boettcher et al. (2008) were adopted for the shoulder muscles (i.e., the "empty can" task for the three deltoids, the "palm pres" task for the PM, and the "internal rotation 90°" task for the LD). A resisted arm curl was used for BB and BRA, and the Biering-Sorenson task was used for ERL. The participants performed each MCV task three times for 5 s with 1-minute intervals between repetitions. Verbal encouragement was provided during repetitions.

Following the MVC assessment, participants performed the three tasks presented in the Section 2.4 in the order of presentation. The starting condition, either with the exoskeleton ("Exo" condition) or without it ("Free" condition), was randomized. Prior to performing the tasks, participants were given the opportunity to familiarize themselves with the tasks, adjust to the imposed pace, and find their preferred pace, if applicable. Each task was repeated three times under each condition, with a two-minute break between repetitions. A five-minute rest period was observed between the change of condition and task.

2.4. Real-world ergonomic tasks

The first task tested was an overhead assembly activity (Fig. 2a). Participants were instructed to pick up a screw from a box placed on a table with their non-dominant hand and screw it into one of the T-slot nuts placed in an aluminum profile in front of them. Participants used their dominant arms for screwing with a hex key. A total of 10 nuts were arranged in the aluminum profile, spaced 8 cm apart from each other. Therefore, the participants placed ten screws during each task repetition and performed it three times in each condition with a two-minute break between repetitions. The height of the aluminum profile was set to ensure that participants started screwing with their dominant shoulder and elbow flexed at 90°. For the assessment of the shoulder and elbow flexion angle, a clinometer app available for smartphones was used (Lin et al. (2019); Charlton et al. (2015)). A pace was not imposed; participants were asked to work at the maximum speed, allowing them not to make errors during the task execution.

The second task performed was bricklaying (Fig. 2b), which involved transferring ten bricks from a table to a second one placed in front. The height of the second tabletop was adjusted to the participants' navel height. The bricks were initially arranged in two piles, and the participants were instructed to recreate these piles on the second table using their dominant arm. A pace of 15 repetitions per minute was imposed using a metronome. The average weight of the bricks is 2 kg. Three sets of the task were performed for the Exo and Free conditions, with two minutes break between repetitions.

The third task tested involved the movement of a box from the floor to the top of a table (Fig. 2c). The participants had to rotate 90° as the box was initially positioned in front and alongside the table. The height of the tabletop was adjusted to ensure that participants assumed a final position with the shoulders flexed at 90°. The clinometer app presented before was used again here to adjust the tabletop height according to the shoulder flexion angle. Two boxes with the same dimensions (70.5×39.5×31 cm) and weighing 10 kg were used. The same pace of 15 repetitions per minute, used for the bricklaying task, was imposed using the metronome. Participants performed six consecutive lifts and repeated the entire task three times for each condition. An operator was responsible for removing the box from the table and placing the subsequent in the starting position on the ground. Therefore, participants only had to lift the box during the task.

2.5. Data processing and statistical analysis

The EMG data processing and analysis were conducted using MATLAB R2023a (The MathWorks, Inc., Natick, MA, USA). The raw EMG data from each muscle were filtered with a bidirectional fifth-order Butterworth filter with a passband of 10-450 Hz.

The EMG data were segmented into bursts using the onset/offset segmentation proposed by Yang et al. (2017). First, this method requires applying a Teager-Kaiser Energy (TKE) operator to the signal to

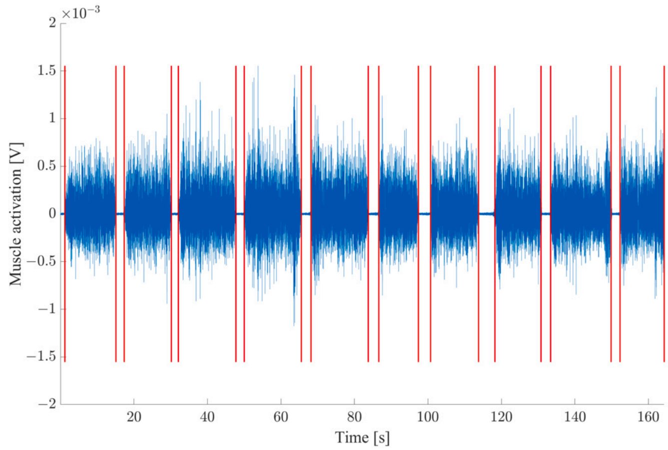

Fig. 3. Results of the segmentation process. The EMG activation bursts are highlighted by two vertical red lines indicating start and endpoints. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

accentuate its amplitude variation. Subsequently, two image enhancement technologies are used (i.e., morphological close operator (MCO) and morphological open operator (MOO)) to detect activation bursts and discard false positives. This method requires the definition of three parameters, namely, the scale factor (j) for the noise standard deviation (σ_n) and the size (in seconds) of the two 1-D rectangle structuring elements used in MCO (t_1) and MOO (t_2) (Yang et al. (2017)). These two parameters, as reported by Yang et al. (2017), rely on j. The scale factor is used for computing the threshold value (th) for the onset and offset points identification. th is obtained by summing the $j \cdot \sigma_n$ product to the mean value of the noise (μ_n), Eq. (1).

$$th = \mu_n + j \cdot \sigma_n \quad (1)$$

j itself should be set in accordance with the signal-to-noise ratio as shown by Li et al. (2007).

In our analysis, we did not compute the segments for every muscle. Instead, we segmented the most representative muscles for a specific task and then used these computed segments also for the analysis of the other muscles. In particular, we used the left and right AD for the overhead assembly task and the dominant arm AD, BRA, and ERL for the bricklaying and box moving tasks. For the bricklaying and box moving tasks, the AD was chosen as a reference for the muscles acting on the shoulder (i.e., AD, MD, PD, PM, LD), the BRA for itself and the BB, the ERL for itself only. The two anterior deltoids were chosen for the screw task as it can be seen as a shoulder flexion in the sagittal plane, and this muscle is active throughout the entire movement range. The AD, BRA, and ERL were selected for the bricklaying and box moving tasks due to their more complex movement, and because the arm and elbow did not have the synchronization that allowed us to use the AD as reference for all the muscles as done for the overhead assembly task.

For each task, the parameters t_1 and t_2 were adjusted based on the task duration and the parameter j according to the SNR of the recording. A value of t_1 equal to 70 ms was found to be suitable for all tasks. t_2 was set at 1500 ms for the overhead assembly task, while it was set at 500 ms for the other two. Fig. 3 presents the results of the segmentation of the signal relative to the right AD muscle recorded during the screw task, with $t_1 = 70$, and $t_2 =$ 1500, $j = 15$. In the work of Li et al. (2007) a value between 6 and 8 for the scale factor is suggested, as the latency of the onset detection has a minimum in this range for an SNR below 8. However, the study also shows that the latency tends to zero even using j between 8 and 23 for SNR values greater than 8.

Once obtained the intervals from the reference muscles, the others belonging to the same file were segmented. The root mean square (RMS) was calculated using a 100 ms moving window (no overlap) to assess the EMG amplitude, and subsequently, the average RMS of the recording was computed. The three average RMS values obtained from the file, corresponding to three repetitions of tasks performed under the same condition (with and without the exoskeleton), were then averaged and normalized to the MVC. The MVC value was also obtained by computing the RMS using a 100 ms moving window without overlap over the MVC recordings. Finally, the mean activation value among the 18 participants was computed for every muscle and condition. The difference in muscle activation between Free (A_{Free}) and Exo (A_{Exo}) condition was computed and expressed as a percentage of the activation in the Free condition Eq. (2).

$$\Delta A\% = (A_{Exo} - A_{Free})/A_{Free} \cdot 100 \quad (2)$$

The subsequent statistical analysis was performed in MATLAB R2023a. A Shapiro–Wilk test was first performed to assess the normality of the data. Subsequently, Paired Sample T-Test was used to assess statistical differences between the two conditions for the muscles on which normality was verified. In case the data did not follow a normal distribution, the Wilcoxon signed-rank test was utilized. A significance level (p) equal to 0.05 was applied for both methods. Additionally, the effect size (ES) between the two conditions was computed using Cohen's d method for the normally distributed data. When the Wilcoxon Signed-rank test was used, the effect size was computed using the method proposed by Rosenthal (1994), where the effect size was computed as $r = Z/\sqrt{N}$. With Z being the z-statistic of the Wilcoxon test and N the number of paired samples. For reference, a value below 0.3 is considered indicative of a small effect, between 0.30 and 0.5 a moderate and over 0.5 a large effect (Rosenthal (1994); Simoni et al. (2020)).

3. Results

In the following paragraphs, the results from the three tests are reported. The differences in activation between the two conditions are reported as percentages of the activation in the Free condition. In Table 2 the results from the three tests are summarized, and the difference in activation between the two conditions is expressed as a percentage of the mean MVC across subjects.

3.1. Overhead assembly task

Fig. 4 presents the results of the analysis of the muscular activity during the overhead assembly task. When the exoskeleton was used, a statistically significant reduction in the activity levels of all three deltoid muscles was observed on both the dominant and non-dominant sides. On the dominant side, the percentage difference of the activation level was ΔA% = -27.64 ± 5.44% (p = 7.96e-05, d = -1.7) for the AD, ΔA% = -38.77 ± 9.75% (p = 1.96e-04, r = -0.88) for the MD, and ΔA% = -28.03 ± 16.92% (p = 2.33e-04, r = -0.87) for the PD. On the non-dominant ΔA% = -45.46 ± 4.52% (p = 3.12e-06, d = -3.35) for the AD, ΔA% = -33.92 ± 8.35% (p = 0.0021, r = -0.72) for the MD, and ΔA% = -22.11 ± 12.86% (p = 1.96e-04, r = -0.88) for the PD. Using the exoskeleton also resulted in a statistically significant difference in the activity of the BB and the PM, which have roles in shoulder flexion. For the BB, on the dominant side, ΔA% = -15.96 ± 10.36% (p = 0.048, r = -0.47), and on the non-dominant side, ΔA% = -23.4 ± 9.23% (p = 0.0065, r = -0.64). Whereas for the PM, ΔA% = -20.20 ± 5.56% (p = 0.0096, r = -0.61) on the dominant side, and ΔA% = -37.34 ± 6.99% (p = 1.96e-04, r = -0.88) on the non-dominant side. The BRA and the LD showed a no n-significant decrease in their activity during the task (i.e., -8.85% and -4.68% for the BRA, and -5.99% and -1.92% for the LD) when the participants were using the device. The ERL exhibited a different behavior on the two sides, with a non-significant increase in activation on the dominant side ΔA% = 6.99 ± 7.31% and a significant decrease on the opposite side ΔA% = -13.78 ± 8.09% (p = 0.012, d = -0.57).

Table 2
Differences in muscle activation with and without exoskeletons (expressed as a percentage of maximum voluntary contraction) for the work tasks.

Tasks	Muscles															
	Dominant side								Non dominant side							
	AD	MD	PD	BB	BRA	PM	LD	ERL	AD	MD	PD	BB	BRA	PM	LD	ERL
Overhead assembly	-3.41	-2.11	-0.49	-0.65	-0.18	-2.70	-0.33	0.79	-6.69	-1.78	-0.63	-1.54	-0.11	-3.21	-0.21	-0.62
Bricklaying	-1.64	-0.82	0.47	0.45	0.12	-0.83	0.06	0.48	-	-	-	-	-	-	-	-
Box moving	-7.65	-1.73	2.02	1.60	0.60	0.005	1.43	1.68	-4.37	-2.91	0.81	-0.42	0.84	0.38	1.42	-0.002

Note: [green] significant reduction in activation using the exoskeleton.
[red] significant increase in activation using the exoskeleton.

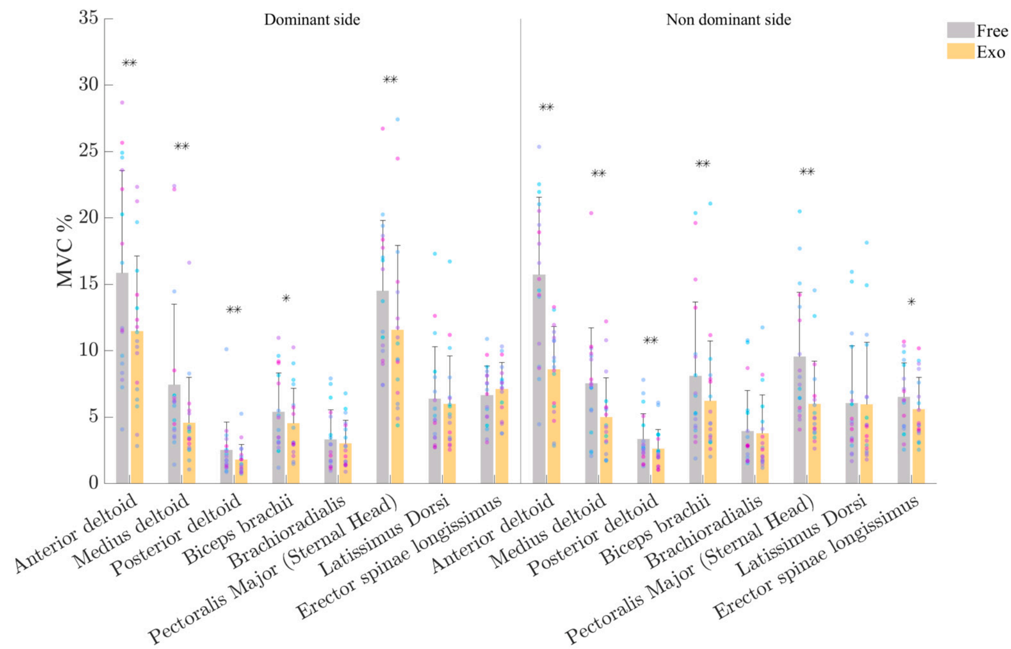

Fig. 4. Comparison of the mean muscle activation between participants in the two conditions, Free (gray) and Exo (orange), during the overhead assemby task. The error bars represent the standard deviation of the mean. The symbol (∗) indicates a statistical significance level < 0.05 of the difference between the two conditions, the symbol (∗∗) a p-value < 0.01. The colored dots represent the average muscle activation during the task for each participant.

3.2. Bricklaying task

The results of the muscular activity analysis are presented in Fig. 5. Only the results relative to the dominant side are shown, as the participants did not use their non-dominant one. Only the three deltoids presented a significant difference in activation. The activation of the AD and MD decreased: $\Delta A\% = -19.03 \pm 6.69\%$ ($p = 6.35e\text{-}04$, $d = -0.95$) for the AD, $\Delta A\% = -15.01 \pm 8.47\%$ ($p = 0.020$, $r = -0.55$) for the MD, whereas the PD activation increased: $\Delta A\% = 15.05 \pm 12.58\%$ ($p = 0.02$, $d = 0.40$).

3.3. Box moving task

Fig. 6 presents the results of the analysis of the muscular activity during the box-moving task. The AD presented a significant decrease in activity on both sides: $\Delta A\% = -32.10 \pm 3.40\%$ ($p = 4.52e\text{-}04$, $d = -3.15$) and $\Delta A\% = -16.46 \pm 4.27\%$ ($p = 0.0012$, $d = -1.29$), dominant and non-dominant respectively. The same trend was observed in the MD with $\Delta A\% = -11.21 \pm 4.80\%$ ($p = 0.037$, $d = -0.78$) on the dominant side, and $\Delta A\% = -15.86 \pm 5.52\%$ ($p = 0.011$, $r = -0.60$) on the non-dominant side. The PD presented an increase in activity, significant: $\Delta A\% = 16.20 \pm 7.08\%$ ($p = 0.014$, $d = 0.76$) on the dominant side, and not significant on the non-dominant side. The arm muscles BB and BRA, as well as PM and ERL, did not show a significant difference in the activation level on either side. Increased activity was observed in the LD, significant on both sides, respectively: $\Delta A\% = 14.64 \pm 7.37\%$ ($p = 0.0057$, $r = 0.65$) on dominant, and $\Delta A\% = 15.47 \pm 8.01\%$ ($p = 0.019$, $r = 0.55$) on non-dominant side.

4. Discussion

The study is aimed to comprehensively assess the influence of an upper limb exoskeleton on muscular activity during various tasks requiring different arm positions and ranges of motion. Our main finding is that the exoskeleton is able to reduce AD and MD activity across all tasks. These muscles are the main drivers of shoulder motion in the chosen tasks. Therefore, our study demonstrates that the exoskeleton can reduce shoulder muscle loading even in tasks performed below the optimal device operating range. However, the use of the exoskeleton increased the activation of shoulder extensor muscles (i.e., PD and LD) when the task was mainly performed below a 90° shoulder flexion angle. The principal reason for this increase might be that the users had to counteract the assistance of the device to work in this range and to lower their upper limbs. The exoskeleton did not significantly increase the activation of muscles in other observed body regions such as BRA and ERL. This suggests that it did not overload these regions by transferring part of the load or constraining the movement.

4.1. Overhead assembly

The results obtained during the overhead assembly show the effectiveness of this exoskeleton in supporting repetitive quasi-statistic tasks performed overhead. All recorded shoulder flexor muscles presented a

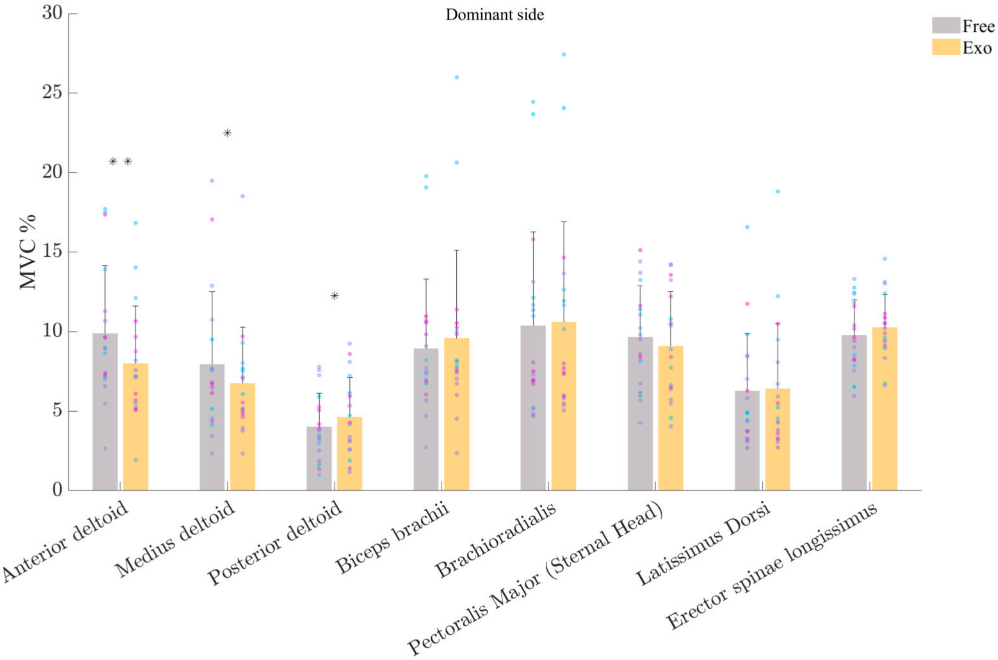

Fig. 5. Comparison of the mean muscle activation between participants in the two conditions, Free (gray) and Exo (orange), during the bricklaying task. The error bars represent the standard deviation of the mean. The symbol (*) indicates a statistical significance level < 0.05 of the difference between the two conditions, the symbol (**) a p-value < 0.01. The colored dots represent the average muscle activation during the task for each participant.

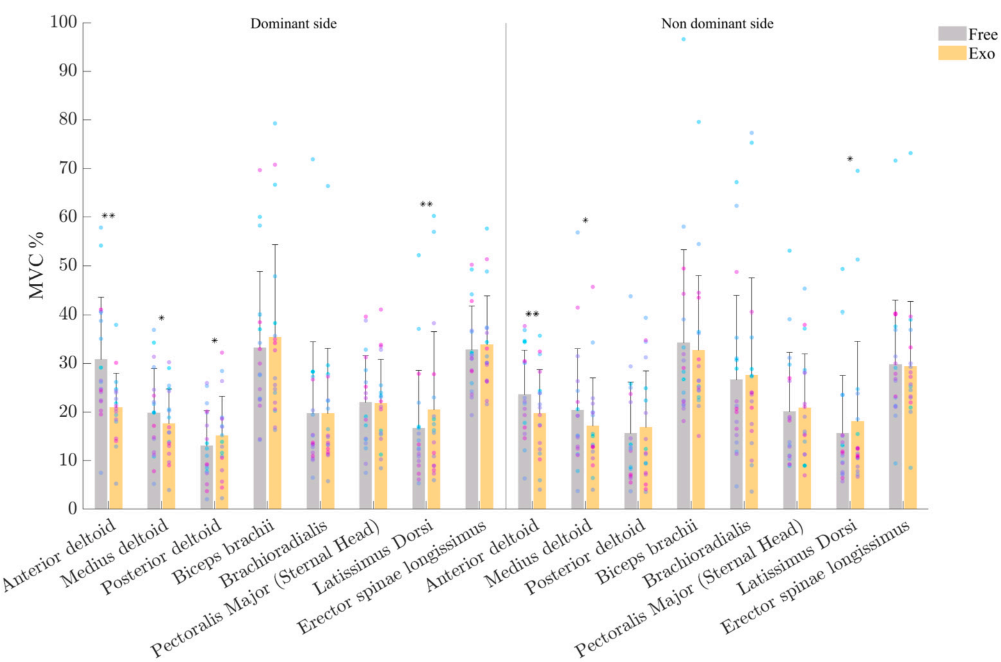

Fig. 6. Comparison of the mean muscle activation between participants in the two conditions, Free (gray) and Exo (orange), during the box moving task. The error bars represent the standard deviation of the mean. The symbol (*) indicates a statistical significance level < 0.05 of the difference between the two conditions, the symbol (**) a p-value < 0.01. The colored dots represent the average muscle activation during the task for each participant.

significant decrease in activity, with a maximum of -45.46 ± 4.52% on the non-dominant side AD. The presence of the exoskeleton did not lead to an increase in activity of any of the investigated shoulder extensor muscles (i.e., PD and LD). On the contrary, the activity of both muscles decreased. In particular, PD activity presented a significant decrease (i.e., -28.03 ± 16.92% and -22.11 ± 12.8% for the dominant and non-dominant sides, respectively). It is difficult to say whether these muscles increased their activity when the participants were lowering their arms, as this phase was relatively short compared to the phase where the shoulder was in a quasi-static position at 90°. Overall, all the muscles responsible for shoulder motion exhibited decreased activity, suggesting a reduced total load acting on this joint. Our findings are positive, as reducing the total load experienced by a joint decreases the risk of MSD, particularly in repetitive tasks (Gallagher and Heberger (2013)). Our findings align with those presented in previous studies where devices from other exoskeleton brands were tested in similar tasks (Kim et al. (2018); Alabdulkarim et al. (2019); Schmalz et al. (2019); Maurice et al. (2020); Engelhoven et al. (2019)).

The general decrease in muscular activity observed in our study can be seen in connection with the result of a lower heart rate found by

Moyon et al. (2019) when using the Skelex device. The two results are related, and both indicate a lower metabolic cost of the task. During our tests, we observed a decrease in the activity of the BB and a non-significant change in BRA. This result can be seen in contrast with the finding of an increased level of discomfort perceived at the elbows/forearms region in the study by Moyon et al. (2019). However, the task setup used by Moyon et al. (2019) and in our study differ, as the participants in Moyon et al. (2019) were placing the screw in front of them and using a heavier tool (a drill) than the one used in our study.

Regarding the impact on other body regions not directly supported, the exoskeleton reduced the activity of the elbow flexors. The triceps brachii was not analyzed due to difficulties in placing the EMG sensors donning the exoskeleton cuff. Of difficult interpretation were the results found on the ERL. A significant decrease in activation was observed on the non-dominant side, while a non-significant change was present on the dominant side. One possible explanation is that participants were leaning to the side to gain a better view of where the screws needed to be placed. However, the exoskeleton may have restricted this motion.

4.2. Bricklaying task

During the bricklaying activity, the exoskeleton reduced the activity of one of the three shoulder flexor muscles analyzed, the AD. The increase in activity found for the shoulder extensor muscles, significant on the PD, might be attributed to the participants having to stop the exoskeleton in the phase of support below 90°. Additionally, MD activity was significantly reduced. Overall, the muscle activity around the shoulder region decreased when the exoskeleton was worn, suggesting that the load acting on this area was reduced during the task. No significant changes were observed in the activation of muscles involved in torso flexion/extension and rotation, such as LD and ERL, indicating that the exoskeleton did not significantly overload this region or constrain the upper body rotation.

There are no previous studies evaluating the influence of an exoskeleton on this specific task, and studies on tasks performed mainly below shoulder level are also lacking. One study by Spada et al. (2018) evaluated mounting the seal on the car rear door, which was partially performed below shoulder level. The workers involved in Spada et al. (2018) reported increased exertion when working at waist level or below, as they had to contrast the device to maintain that posture. This result aligns with the increase in activation of the shoulder extensor muscles that we found during the bricklaying task.

4.3. Box moving task

For this task, our test showed that AD and MD activation was significantly reduced on both sides when the exoskeleton was used. No other significant changes in activity were found in other shoulder flexor muscles, such as PM and BB. The results found for AD and MD agree with the findings of previous studies (Seiferheld et al. (2022); Theurel et al. (2018); Bock et al. (2022b)).

In Theurel et al. (2018), a comparable task was performed, but with an exoskeleton for upper limb support that differs from the one used in our study, as the support is provided directly to the user's hands and not to the upper arm like the Skelex device. The work presented in Seiferheld et al. (2022) evaluated the implementation of an exoskeleton similar to the Skelex device to support the movement performed by supermarket workers for placing crates on supermarket shelves. They performed the evaluation with musculoskeletal simulation software, driving the model with kinematic data. Bock et al. (2022b) tested a prototype exoskeleton for upper limb support in a frontal lifting task from the ground.

The observed changes in AD and MD activity in our study are consistent with the simulation results presented by Seiferheld et al. (2022) and the findings of Bock et al. (2022b). Additionally, the significant increase in LD activity observed in our study also agrees with the results presented in Seiferheld et al. (2022) and Bock et al. (2022b). In contrast with the findings obtained from the simulations in Seiferheld et al. (2022) was the increase of activity we found for the PD, whereas a decrease was found in Seiferheld et al. (2022). The increase in PD aligns with the increase in LD activity, as both muscles are involved in shoulder extension. The increase in the activity of LD might also be due to the device constraining the upper body motion of the participants as the LD is also involved in the torso movements. However, the ERL did not show a significant difference in activation, suggesting that the exoskeleton did not overload the back during this task. These findings are consistent with the results reported by Theurel et al. (2018). Lastly, no significant difference in activation was observed for the BB and BRA muscles, suggesting that the participants did not involve these muscles more for lifting the box when using the exoskeleton.

5. Limitation

The study was conducted in a controlled laboratory environment where variables, such as dust or debris, that could interfere with the proper functioning of the exoskeleton and lower its efficacy are prevented. The population was also a possible limitation as all participants were not professionals in any of the three tasks selected for the study. Additionally, the participants did not represent the whole working age group and genders, as all participants were male, and the older participant was 38. In 2022, the median age for US construction and manufacturing workers was 42.4 and 44.3, respectively (US), and in the European Union, the age group 25-64 years includes more than the 90% of workers in both sectors (EU). Evaluating the exoskeletons on older persons can be important and interesting as workers from these age groups are the most affected by MSDs (Kok et al. (2020)). One last limitation is that only one exoskeleton was used in the study, Skelex 360; different devices might give different results.

6. Conclusion

In this study, the performance of an upper-limb exoskeleton is comprehensively assessed through three tasks involving operations both over and below the shoulder level. The results obtained highlight the effectiveness of this device in supporting overhead work. The Skelex exoskeleton significantly reduced the activation of all muscles involved in the shoulder flexion without increasing the activation of back muscles, as the ERL, or of antagonist muscles of the shoulder flexion. Furthermore, a reduction in activation was also observed for the AD and MD during the other two tasks performed at lower shoulder flexion angles. However, an increase in PD activity was observed during the bricklaying and box moving task, with an additional increase in LD activity during the latter task only. These findings suggest that applying an exoskeleton in these tasks might still be beneficial for shoulder support, as the overall muscular activation around that joint was reduced. Further field studies on the application of exoskeletons for shoulder support in tasks performed at lower shoulder flexion angle range are required to better evaluate the applicability of these devices for tasks that require working below shoulder level, such as bricklaying and box moving tasks.

Declaration of competing interest

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

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