The amount of support provided by a passive arm support exoskeleton in a range of elevated arm postures

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Abstract

Background: The use of arm support exoskeletons is an upcoming strategy to mechanically support workers during elevated arm tasks. In the present study, we evaluated the effects of wearing a passive exoskeleton, on the shoulder moment and on the activity of six muscles in the shoulder region, in a range of elevated arm postures.
Methods: Twelve participants were asked to maintain a predefined static shoulder posture in a with and without exoskeleton condition. The postures were composed of five elevation angles (30° – 150°) and three horizonal abduction angles (0° - 60°). During the static postures we obtained the supportive moment provided by the exoskeleton by measuring the interaction force, as well as muscle activity by measuring EMG of six relevant muscles. We compared the moment that was required from the subjects to maintain the arm postures as well as the muscle activity in the with and without exoskeleton conditions.
Results: The supportive moment provided by the exoskeleton (0.5-6.1 Nm; up to 56% of the required moment) implied a significant reduction of the shoulder moment to be generated by the subject. This resulted in a reduction in muscle activity in three out of six muscles in the shoulder region. These effects were dependent on the arm posture, particularly on the vertical arm elevation rather than the horizontal abduction. The mechanical support was highest at the VE angles that were most demanding (90° and 120°). This caused the required moment from the subject to be evened out over different shoulder angles. Muscle activity was reduced in three out of six muscles in the shoulder region. For three muscles, the effects were dependent on the elevation angles. Increased muscle activity was seen in some antagonistic or stabilizing muscles in extreme angles.
Conclusion: Our results emphasize the importance of analyzing the task demands, such as working posture, when selecting or designing arm support exoskeletons.

Introduction

Despite robotization and automatization, the exposure to heavy work has not significantly declined over the past years (Eurofound, 2017). Heavy work is still prevalent in manufacturing, construction and agriculture (Eurofound, 2017). Various types of heavy work, i.e. frequent exposure to manual handling tasks, heavy lifting and the exposure to prolonged body postures like trunk-bending or arm elevation, increase the risk of developing musculoskeletal disorders (MSDs) (Da Costa & Vieira, 2010; Jaffar, Abdul-Tharim, Mohd-Kamar, & Lop, 2011). MSDs are one of the most common work-related disorders. For instance, more than 42% of the workers in the European Union suffer from shoulder and neck pain (Eurofound, 2017). It is particularly relevant in our ageing population to reduce the exposure to heavy work risks, and thus, to create a sustainable working culture which allows elderly workers to remain employed longer under healthy working conditions (Duell, 2015).

A new strategy to reduce the risk on MSDs in heavy work could be the use of exoskeletons in the workplace. Exoskeletons are devices that are worn on the body. They reduce mechanical loads on body structures by contributing to the generation of joint moments that are required for specific postures or movements (de Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016). Arm-support exoskeletons for instance, aim to reduce the loads on shoulder structures by contributing to the shoulder moment that is required in elevated arm work.

The effectiveness of several arm-support exoskeletons has been evaluated in laboratory settings for specific tasks, such as overhead drilling, sanding, and lifting (Alabdulkarim & Nussbaum, 2019; Huysamen et al., 2018; S Kim et al., 2018; Sunwook Kim et al., 2018; Moyon, Poirson, & Petiot, 2018; Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2017). Positive effects are reported in terms of contribution to the shoulder moment, of reduction in the activation of shoulder muscles and of reduced perceived (dis)comfort. However, the usability of the exoskeletons in real-life working situations is still considered to be a big challenge. One issue here is that the above-mentioned results were obtained within a limited range of arm elevation angles, while many jobs in practice show a wide envelop of arm elevation postures. Moreover, the exoskeletons used in these studies were all passive, i.e. providing mechanical support by use of a spring-like mechanisms instead of actuators. This mechanism generally implies that the amount of support depends on the level of arm elevation. For practitioners considering the adoption of an arm-support exoskeleton in a specific work situation, it would be helpful to be informed about the mechanical support to be expected throughout a wide envelop of shoulder angles rather than in a specific elevation angle.

The aim of this paper therefore is to assess the amount of support that is provided by a passive arm support exoskeleton over a wide range of arm elevation postures. The amount of support is assessed by evaluating the supportive moment provided by the exoskeleton as well as its effect on the activation of relevant muscles in the shoulder region. Our research question is: to what extent does a passive arm-support exoskeleton contribute to the shoulder moment that is required in a range of arm elevation angles and how does it affect the activation of shoulder muscles?

Methods

Participants

Twelve healthy, right-handed male participants, with average age 25 (SD 1.3), height 1.83 m (SD 0.8) and weight 77.8 kg (SD 8.7), volunteered to participate in the study. None of the participants reported shoulder pain in the previous three months. Participants signed an informed consent approved by the ethics Committee of TNO, after being informed about the procedures of the experiment.

Materials

We evaluated a passive exoskeleton (SkelEx, Rotterdam, The Netherlands), which generates a supportive force, when raising the arms, through a spring-like mechanism (Figure 1). The exoskeleton is worn like a backpack, with two shoulder straps and a hip belt. The arm support is provided through padded cuffs under each upper arm, which are attached to springs originating at the back.

Figure 1. SkelEx exoskeleton

Muscle activity levels were obtained through surface Electromyography (EMG) using Bipolar Ag/AgCl (AMBU Blue Sensor N) electrodes which were recorded using a Porti 7 system (TMS, Enschede, The Netherlands). EMG signals were sampled at a rate of 2048 samples/s and band-pass filtered (10-500 Hz) using EMG Suite Version 1.1 (ERGOcare, Faculty of Human Movement Sciences – Vrije Universiteit Amsterdam, The Netherlands).

A single axis force transducer formed the connection between the arm cuff and the exoskeleton frame, to measure the supportive force applied by the exoskeleton perpendicular to the exoskeleton arm (Figure 2). The force recording was measured at a sampling rate of 11 Hz. In the with exoskeleton condition the data from the force sensor was used to trim the obtained signals. An inertial measurement unit (IMU) (GCDC Human Activity Monitor, Gulf Coast Data Concepts, LLC, Waveland, MS, USA) was used for trimming the obtained signals in the without exoskeleton condition.

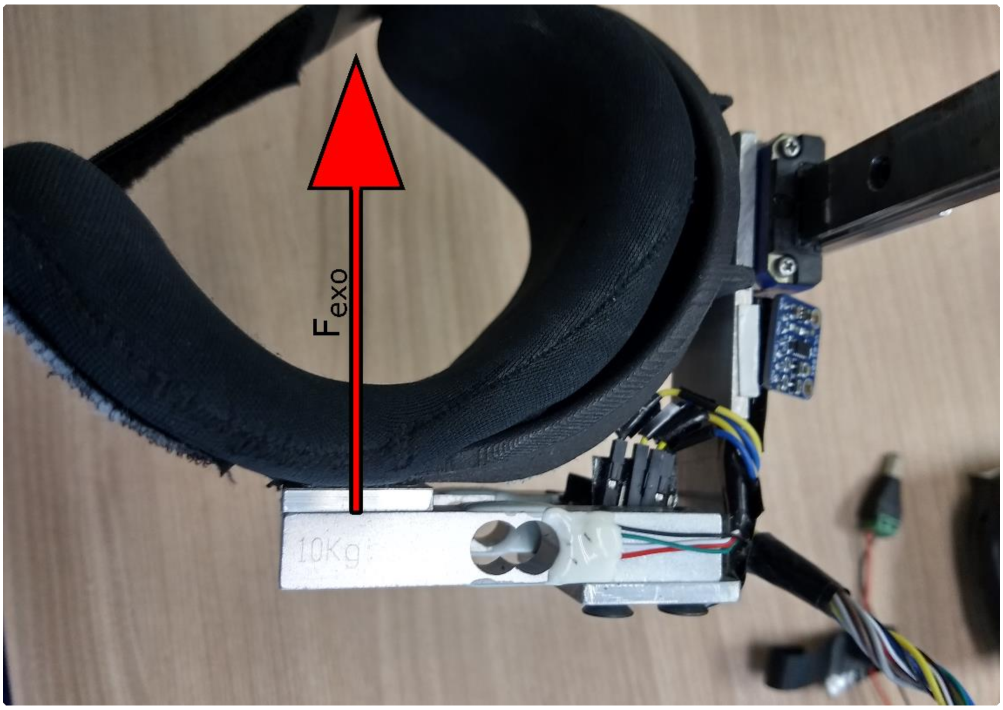

Figure 2 Set up of the 1-axis force transducer. A single axis force transducer formed the connection between the arm cuff and the exoskeleton frame

Experimental set up

The required postures were obtained by aligning the arm to reference lines. Two video cameras recorded the shoulder angles: one through a glass wall, on which the preferred vertical elevation (VE) angles were taped, and one from overhead, facing down, looking at the horizontal abduction angles (HAb) (Figure 3C). The captured video was relayed to the participant monitored by two test leaders. Feet were placed, so that the lateral malleoli were directly underneath the acromion, as checked with a plumb line, putting the right shoulder joint center (SJC) approximately at the origin of the goniometer. To prescribe HAb, participants stood with their feet in line with the goniometer and aimed to position their arms, fully extended, such that they occluded the taped angle guide (the long black line, Figure 3 A,B,C) on the floor. Similarly, VE angles were observed through a glass wall, on which a reference for the desired shoulder angles was marked with tape. The angles were drawn and taped on the other side of the glass originating from the marked SJC on the participant's arm, as presented in Figure 3D. Participants aimed to position the arm so that the SJC marker aligned with the taped vertical reference line and the elbow marker was occluded by the taped angle, therefore aligning the body and arm in the specified VE angle.

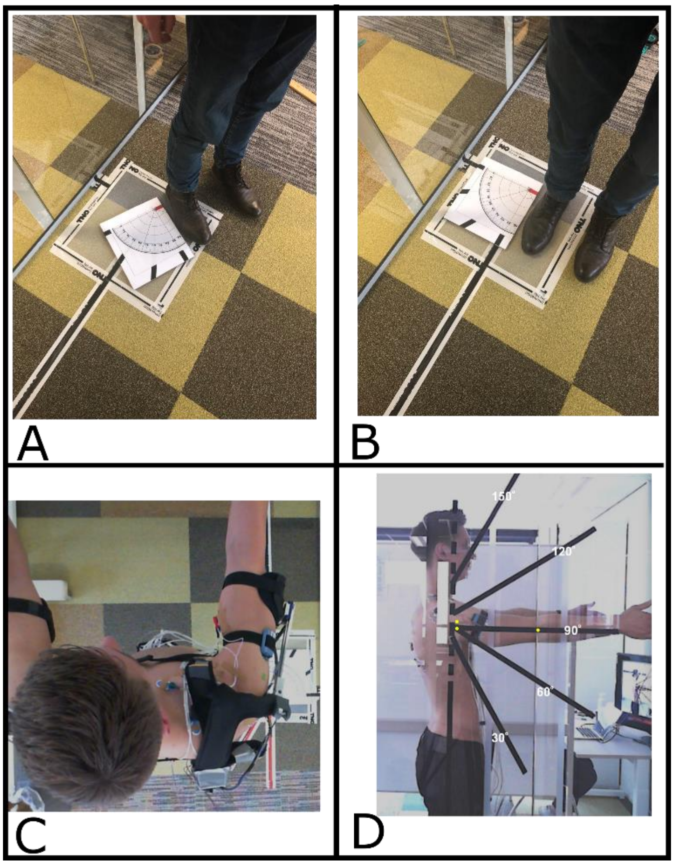

Figure 3 A. Goniometer to position body and prescribe shoulder HAb angle 60°. B: Goniometer to position body and prescribe shoulder HAb angle 0°. C: Camera perspective for the Hab angle. D: Camera perspective for the VE angle.

Procedures

Firstly, EMG electrodes were positioned according to SENIAM guidelines, with an inter-electrode distance of 20 mm. The skin was shaved and rubbed with alcohol wipes. We measured the following muscles on the right side of the body: Deltoid Anterior (DA), Deltoid Posterior (DP),Upper Trapezius (UT), Lower Trapezius (LT), Latissimus Dorsi (LD) and Biceps Brachii (BB).
Next, anthropometric measurements were obtained to estimate the inertial properties of the arm, necessary for estimating torque around the shoulder. The shoulder joint center (SJC) of the right arm was defined and marked on the subject as the point through which the axes of rotation run in both planes (sagittal and horizontal). When the arms were elevated, a vertical translation of the SJC marker occurred due to skin and muscle movement. Therefore, a second SJC was defined with the arm at 90° flexion to match recorded SJC height. The elbow joint was marked at the lateral epicondyle of the humerus. The markers at the shoulder and elbow were used as reference points that lined up with markers on the window.

Subsequently, participants were familiarized with the experimental equipment, the required postures and the fitting of the exoskeleton. During the experiment, participants performed a task in which they had to adopt a combination of five different vertical arm elevation levels (VE: 30°, 60°, 90°, 120° and 150°) and three horizontal abduction angles (HAb: 0°, 30°, 60°), with and without wearing the exoskeleton (Figure 3). All fifteen postures were adopted bilaterally.
The first six participants started the task with the exoskeleton, and the last six without. The order of postures within the task was systematically varied across participants. Postures were maintained for 10s followed by a break of 10s, in which the arm went back to a neutral position.
Maximal voluntary contraction (MVC) measurements were performed at the end of the experiment

to prevent a fatiguing effect on the static task. Three 5-second MVC measurements were performed against manual resistance provided by the investigators, similar to the proposals for upper body MVC test arrangements in Konrad (2006) and Al-Qaisi and Aghazadeh (2015), and with 10 seconds rest in between measurements. A recovery period of 3 minutes was maintained between different muscle MVC measurements.

Outcome measures

Shoulder moment

We are interested in the required joint moment that a subject needs to develop to keep their arm in a desired posture and whether this is affected by wearing an exoskeleton (M_{subj}). The total moment (M_{tot}) around the shoulder to oppose the pull of gravity was estimated from the obtained inertial parameters for all required shoulder angles (De Leva, 1996). The assumption was made that the elbow was fully extended at all times, as per instructions. The total joint moment was calculated for each VE angle and was assumed constant for every HAb angle. When wearing the exoskeleton, the total moment is the sum of the moment delivered by the participant and the moment provided by the exoskeleton (equation 1). The moment provided by the exoskeleton was calculated using force data obtained from the force sensor in the arm cuff (F_{exo}), and the moment arm, which was the distance from the SJC to this sensor (r_{exo}) times the sine of the VE angle (equation. 2). Without wearing an exoskeleton, the total moment equals M_{subj}

With Exo:

$$M_{tot} = M_{subj} + M_{exo} \qquad \textit{(eq. 1)}$$

$$M_{exo} = F_{exo} * r_{exo} * sin(VE) \qquad \textit{(eq. 2)}$$

The signals were trimmed by visually inspecting the force signal and selecting the constant phase of of each 10s static tasks. Mean force of each interval was then used to calculate the moment of the specific posture.

Muscle Activity

Followingly, they were trimmed to contain only the static portion of the task. The EMG signals were normalized to the MVC value for each muscle, which was obtained by determining the highest RMS value over 500ms time windows (Konrad, 2005). Finally, the mean muscle activation was obtained by calculating the RMS over the trimmed and normalized signal.
All digital processing and calculations were performed in MATLAB (The MathWorks Inc., Natrick, MA, USA).

Statistics

Statistical analyses were performed using SPSS (IBM SPSS Statistics v21.0.0), accepting significant differences at $p < 0.05$. Effects of wearing an exoskeleton on M_{subj} were analyzed using a three-way repeated measures ANOVA, with independent factors exoskeleton (Exo, 2 conditions: with and without), HAb (3 angles: 0°, 30°, 60°) and VE (5 angles: 30°, 60°, 90°,120°,150°). Additionally the effect of VE on M_{exo} was tested using a 2-way repeated measures ANOVA with independent factors

HAb and VE. This was done to explore the Exo * VE effect which was found in the ANOVA described above.
Finally, the effects of the exoskeleton on mean EMG amplitude between the two conditions in the static task were analyzed for each muscle (6 total) using a similar three-way ANOVA for repeated measures. Post hoc comparisons were done for the interaction effects that included the factor Exo, using Bonferroni corrections.

Results

Moment provided by the exoskeleton

Throughout all 15 measured postures, the exoskeleton provides a moment in the range of 0.5-6.1 Nm around the shoulder joint, which corresponds to 10.1 to 56.0% of the total required moment. A clear difference in M_{exo} over different VE angles was seen, with an optimum reached between 90 and 120 degrees. Horizontal abduction had a smaller effect

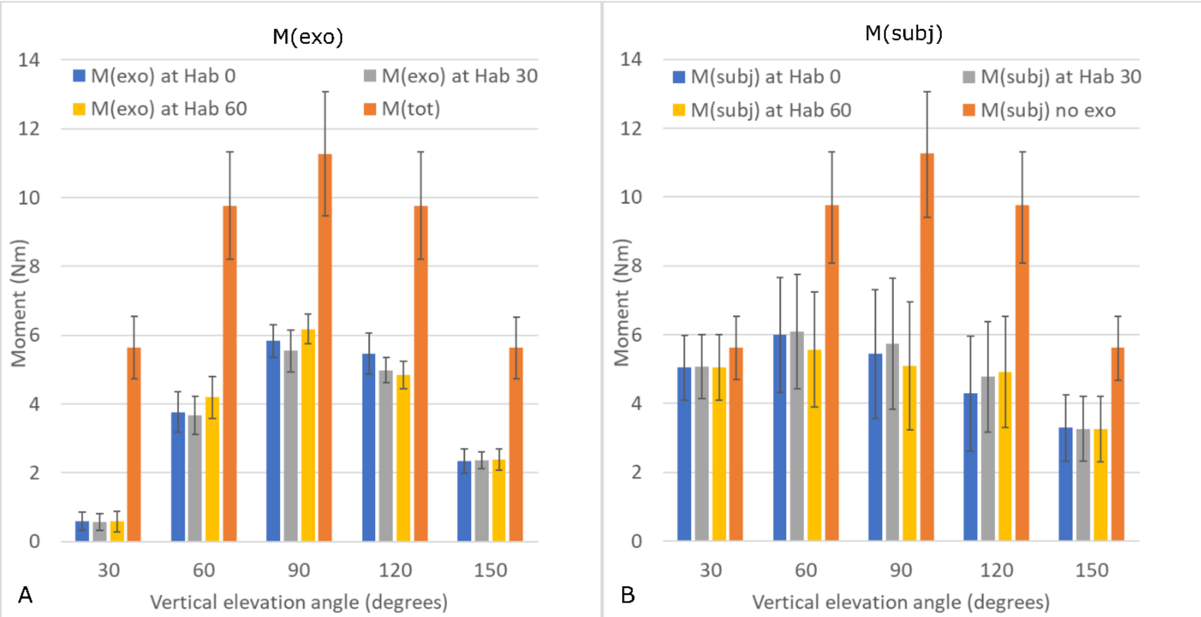

Figure 4A).

A larger supportive moment from the exoskeleton (M_{exo}), implies a reduced moment to be generated by the subject (M_{subj}). Repeated Measures ANOVA results on M_{subj} and interaction effects are presented in Table 1. To evaluate the nature of the interactions, post hoc comparisons of the interaction effect of Exo * HAb, Exo * VE, and Exo * HAb * VE were performed.
A significant three-way interaction of the factors vertical and horizontal shoulder angles and wearing an exoskeleton, was found. However, M_{subj} was mainly affected by VE angle and only slightly altered by the HAb angle. At VE angles 60° and 90°, M_{subj} was smallest at HAb 60°, followed by 0° and 30°. Whereas at VE 120°, respectively HAb 0°, next 30° and lastly 60° resulted in the smallest observed M_{subj}. For VE 30° and 150°, M_{subj} did not change significantly over different HAb angles.

Considering the Exo * VE interaction, it appears that the effect of exoskeleton on M_{subj} is significant in all VE conditions. However, it seems that the reduction in M_{subj} due to M_{exo} changes over VE angles. To test for which VE angles the difference in M_{exo} was significant, an additional 2 way ANOVA was performed on M_{exo}. It was found that M_{exo}, which was significantly affected by VE ($p<0.001$), is largest at 90° and 120° VE. Also, the reduction at 60 was significantly larger than the reduction at 0, while the reduction at 120 was larger than at 150. As a result, the range of M_{subj} across all postures became smaller when wearing an exoskeleton: 5.4-10.8 Nm in the without-exoskeleton condition decreases to 3.0 to 5.5 Nm in the with-exoskeleton condition (

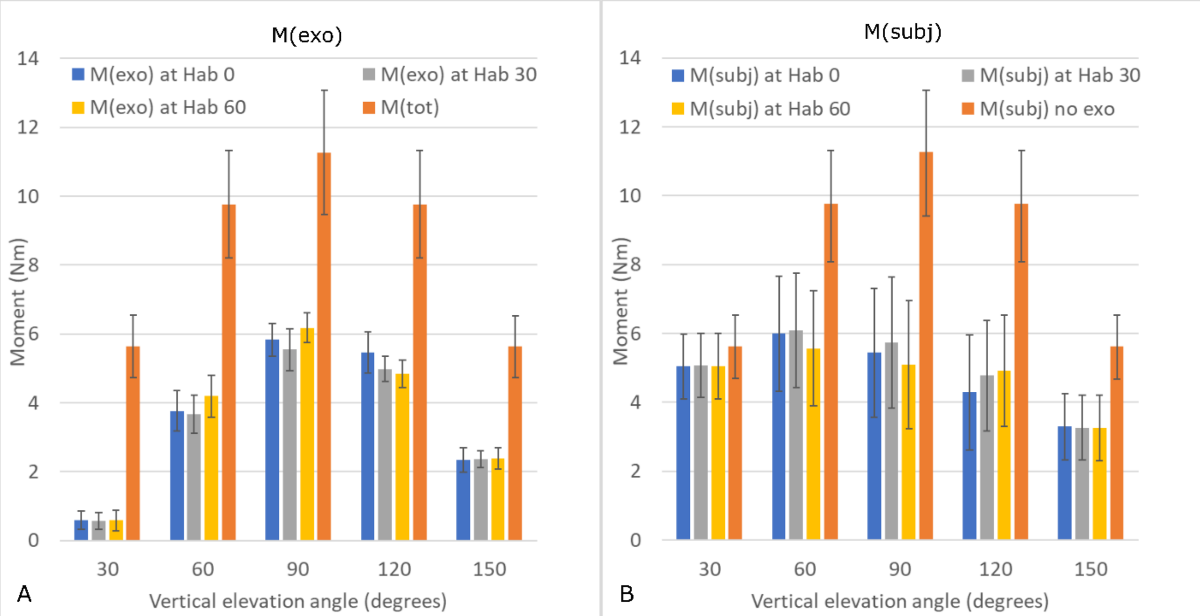

Figure 4B).

Regarding the Exo * HAb interaction, M_{subj} appeared to be reduced by the exoskeleton at all HAb angles. The interaction consisted of a small but significant variation in M_{subj} across different HAb angles, which was present in the with-exo condition, but absent in the without-exo condition.

Table 1 Three-way analysis of the effect of exoskeleton (Exo; with or without) and arm postures (HAb, VE) on the moment required from the subject M_subj.

Source	*p*
Exo	**<0.001**
HAb	**0.012**
VE	**<0.001**
Exo * HAb	**0.012**
Exo * VE	**<0.001**
HAb * VE	**<0.001**
Exo * HAb * VE	**<0.001**

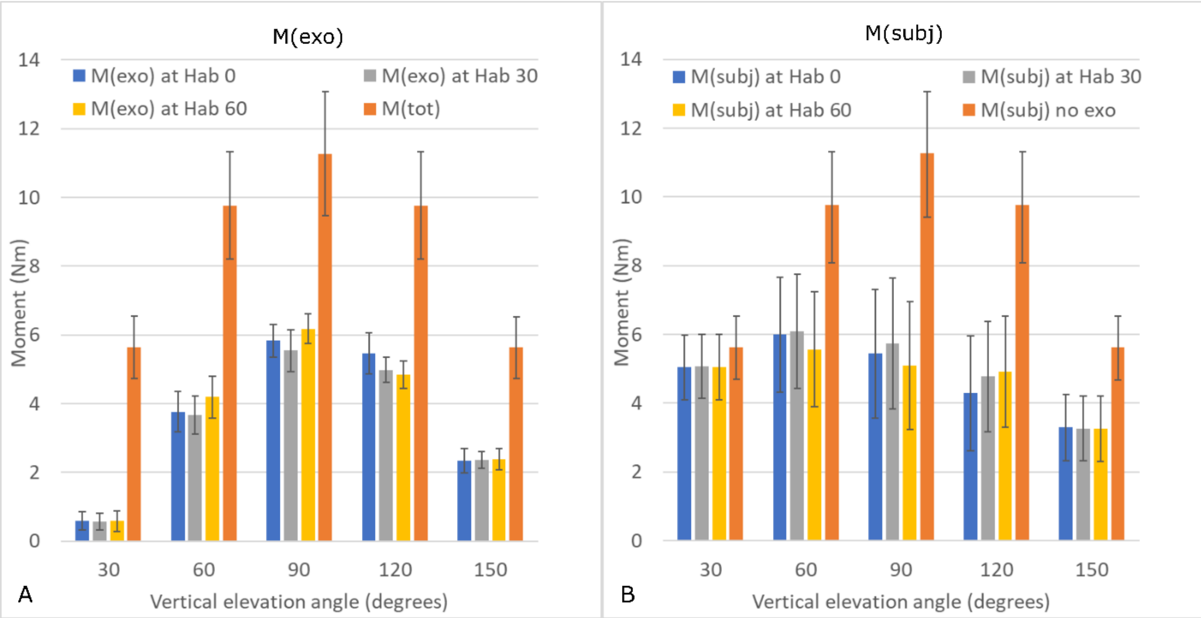

Figure 4A. The supportive moment provided by the exoskeleton in each combination of VE angle and HAb angle and the total moment (M_{tot}, which is calculated for each VE, but is assumed to be *constant across HAb.*
Figure 4B. The required moment from the subject (M_{subj}) to maintain the requested posture in the with and without exoskeleton condition.

Muscle activity

Table 2 shows the repeated measures ANOVA results of the effects of wearing an exoskeleton and of the different postures on the EMG amplitudes. For three muscles a significant main effect on muscle activity of the exoskeleton was found: When wearing the exoskeleton, EMG amplitudes were generally significantly lower for the muscles DA, UT, and LD.

The ANOVA showed interaction effects of exoskeleton * VE for the UT and LT muscles. Post-hoc tests for the UT muscle indicate that the effect of Exo was modified by the VE angle, such that the reduction in EMG amplitude was highest at VE 150° (mean difference of 12.60% MVC, p<.001) and was smallest and not significant at 30°. In contrast, for the LT muscle, post hoc tests on the interaction effects of Exo * VE, indicate that the effect of Exo was also modified by the VE angle, such that the reduction in EMG amplitude was highest at VE 60° (mean difference of 3.35% MVC, p=.026). Remarkably, we found for the LT muscle an increase in EMG amplitude as a result of wearing the exoskeleton at the vertical arm elevation angle of 150° (mean difference of 3.18% MVC, p=.043).

Table 2 Three-way Repeated Measures ANOVA results of the effect of exoskeleton (Exo; with or without) and arm postures (HAb, VE) on the muscle activity in different muscles.

Source	*DA*	*UT*	*DP*	*LT*	*LD*	*BB*
Exo	**0.002**	**<0.001**	0.644	0.078	**0.012**	0.322
HAb	0.504	**<0.001**	**0.001**	0.337	0.474	0.294
VE	**<0.001**	**<0.001**	**0.001**	**<0.001**	0.060	0.231
Exo * HAb	0.246	0.266	0.686	0.911	0.411	0.507

Exo * VE	0.550	**<0.001**	0.385	**0.009**	0.115	0.260
HAb * VE	0.420	0.082	0.275	**0.012**	0.328	0.121
Exo * HAb * VE	0.575	0.192	0.202	0.672	0.316	0.442

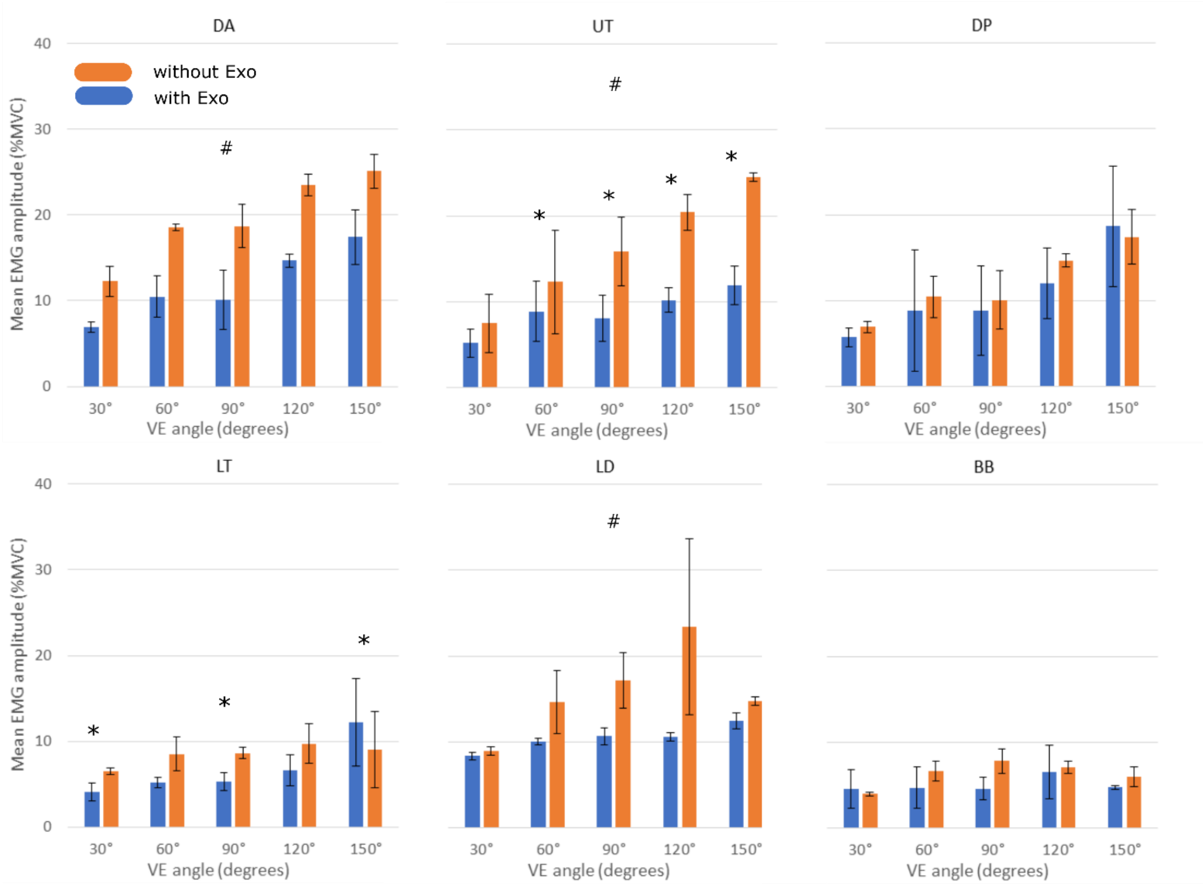

*Figure 5. Mean EMG amplitude (%MVC) over different VE angles, with and without the exoskeleton. HAb angles were averaged because no interaction effect between the exoskeleton conditions and HAb angle was found for any of the muscles. Significant main effects of the exoskeleton are indicated (#), as well as significant effects of exoskeleton conditions in case of Exo*VE interactions(*).*

Discussion

In this study we evaluated the effectiveness of a passive arm support exoskeleton on the shoulder moment and muscle activity across a range of arm elevation angles. Overall, we found that the moment support provided by the exoskeleton implied a significant reduction of the shoulder moment to be generated by the subject. This resulted in an overall reduction in muscle activity in three out of six muscles in the shoulder region. For three muscles, the effects were dependent on the arm position, particularly on the vertical arm elevation rather than the horizontal abduction.

Supportive moment

Regarding the supportive moment, it is essential to note that we used a passive exoskeleton, which provides support through a spring-like mechanism. This mechanism provides support over a limited angle range. We found that the supportive moment provided by this exoskeleton was highest at a VE angle of 90°, which is the elevation angle at which the largest total moment is required. Moreover,

the supportive moment was found to be lowest at the extremes, 30 and 150 degrees, where the required total moment tends to decrease. As a result of this, the variation in M_{subj}, over different VE angles, was lower in the with-exoskeleton vs. the without-exoskeleton condition.
Beside the range of effectivity, the size of the supportive moment depends on the characteristics of the spring-like mechanism. Across 60° to 120° VE, we found a supportive moment ranging from approximately 4 to 6 Nm, which corresponds roughly to 50% of the total required moment. Previously a study on the effect of changing the support setting of a passive exoskeleton from 0 to 20Nm showed that medium support settings were favorable based on antagonist muscle activity and subjective reports. (Van Engelhoven et al., 2018). The selected torque settings were not verified experimentally, or expressed relative to the required moment. To the authors knowledge, no other reports on the supportive moment of similar types of industrial exoskeletons have been published thus far.

Muscle activation

Regarding the exoskeleton effect on muscle activity, an overall significant reduction was found in the DA, UT and LD muscle. The effect on muscle activity was dependent on VE angle in the UT and LT muscles. For the UT it was found that the exoskeleton had the greatest reductions at the larger elevation angles. In contrast, for LT the largest VE angles resulted in a slightly higher, instead of lower, muscle activity in the with-exoskeleton vs. without-exoskeleton condition. However, the practical relevance of this effect is small, since the level of activity of the LT is rather low. A similar, but non significant increase of muscle activity at 150° in the with exoskeleton condition is seen for DP. DP is involved in horizontal abduction and this movement could become obstructed in extreme VE and HAb angles with the exoskeleton model that we tested. This obstruction could explain the (non-significant) increased muscle activity and the large standard deviation of the DP at the highest VE angles. The overall lower muscle activity of the DA and UT muscles in the with-exoskeleton condition can be explained by their agonist function in keeping the arms in an elevated posture, particularly at the larger VE and HAb angles (Platzer, 2000). Other agonist muscles, BB and DP, appear to be less active or show more variation, which could explain the absence of an exoskeleton effect on these muscles. The reduced LD activity in the with-exoskeleton condition could be explained by its stabilizing function in combination with a lower stabilization need when the exoskeleton is worn.

Previous studies also showed a reducing effect of an arm-support exoskeleton on the muscle activity of agonist muscles. In an overhead assembly task, (Van Engelhoven et al., 2018) and (Alabdulkarim & Nussbaum, 2019), reductions in muscle activity were also reported for the agonist muscles. Depending on the support settings of the exoskeleton and the investigated muscle, the reductions ranged from 18 – 80% (Van Engelhoven et al., 2018). The reduction is comparable to our findings, although, considering the lower supportive moment provided by the exoskeleton tested in our study, the reduction we found is relatively high.
Previous studies have also reported some increases in muscle activation in antagonistic muscles due to wearing an exoskeleton, for instance, of the Triceps Brachii and Infraspinatus (Van Engelhoven et al., 2018), and of the Iliocostalis Lumborum (Rashedi, Kim, Nussbaum, & Agnew, 2014).

Type of exoskeleton

In summary, the exoskeleton provides mechanical support and reduces the muscle activation of some agonist muscles, and these effects depend on vertical elevation angles. These effects depend on the type of the exoskeleton and its mechanical support settings (Alabdulkarim & Nussbaum, 2019), more specifically, the spring characteristics in passive exoskeletons and the actuators output in active exoskeletons (Sylla, Bonnet, Colledani, & Fraisse, 2014; Van Engelhoven et al., 2018). A selection of larger support settings might seem to be most effective, but actually turns out to become counterproductive, leading to more antagonistic muscle activity (Van Engelhoven et al., 2018).

(Huysamen et al., 2018) showed that the effectivity of an arm-support exoskeleton also depends on the type of task, e.g. the amount of weight carried in the hands. At higher weights, they increased the mechanical support setting and found larger reductions in muscle activity in some agonists.

Compared to active exoskeletons, passive exoskeletons are lighter, less complex, and interfere less with the wearer, which brings passive exoskeletons closer to being implemented in practice (de Looze et al., 2016). However a passive exoskeleton actuated by a spring mechanism, like the one used in the current experiment, only provides a supportive moment when the spring is put under tension. As a result, movements in the opposite direction to the force of the spring could require more effort. However, we did not see such effects in antagonist muscles, probably due to the fact that our task was static and the moment generated by the Exo was lower than the gravitational moment. It is therefore important to design the passive mechanism in such a way that the exoskeleton provides the desired support when it is most needed.

Active exoskeletons might cope better with dynamic requirements of support, especially when handling loads. Nonetheless, the development of active exoskeletons is still at an early stage, control algorithms need to be optimized and other aspects (limited freedom to move, weight of actuators, size of exoskeleton, and costs) still hinder acceptance in practice (de Looze et al., 2016). Additionally, active arm support exoskeletons for industrial applications are not readily available.

Limitations

We evaluated the exoskeleton in a lab setting with an artificial task, to study the effect over a wide range of shoulder postures. Further research is needed to evaluate the applicability of exoskeletons (from which the support characteristics are known) in real working situations.

EMG was investigated in this study, as is often done to evaluate the use of exoskeletons. A reduction in muscle activity is related to reduced strain in the muscle, on tendons and on ligaments. These may result in a reduction of the prevalence of work-related MSDs (Jaffar et al., 2011). The eventual effect of these type of exoskeletons on MSDs will only become apparent when they will be implemented and studied on a large scale. Another practically relevant effect of an exoskeleton might be the reduction of muscle fatigue. Due to the observed decrease in activity in various muscles, it can be expected that the time to fatigue or endurance time in elevated arm work would increase.

Finally, we cannot exclude that other antagonist muscles that we did not measure, such as the Pectoralis Major, may also become more active when wearing an exoskeleton at the highest elevation angles.

Practical implications

Our study shows the effectivity of a passive arm support exoskeleton throughout a range of postures. The results may help practitioners that are considering the adoption of an exoskeleton in the work place. The arm support exoskeleton that we tested clearly shows that the mechanical support reaches its maximum at the elevation angles ranging from 60° to 120° where the required support is also highest. In contrast, for elevation angles below 30 degrees, this exoskeleton provided significantly less support. Depending on the task, other support characteristics might be required. We advocate to adapt the mechanical support settings or effectivity range to the actual specific working envelop of postures.

A limitation of our study is that we involved static postures only, while in practice the work could be dynamic (e.g. plastering) or quasi-static (overhead assembly). Even in the last case though, a worker needs to move from one quasi-static-position to another. From our own experience with arm-support exoskeletons on the shop floor in factories, we know that the acceptance of exoskeletons is hindered when the device restricts or even opposes required movements.

Conclusion

The passive arm support exoskeleton that we evaluated in this study provides up to 50% of the required torque when keeping the arm elevated in a static position. The amount of support was dependent on the arm elevation angle, with the highest support at those arm postures where support is most needed. Furthermore, in most angles a reduction in muscle activity was seen, which might result in reduced fatigue on a short-term and reduced MSD prevalence rates on a longer term. However, in the smallest (30°) and largest elevation angles (150°) under investigation, the mechanical support was significantly less and muscle activity in some antagonistic or stabilizing muscles might have even increased. This emphasizes the importance of analyzing the task demands, such as working posture but also time aspects, when selecting and/or properly designing or adjusting arm support exoskeletons.

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