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Effects of the Auxivo CarrySuit occupational exoskeleton when carrying front and side loads on a treadmill

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ABSTRACT

Low-cost exoskeletons can effectively support workers in physically demanding jobs, but most such exoskeletons have been developed to support repetitive lifting or uncomfortable static postures. Very few low-cost exoskeletons have been designed to support walking while carrying heavy objects, which would be beneficial for jobs such as moving furniture and warehouse work. This paper thus presents a single-session lab evaluation of the Auxivo CarrySuit, a low-cost upper-body exoskeleton designed for carrying objects that would normally be held with the arms. Twenty participants carried four loads (box or two bags, 20 or 40 lb total weight) for 2 min each on a treadmill with and without the CarrySuit. Across all loads, the CarrySuit significantly reduced the mean electromyogram of the middle trapezius (partial eta-squared = 0.74 – from 16.1% to 8.8% of maximum voluntary contraction value) and anterior deltoid (partial eta-squared = 0.26 – from 3.0% to 1.1% of maximum voluntary contraction value) with no corresponding increase in lower back muscle activation. Furthermore, maximum heart rate and Ratings of Perceived Exertion were also reduced by the CarrySuit, and discomfort was shifted from the upper body to the legs. While arm EMG was not measured, it is likely that it was also reduced due to the unloading of the arms. The CarrySuit can thus be considered beneficial in the short term, though longer-term evaluations with actual workers are needed to determine practical benefits.

1. Introduction

The last few years have seen rapid development of low-cost exoskeletons for workers in physically demanding jobs such as airport baggage handling and warehouse work (Bär et al., 2021; Kermavnar et al., 2021). While exoskeletons are popularly seen as expensive motorized devices such as the Hybrid Assistive Limb (Suzuki et al., 2007), modern low-cost occupational exoskeletons instead rely on passive elements such as carbon fiber beams (Alemi et al., 2019), elastic bands (Goršič et al., 2022; Lamers et al., 2018) and springs (Huysamen et al., 2018) to store and release energy as well as redistribute loads onto other parts of the body. Such passive devices can be manufactured at a much lower cost than larger powered exoskeletons but can nonetheless achieve positive results. For example, when lifting heavy objects, low-cost occupational exoskeletons have been shown to reduce muscle activation and fatigue in the lower back during short-term lab studies (Alemi et al., 2019; Goršič et al., 2021; Koopman et al., 2020; Lamers et al., 2020; Luger et al., 2021), and have shown promising results in field trials (Yandell et al., 2020). By reducing the load on the lower back during lifting, such exoskeletons may thus help reduce the incidence of work-related musculoskeletal disorders (James et al., 2018; Swain et al., 2020) and thus broadly improve human quality of life.

Most low-cost occupational exoskeletons have been developed to support repetitive lifting tasks (e.g., loading luggage onto an airplane, loading boxes onto shelves) (Alemi et al., 2019; Goršič et al., 2022; Lamers et al., 2018; Luger et al., 2021), uncomfortable static postures (e.g., overhead work, leaning) (Goršič et al., 2022; Lamers et al., 2018), and unencumbered gait (Goršič et al., 2020). However, to the best of our knowledge, very few low-cost exoskeletons have been designed to support walking while carrying heavy objects, which would be beneficial for jobs such as moving furniture and warehouse work. The U. S. Bureau of Labor Statistics has found that jobs involving carrying heavy objects commonly result in occupational injury/illness and require time away from work due to overexertion (U.S. Bureau of Labor Statistics, 2016),

Abbreviations: AD, anterior deltoid; BPD, Body Part Discomfort Scale; EMG, electromyography; ES, erector spinae; HR, heart rate; MT, middle trapezius; MVC, maximum voluntary contraction; RA, rectus abdominis; RMANOVA, repeated-measures analysis of variance; RMS, root mean square; RPE, Rate of Perceived Exertion.

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emphasizing the need for support. However, our previous evaluations showed that low-cost occupational exoskeletons designed for lifting were not beneficial when walking while carrying objects (Goršič et al., 2021, 2022). While powered exoskeletons for carrying (rather than lifting) heavy loads do exist (Mooney et al., 2014; Walsh et al., 2007), they are not occupational exoskeletons and are heavier and more expensive than low-cost unpowered devices. Thus, new and different exoskeleton technologies are needed to effectively and affordably support carrying.

In this paper, we focus on, to our knowledge, the first commercially available passive upper-body occupational exoskeleton for carrying heavy objects: the CarrySuit by Auxivo AG (Schwerzenbach, Switzerland). As a fully passive device, it achieves lower cost and weight than battery-powered devices (Mooney et al., 2014; Walsh et al., 2007); furthermore, its upper-body occupational design (which focuses on carrying objects with the arms) makes it differ from military exoskeletons that focus on trunk-worn loads such as backpacks (Diamond-Ouellette et al., 2022). The CarrySuit could therefore achieve broad adoption in diverse fields as well as encourage development of other similar devices – but only if it shows positive effects. We thus conducted a first lab evaluation of the CarrySuit's effects while carrying front and side loads on a treadmill for brief periods of time. Our goal was to determine whether the CarrySuit reduces muscle activation and overall exertion in laypersons without detrimental side-effects such as discomfort or shifting load to other muscles, both of which had been observed in our prior work with other devices (Goršič et al., 2020). Such evaluations with laypersons and simple lab tasks are common in first studies of an exoskeleton to establish its feasibility before moving to tests with actual workers in occupational environments (Bär et al., 2021; Kermavnar et al., 2021). We hypothesized that the CarrySuit would significantly reduce heart rate (HR) and middle trapezius (MT) electromyogram regardless of type or weight of load, and that there would be no significant increase in erector spinae (ES) or rectus abdominis (RA) EMG.

2. Materials and methods

2.1. Participants

Twenty participants (9 women, 11 men) with no history of chronic back pain or back injury were recruited from the student and employee population of the University of Cincinnati. They were 23.7 ± 5.7 (mean ± standard deviation) years old (range 19–37), with heights of 171.9 ± 11.6 cm (range 153–189) and masses of 73.3 ± 18.8 kg (range 54–133). One participant was left-handed. The sample size was selected based on review papers in the area of occupational exoskeletons (Bär et al., 2021; Kermavnar et al., 2021), which found very few studies with more than 20 participants. Exclusion criteria were: under 18 years old, allergy to latex/adhesives, pregnancy, chest/waist size above 5XL, inability to walk or lift objects, or a history of any of the following: spinal cord injury, heart attacks/surgery/failure, stroke, traumatic brain injury, chronic obstructive pulmonary disease, unreasonable breathlessness, spinal osteoporosis, spinal metastases, recent trunk/leg surgery, or any other degenerative spinal disorder or neurological disorder that affects spinal neurons.

2.2. Auxivo CarrySuit

A participant wearing the CarrySuit is shown in Fig. 1. Per the manufacturer, the exoskeleton is intended for loads that would normally be carried with the hands. The load should be transferred by the exoskeleton directly to the trunk and partly directly to the hip, thus unloading the upper extremities and the spine.

The device weighs 5.6 kg and comprises a rigid upper-body

Fig. 1. A participant wearing the Auxivo CarrySuit (Auxivo AG, Switzerland): front, back and side views. The participant is also wearing the sensors used in the study: a heart rate wristband and electromyography sensors on the shoulders, lower and upper back (not visible).

exoskeleton frame that can be adjusted in length to fit the user from hips to slightly above shoulder height. Adjustable straps around the hip level can be tightened at the abdomen and low back so that most of the exoskeleton weight sits on the user's hips. A soft weblike material between the user's back and the rigid frame stretches from the low back to the shoulders and connects with the shoulder straps on the sides. Another strap is used at chest level to fit and stabilize the upper part of the exoskeleton.

To carry loads, two adjustable-length straps are attached to the frontal part of the shoulder straps. These have hooks at the end that can be used to carry loads directly (Fig. 2 and Fig. 3) or be further extended with special attachments for specific load types. These special attachments were not used in our study.

2.3. Study protocol

The study was approved by the University of Cincinnati Institutional Review Board, protocol #2021–1099. Each participant took part in one ~ 90-minute session. The CarrySuit was demonstrated, the study was explained, the participant gave informed consent, and demographic data were collected. The exoskeleton was then fitted to the participant following manufacturer instructions. A twenty-pound box was attached to the exoskeleton, and participants carried the box on the treadmill for a few minutes to get comfortable with the setup and determine their preferred walking speed. They were asked to choose a comfortable speed between 1 and 2 miles/h. During this time, any reported comfort issues were addressed via exoskeleton adjustments. EMG electrodes (section 2.4) were applied, participants completed maximum voluntary contraction (MVC) tests for all evaluated muscles, and an E4 HR wristband was attached.

Data collection was done in two blocks: one with the exoskeleton and one without it, with half the participants performing the exoskeleton block first. Each block consisted of four 2-minute tasks performed at the participant's preferred walking speed:

- carrying a plastic box with handles and a 20-lb weight in it, in front of the body at waist level,
- carrying the same box with a 40-lb weight in it,
- carrying two plastic bags with a 10-lb weight in each, one on each side/using both hands,
- carrying the same bags with a 20-lb weight in each.

When carrying objects without the exoskeleton, participants were told to hold the box by the handles around waist level and to hold the bags by the handles. Photos of participants carrying loads with the exoskeleton are shown in Fig. 2 (box) and Fig. 3 (bags). Transitions between tasks were done as quickly as possible; changing load weight took about 10 s while changing load type (detaching bags and attaching box or vice-versa) took about 30 s.

There was a 10-minute break between the two blocks where participants sat down and rested. The order was counterbalanced so that half of the participants performed the exoskeleton block first. All sensors were checked before the second block and adjusted as needed. EMG was continuously monitored; if signal quality was poor due to electrode movement, the corresponding electrode was reattached before the next task; this occurred during two task transitions across all participants. Participants rated their perceived exertion after each task and their perceived discomfort after each 40-lb task (section 2.4). After the second block, all sensors were removed, participants were asked about their overall subjective experience, and a $25 gift card was given.

Fig. 2. A participant carrying the box with the exoskeleton on the treadmill, front and side views.

Fig. 3. A participant carrying the bags with the exoskeleton on the treadmill, front and side views.

2.4. Measurements

Three measurement types were taken: HR, EMG and self-report ratings.

HR signals were measured using the E4 wristband (Empatica Inc., Boston, USA). Mean and max HR was calculated over each block, as HR responses to individual task demands may be delayed.

EMG was measured from the left and right RA, ES, MT and anterior deltoid (AD) using the Trigno Avanti wireless system (Delsys Inc, Boston, MA) at 1926 Hz. The Avanti system consists of reusable bipolar electrodes with a 10-mm interelectrode distance. The skin was cleaned and shaved if needed, and electrodes were placed following SENIAM recommendations (Hermens et al., 1999): for RA, 3 cm from midline of abdomen and 2 cm above umbilicus; for ES, at L3 height, approximately 4 cm left and right from midline of spine; for MT, at 50% between medial border of scapula and spine, at T3 level, in direction of line between T5 and acromion; for AD, at one finger width distal and anterior to acromion, in direction of line between acromion and thumb.

All self-report scales were described orally by the experimenter just before data collection, and all answers were given orally on discrete numeric scales. Reminders about scale definitions were given as needed. The scales were:

- After each task, participants self-reported perceived exertion on the Rate of Perceived Exertion (RPE) scale (Day et al., 2004) between 0 (nothing at all) and 10 (very, very heavy), with 1 representing very light, 3 moderate, 5 heavy and 7 very heavy.
- After each 40-lb task (box or bags), participants completed the Body Part Discomfort Scale (BPD) (Corlett & Bishop, 1976). They were shown a chart of body regions and pointed at regions with any discomfort; they then rated discomfort in each region between 1 (mild) to 5 (severe). While the original BPD has separate regions for the left and right thigh, these were combined for our study due to the symmetry of the tasks; the same was done for leg regions.
- After completing both blocks, participants rated how much effort it took to perform tasks with the exoskeleton relative to no exoskeleton. Answers were given on a scale from + 5 (much easier with exoskeleton) to −5 (much easier without), with 0 representing no difference and ± 1 and ± 3 representing mildly and moderately easier. This is an ad-hoc scale used in our previous exoskeleton studies (Goršič et al., 2021, 2022).

Finally, participants were asked to describe any good things about the exoskeleton, any bad things about it, and any other comments.

2.5. Signal processing for EMG

EMG signals were segmented into individual 2-minute task intervals. Each signal segment was visually inspected for artifacts: sections of the signal where the amplitude was over ~ 300% of MVC value, indicating electrode motion. If artifacts were present for more than half of a task interval, that EMG signal was discarded for that interval. If they were present for less of that time, sections with artifacts were removed and analysis was done on the remaining signal.

Signals were zero-phase filtered with a fourth-order Butterworth bandpass filter (20–450 Hz), rectified, and zero-phase filtered with a fourth-order Butterworth 10-Hz lowpass filter to obtain linear envelopes. RMS and mean envelope values were calculated over the 2-minute interval, then divided by maximum values obtained during corresponding MVC tests. Finally, since the tasks involve symmetrical loads, RMS and mean values of the left and right muscle were averaged. This resulted in eight EMG outcome variables per task: RMS and mean EMG of 4 muscles (RA, ES, MT, AD). For full disclosure, we also performed a second analysis where RMS and mean EMG of the left and right muscle were analyzed separately but found very similar results and thus do not report them.

2.6. Statistical analysis

All statistical tests were done using SPSS Statistics 28 (IBM Corporation, Armonk, NY).

For EMG and RPE, three-way repeated-measures analyses of variance (RMANOVA) were done for each outcome variable. Each RMANOVA had three two-level factors: presence of exoskeleton (with/without), load type (box/bags) and load weight (20/40 lb). For each RMANOVA, significance and effect size (partial eta-squared – $p\eta^2$) are reported for all main and interaction effects.

For HR, paired t-tests were used to compare maximum and mean HR between no-exoskeleton and exoskeleton blocks.

For the ad-hoc scale of how much effort it took to perform tasks with the exoskeleton, a one-sample *t*-test was used to compare ratings to a mean of zero. Discomfort ratings were reported descriptively.

3. Results

Two participants dropped the load in the 40-lb bag task before the 2-minute interval ended (one with, one without exoskeleton), but enough data were acquired to still include them in analysis. In 8 task intervals across all participants, EMG data of one muscle were discarded due to artifacts, and data from the other muscle of the same type were used without left–right averaging. No significant deviations from normal distributions were found in the data, supporting the use of three-way RMANOVA.

3.1. EMG

RMANOVA results are presented in Table 1. Main effects of the exoskeleton were observed for the MT and AD. Averaging across all participants and all load types/weights:

- MT RMS EMG: 18.1 ± 9.8 % of MVC value without exoskeleton, 9.9 ± 5.4 % with it,
- MT mean EMG: 16.1 ± 8.8 % of MVC without exoskeleton, 8.5 ± 4.7 % with it,
- AD RMS EMG: 4.0 ± 2.8 % of MVC without exoskeleton, 1.6 ± 1.8 % with it,
- AD mean EMG: 3.0 ± 2.1 % of MVC without exoskeleton, 1.1 ± 0.8 % with it.

Figs. 4 and 5 show mean EMG in all tasks for the MT (Fig. 4) and AD (Fig. 5).

Interaction effects of exoskeleton * load weight were observed only for the MT. Averaging MT results across all participants and both load types:

- RMS EMG for 20 lb: 12.5 ± 5.0 % of MVC without exoskeleton, 8.1 ± 4.2 % with it,
- RMS EMG for 40 lb: 23.6 ± 10.2 % of MVC without exoskeleton, 11.7 ± 5.9 % with it,

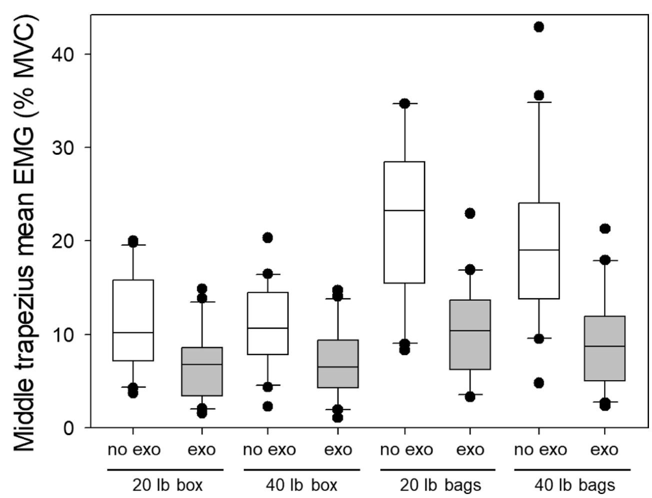

Fig. 4. Mean middle trapezius electromyogram (EMG) in all tasks, expressed as percentage of maximum voluntary contraction (MVC). The middle bar represents the median, top and bottom box edges represent 25th and 75th percentiles, whiskers extend to the most extreme observation within 1.5 times interquartile range from the nearest quartile, and circles represent individual outliers. Repeated-measures analysis of variance indicates a main effect of the exoskeleton and an interaction effect of exoskeleton * load weight.

Table 1
Results of repeated-measures analyses of variance on mean and root-mean-square values of electromyogram envelopes for all four muscles. Presented as p-values and partial eta-squared ($p\eta^2$) values for three main effects (exoskeleton, load type, load weight) and interaction effects. Results with $p < 0.05$ are bolded.

	rectus abdominis				erector spinae				middle trapezius				anterior deltoid			
	mean		RMS		mean		RMS		mean		RMS		mean		RMS	
	p	Pη^2	p	pη^2	p	pη^2	p	pη^2	p	pη^2	p	pη^2	p	pη^2	p	pη^2
exoskeleton	0.97	0.00	0.77	0.01	0.87	0.00	0.96	0.00	**<0.001**	**0.74**	**<0.001**	**0.71**	**0.02**	**0.26**	**0.02**	**0.25**
load type	0.51	0.02	0.47	0.03	**<0.001**	**0.88**	**<0.001**	**0.85**	0.06	0.17	0.14	0.11	0.11	0.13	0.06	0.18
load weight	**0.03**	**0.22**	**0.047**	**0.19**	**<0.001**	**0.79**	**<0.001**	**0.76**	**<0.001**	**0.83**	**<0.001**	**0.80**	**0.02**	**0.26**	**0.01**	**0.37**
exo * type	0.70	0.01	0.39	0.04	0.51	0.02	0.32	0.05	0.16	0.10	0.34	0.05	0.74	0.01	0.31	0.06
exo * weight	0.16	0.10	0.77	0.01	0.41	0.04	0.24	0.07	**<0.001**	**0.61**	**<0.001**	**0.59**	0.08	0.15	0.82	0.00
type * weight	0.95	0.00	0.75	0.01	**0.02**	**0.25**	**0.03**	**0.22**	**0.01**	**0.30**	0.051	0.19	0.78	0.00	0.94	0.00
3-way	0.08	0.15	**0.02**	**0.11**	**0.049**	**0.19**	**0.03**	**0.22**	0.44	0.03	0.49	0.03	0.59	0.16	0.68	0.01

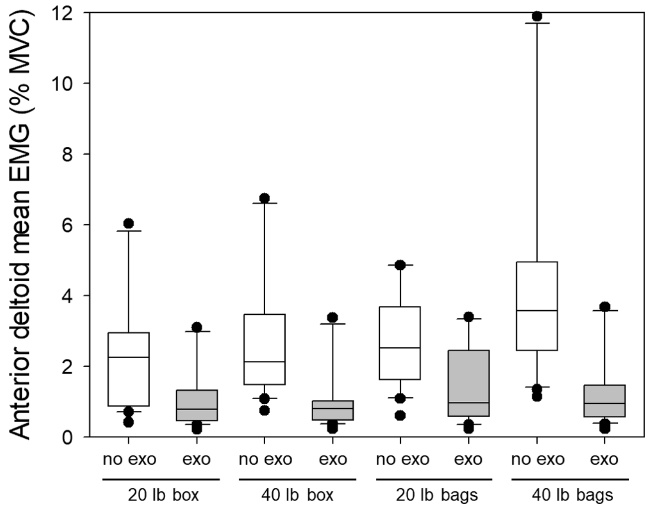

Fig. 5. Mean anterior deltoid electromyogram (EMG) in all tasks, expressed as percentage of maximum voluntary contraction (MVC). The middle bar represents the median, top and bottom box edges represent 25th and 75th percentiles, whiskers extend to the most extreme observation within 1.5 times interquartile range from the nearest quartile, and circles represent individual outliers. Six outliers above 12% of MVC were truncated. Repeated-measures analysis of variance indicates a main effect of the exoskeleton and no exoskeleton interaction effects.

- mean EMG for 20 lb: 11.1 ± 4.7 % of MVC without exoskeleton, 6.9 ± 3.7 % with it,
- mean EMG for 40 lb: 21.1 ± 9.2 % of MVC without exoskeleton, 10.0 ± 5.0 % with it.

Finally, no interaction effects of exoskeleton * load type were observed, indicating that the load type (box or bag) did not change the exoskeleton's effect.

3.2. Heart rate

Maximum HR was 110.4 ± 12.2 beats/min during the no-exoskeleton block and 103.0 ± 10.4 beats/min during the exoskeleton block; the difference was significant ($p = .005$). Mean HR was 89.9 ± 4.9 beats/min during the no-exoskeleton block and 87.5 ± 4.6 beats/min during the exoskeleton block; the difference was not significant ($p = .103$).

3.3. Self-report ratings

For the ad-hoc scale of how much effort it took to perform tasks with the exoskeleton vs. no exoskeleton, ratings were 2.0 ± 2.0, indicating mild to moderate exoskeleton assistance; the rating was significantly different from zero ($p < .001$).

For RPE, the 3-way RMANOVA found significant main effects of the exoskeleton ($p = .037$, $p\eta^2 = 0.22$), load type ($p = .001$, $p\eta^2 = 0.49$) and load weight ($p < .001$, $p\eta^2 = 0.90$) as well as an interaction effect of exoskeleton * weight ($p = .003$, $p\eta^2 = 0.40$). RPE values in each task are shown in Fig. 6.

For the BPD, Table 2 shows how many participants reported any discomfort in each region. For an illustration of how discomfort shifts as a result of the exoskeleton, Table 3 shows discomfort ratings during box carrying for participants who reported discomfort.

3.4. Final subjective impressions

When asked to describe good things about the CarrySuit, the most common topics were:

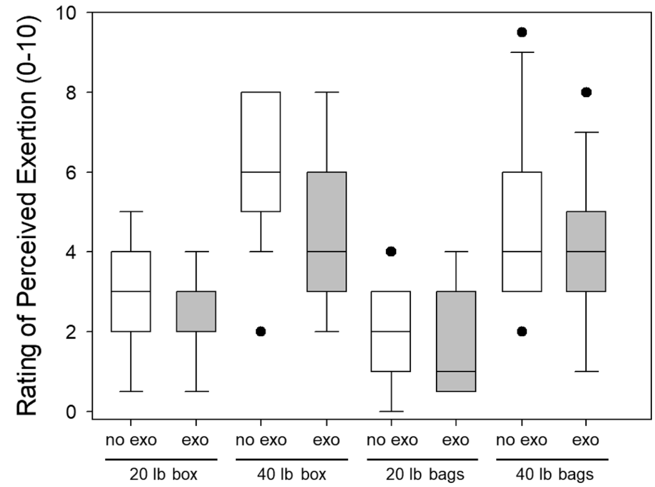

Fig. 6. Ratings of Perceived Exertion in all tasks. The middle bar represents the median, top and bottom box edges represent 25th and 75th percentiles, whiskers extend to the most extreme observation within 1.5 times interquartile range from the nearest quartile, and circles represent individual outliers. Repeated-measures analysis of variance indicates a main effect of the exoskeleton and an interaction effect of exoskeleton * load weight.

- it took weight off the shoulders, arms, neck (mentioned by 10 participants),
- helpful, better support, easier to carry loads (7 participants),
- it felt nice, more comfortable (4 participants).

Notably, one participant stated: "nothing, easier to carry with my hands".

When asked to describe bad things about the Carrysuit, the most common topics were:

- uncomfortable/painful/tight around hips (9 participants),
- awkward/difficult to walk with (4 participants),
- too much weight on legs (3 participants).

Notably, one participant stated: "not that great for carrying bags but great for the box".

When asked for any other comments, participants mentioned:

- bags can swing around, affecting stability (3 participants),
- exoskeleton transfers all load to legs, which feels unfamiliar (3 participants),
- more helpful for heavier loads (2 participants).

4. Discussion

The CarrySuit reduced EMG of the MT and AD and thus offloaded the shoulders and upper back; mean EMG reductions were from approximately 16% to 9% of MVC value for the MT and from approximately 3.0% to 1.1% of MVC value for the AD. Arm EMG should also be significantly reduced since the load was transferred off the arms entirely, but this was considered obvious and thus not measured. As another positive of the suit, there was no increase in ES or RA EMG, which would have been expected if the load had been shifted to the lower back. It is admittedly likely that EMG of the hip and leg musculature was increased (as suggested by subjective impressions and increased discomfort in those areas), but this was also not measured – primarily since the Trigno Avanti only has 8 channels. However, even if load was shifted to the hips and legs, overall exertion appeared to still have been reduced by the CarrySuit since RPE values and maximum HR (a common indicator of physiological strain (Bär et al., 2021)) were reduced.

The effects of the CarrySuit, however, are not equal for all

Table 2
The number of participants who reported any discomfort (i.e., above 0) on the Body Part Discomfort Scale in each region and during each 40-lb task.

		neck	shoulder	upper arm	lower arm	upper back	mid back	lower back	buttocks	thighs	legs
no exo	box	2	9	13	14	2	0	0	2	5	3
	bags	5	11	7	14	2	0	0	1	1	1
with exo	box	0	3	0	0	0	0	9	13	13	4
	bags	0	2	0	0	0	1	5	12	9	6

Table 3
Means ± standard deviations of Body Part Discomfort Scale ratings during box carrying, averaged only across participants who reported more than zero discomfort. N/A indicates that no participant reported discomfort in that region in that block. Standard deviations are calculated only when 4 or more participants reported discomfort.

	no exoskeleton	exoskeleton
neck	1.5	N/A
shoulder	2.1 ± 1.4	1.7 ± 0.6
upper arm	3.3 ± 1.1	N/A
lower arm	3.1 ± 1.3	N/A
upper back	2.0	N/A
lower back	N/A	2.7 ± 0.7
buttocks	2.0	2.8 ± 0.9
thighs	1.8 ± 0.8	2.5 ± 1.3
legs	2.0 ± 1.0	2.8 ± 1.5

participants. For example, while maximum HR was overall reduced, three participants exhibited higher maximum HR with the CarrySuit; two of them had negative comments about the exoskeleton ("easier to carry with my hands"). There was no clear relationship between maximum HR changes and other variables. The experimenter did feel that stronger participants seemed less positive about the CarrySuit (as they could carry the load on their own and thus found the exoskeleton "strange"), but this was a subjective observation not supported by data.

4.1. Next steps

The next step would be to test the CarrySuit with actual end-users: people whose jobs involve carrying heavy objects and who thus have more muscle strength and more carrying experience than our current sample of novices. Such evaluations should also be done in work-related scenarios such as ascending/descending stairs, which are common for workers such as movers. They should include heavier loads (e.g., 50 lb) and potentially asymmetric loads where the EMG of the left and right side would be expected to be different.

Furthermore, future evaluations should be done over longer time periods to evaluate effects of habituation or fatigue. We did perform follow-up analyses of the current data to search for effects of time; for example, we used another RMANOVA to check if EMG was different between the first and second block in the session. We found no significant effects of time and thus do not report these results in this paper, but previous work with other exoskeletons has shown such effects (Diamond-Ouellette et al., 2022; Goršič et al., 2022), and this should be investigated in further CarrySuit work. The CarrySuit may actually be considered more beneficial over longer periods where fatigue without the exoskeleton may become more noticeable.

Finally, future evaluations should measure EMG of the lower extremities, as our results do indicate that the load was likely shifted to hip and leg musculature. While measurements of more than 8 EMG channels are not common in the field (Bär et al., 2021; Kermavnar et al., 2021), future studies could potentially measure lower limb EMG with the same number of channels by omitting RA EMG. In the current study, RA EMG was not affected by the exoskeleton and was generally low - mean EMG across participants was below 6% of MVC value in all eight tasks.

4.2. Exoskeleton-load interface

The CarrySuit's hooks must be attached or removed from the carried object whenever the object is lifted or set down; even with practice, our experimenter needed 10–20 s to attach/remove them. This may make the device less popular for occupations where objects are only carried for short distances, as the additional hooking/unhooking time may make the process slower overall. The hooks (and other attachments) may also not be suitable for all objects. Our box included holes through which hooks could be placed, but other loads may not have convenient attachment points, thus requiring additional effort to use with the CarrySuit. Finally, objects attached to hooks may modify gait kinematics; for example, in our case, we found that the bags would swing freely from the hooks while walking and that participants thus tended to keep their hands on the side of the bags to stabilize them.

However, this is not necessarily a limitation of the CarrySuit specifically - it is likely a limitation of any passive exoskeleton designed for carrying heavy loads. Passive exoskeletons for lifting avoid this issue by providing support only via elements built into the exoskeleton itself (Alemi et al., 2019; Goršič et al., 2022; Lamers et al., 2018), but any exoskeleton for carrying would likely require some interface between the exoskeleton and the load in order to shift loading from the arms to the trunk. It is thus necessary to develop general usability improvements to this interface.

4.3. Conclusion

The CarrySuit reduced EMG of the MT and AD and thus successfully offloaded the shoulders and upper back; mean EMG reductions were from approximately 16% to 9% of MVC value for the MT and from approximately 3.0% to 1.1% of MVC value for the AD. While arm EMG was not measured, it was likely also reduced due to the unloading of the arms. There was no increase in ES or RA EMG, indicating that load had not been shifted to the lower back where it could have caused injury. While the load was likely shifted to hip and leg musculature, the lower RPE and lower maximum HR indicate that overall exertion was nonetheless reduced by the CarrySuit. Thus, the exoskeleton can be considered beneficial in the short term.

As the next step, longer-term evaluations with actual workers are required to determine the practical usefulness of the exoskeleton. Additionally, further improvements could be made to the exoskeleton-load interface, which requires hooks to be attached and removed whenever an object is picked up or set down. However, if our results generalize to more realistic settings, the CarrySuit and other similar devices may eventually become broadly adopted in jobs such as construction and logistics. The design features seen in the CarrySuit could also be combined with features seen in devices for lifting heavy objects, thus eventually creating versatile multifunctional occupational exoskeletons that could effectively support workers and reduce the rate of work-related injuries and illnesses.

CRediT authorship contribution statement

Maja Goršič: Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology. **Vesna D. Novak:** Conceptualization, Funding acquisition, Data curation, Writing – original draft, Writing – review &

editing, Visualization, Formal analysis, Methodology, Supervision, Resources, Project administration, Software.

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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