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Title

Using passive or active back-support exoskeletons during a repetitive lifting task: influence on cardiorespiratory parameters.

Authors

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Abstract

The objective of this laboratory study was to assess the cardiorespiratory consequences related to the use of different back-support exoskeletons during a repetitive lifting task. Fourteen women and thirteen men performed a dynamic stoop lifting task involving full flexion/extension of the trunk in the sagittal plane. This task was repeated for 5 min with a 10 kg load to handle. Four conditions were tested: with a passive exoskeleton (P-EXO), with two active exoskeletons (A-EXO1 and A-EXO2), as well as without exoskeleton (FREE). The

oxygen consumption rate and cardiac costs were measured continuously. Results showed a significant reduction in the oxygen consumption rate for all exoskeletons as compared to FREE. This reduction was significantly more important for A-EXO1 (~28%) compared to A-EXO2 (~13%) and P-EXO (~7%). Compared to FREE, the cardiac cost was only reduced for A-EXO1 (~24%). Several factors can explain these differences on the cardiorespiratory parameters observed between exoskeletons: the technology used (passive vs active), the torque provided by the assistive device, the weight of the system, but also the level of anthropomorphism (related to the number of joints used by the exoskeleton). Our results also highlighted the lack of interaction between the exoskeleton and sex. Thereby, the three back-support exoskeletons tested appeared to reduce the overall physical workload associated with a repetitive lifting task both for men and women.

Key words

Heart rate, Oxygen consumption, Sex, Workload, Wearable assistive devices.

1. Introduction

Manual handling tasks are generally associated with a high physical workload (Mehta et al. 2014). For example, lifting tasks are known to induce exaggerated biomechanical strains on the back and cardiovascular demand. Many workers involved in this kind of task thus remain exposed to risks of development of low-back pain (Brandt et al. 2018) and cardiovascular diseases (Holtermann et al. 2021). New technologies, such as occupational back support exoskeletons, have been specifically designed to reduce the workload of the task performed by workers (de Looze et al. 2016; Theurel and Desbrosses 2019; Kermavnar et al. 2021). Such systems provide an assistance to the movement, by using deformable materials storing energy like springs or elastic textiles (i.e. passive exoskeletons), or by using robotic motors (i.e. active exoskeletons).

Several studies have shown that back-support exoskeletons can reduce stress on the lower-back muscles during handling tasks (de Looze et al. 2016; Theurel and Desbrosses 2019; Kermavnar et al. 2021). In a recent review, Kermavnar et al. (2021) reported average decreases in lower-back muscle activity during dynamic handling tasks of 18 and 25%, for passive and active exoskeletons, respectively. The relative decreases observed in muscle activity were nevertheless strongly variable (from 6 to 48%), notably depending on the exoskeleton design: for example, the assistive technologies used (passive versus active) (Madinei et al. 2020; Yin et al. 2021), the

structure of the exoskeletons – textile versus rigid (Schwartz et al. 2021) – or the stiffness of assistance (Frost et al. 2009). Moreover, the use of a back-support exoskeleton can lead to many undesired modifications during handling tasks (Kermavnar et al. 2021; Theurel and Desbrosses 2019) on the activity of postural muscle (Luger et al. (2021) and on the kinematics (lower-lumbar flexion (Kim et al. 2020; Koopman et al. 2019b; Simon et al. 2021), or to a greater knee extension (Simon et al. 2021).

In view of the differences in the amplitude of muscular gains, and the undesired effects of back-support exoskeletons, the question of their benefits in terms of reduction of cardiovascular demand must be asked. The limitation of local muscular constraints should not be done at the expense of an increase in cardiovascular demand. Although studies on this subject are rare, it seems that the use of both passive and active exoskeletons has a beneficial effect on the metabolic responses (Del Ferraro et al. 2020). For instance, with regard to energy expenditure, Baltrusch et al. (2019) found a 17% decrease in metabolic cost during a 5-minute handling task performed with a passive back-support exoskeleton (Laevo), compared to without assistance. Moreover, a 4 to 13% energy expenditure reduction was found during symmetric and asymmetric standing and kneeling lifting tasks when using passive exoskeletons (Laevo V2.5 and BackX) (Alemi et al. 2020). Erezuma et al. (2021) also evaluated the Laevo V2.5 passive exoskeleton and observed a decrease of about 5% in metabolic cost during another lifting task. Finally, the use of an active system (prototype MeBot-Exo) yielded an 18% decrease in energy consumption in a recent study (Wei et al. 2020).

However, regarding the cardiovascular responses, the literature appears to be more contrasted. Previous studies reported that the use of exoskeletons could either induce a decrease in cardiac cost (Dewi and Komatsuzaki 2018; Yin et al. 2019) or have no effect (Erezuma et al. 2021; Luger et al. 2021; von Glinski et al. 2019; Ziaei et al. 2021). For example, during a repeated handling task performed with a 10 kg load, Yin et al. (2019) reported a decrease in the mean heart rate with the use of an active exoskeleton (wearable power-assist device developed for the study) compared to without assistance. In contrast, von Glinski et al. (2019), using another active exoskeleton (HAL[®] for Care Support Lumbar Type, Cyberdyne), did not observe any change in cardiovascular responses during a repeated handling task performed with a 17 kg load.

Like the variability of the results of studies concerning the effects of exoskeletons on muscular solicitations, these differences in cardiorespiratory consequences between studies could be related to both the task performed and the characteristics of the exoskeletons. It is therefore difficult to generalize these results and to clearly understand the influence of the exoskeleton design on the cardiorespiratory parameters, markers of the overall

physical workload. New data are needed to provide knowledge that will serve both companies wishing to acquire an exoskeleton, and designers to improve their systems.

At the same time, occupational exoskeletons are intended to assist all workers, regardless of sex. However, men and women present physiological differences, such as, for instance, lower average maximal strength for women than men (Cote 2012; Plamondon et al. 2017). Thus, relative women's physical effort is greater than that of men for the same handled load. In addition, it has been observed that movement strategies during a lifting task could be sex-dependent, with for instance greater hip flexion for women than men (Pan et al. 2020). When using an exoskeleton, Alemi et al. (2020) reported an interaction effect between exoskeleton and sex on lower-back muscle activity. In their study, the use of the BackX exoskeleton resulted in a significant decrease in trunk extensor muscles activity in men and women while the use of the Laevo V2.5 exoskeleton yielded such a muscular activity reduction only for women. This is not entirely in line with Schwartz et al. (2021), who found the same influence on lower-back muscle activity for men and women, whatever the back-support exoskeletons used (Laevo V1 and Corfor). It is also worth noting that most of the studies investigating cardiorespiratory consequences in relation to the use of exoskeletons were conducted with male participants (Del Ferraro et al. 2020). To our knowledge, only two studies have evaluated the sex effect on cardiorespiratory parameters with the use of exoskeletons. Madinei et al. (2020) found a significant reduction in the metabolic cost with the use of two models of passive exoskeletons (Laevo and BackX) for women, while this was only observed for one model (Laevo) for men. Contrariwise, similar decreases in metabolic cost were observed for both men and women in another study with the Laevo exoskeleton (Erezuma et al. 2021). Therefore, the generalization of the cardiorespiratory consequences of using back-support exoskeletons for women, while mainly reported for men, may be questionable due to possible sex specificities during lifting tasks. Thus, more information appears necessary to provide valid data for a better understanding of the influence of exoskeleton use on the overall physical workload of all workers.

Considering these different elements, the main objective of this study was to evaluate the effects of back-support exoskeleton design on cardiorespiratory parameters. We hypothesized that, for a standardized lifting task, active exoskeletons would be more effective than passive ones and reduce oxygen consumption rate and cardiac costs. A second objective was to tease out the possible sex effect on the cardiorespiratory parameters, while wearing exoskeletons.

2. Materials and methods

2.1. Participants

Thirteen men (age: 25 ± 5 years, height: 1.80 ± 0.04 m, weight: 75.5 ± 7.9 kg) and fourteen women (age: 24 ± 6 years, height: 1.66 ± 0.06 m, weight: 63.6 ± 13.3 kg) without musculoskeletal nor cardiorespiratory pathologies participated in this study. All participants realized a training protocol before the experimentations. This training protocol consisted of five sessions of two hours. During each session, the participants performed different handling tasks (including the one proposed in this study) without and with each exoskeleton. This training period helped to minimize the discovery effect associated with the use of a new equipment. Participants gave their written consent after receiving detailed information about the objectives, protocol and possible risks of this study. A national ethics committee approved the study (n° IDRCB 2019-A02901-56).

2.2. Experimental task

The study was conducted in an air-conditioned (with the temperature set at 20°C) and quiet room. Participants performed a standardized manual lifting task in their sagittal plane, consisting of moving a 10 kg box from a platform positioned at ankle height until the thigh height (corresponding to a full extension of the trunk) and vice versa. These successive actions of lifting and lowering the box corresponded to one cycle. Participants performed this task continuously for 5 minutes at an imposed rhythm, using a rhythmic beep (15 cycles / minute), and with the stoop technique, meaning that the trunk flexion/extension was realized with the knees almost straight, but without locking the joint. In addition, participants were asked to handle the box with outstretched arms. The position of the feet was fixed, parallel and hip-width apart. This position was marked at the start of the experiment with tape and was identical for each exoskeleton condition. The lifting task was successively performed with three exoskeletons (described below) and without assistance (FREE). The order of these conditions was randomized and a rest period of 10 minutes in a sitting position was respected between each. This rest period of 10 minutes allowed the measured variables returning to baseline before the start of a new lifting task, avoiding any potential carry-over effect.

2.3. Exoskeletons

One passive (P-EXO) (Figure 1, A) and two active (A-EXO1 (Figure 1, B) and A-EXO2 (Figure 1, C)) back-support exoskeletons were studied.

Insert Figure 1A, 1B and 1C

P-EXO: this passive exoskeleton is the BackX model (S model, 2019) from SuitX (USA). It weighs 4.5 kg and provides a trunk extension torque using springs and a rigid structure, with a joint at the hip level and support points at thigh and chest levels. It allows different morphological adjustments, different operating modes (instant and angle torque engagement mode) and two assistance levels (low and high). For this study, the exoskeleton was adjusted to each participant and was set to the 'instant' mode with the 'high' assistance level, corresponding approximately to a maximum torque of 41 Nm (at 90° flexion). This assistance level was chosen according to the weight to be handled.

A-EXO1: this active exoskeleton is the Exoback model (V1, 2020) of RB3D (France). This device weighs 8.4 kg. This exoskeleton consists of a dorsal box integrating the battery and the electric motor. The latter is connected to the thigh supports using cables to transfer the assistance. Its rigid structure comprises two joints (at the hip and lower-back levels) and support points at thigh, buttock and shoulder levels. This system allows morphological adjustments and many technical settings: support level of the trunk during its flexion; assistance level during the trunk extension; assistance level at the end of the movement; reactivity and softness of the system; and holding torque for isometric tasks. For the study, the assistance level was set to 66%, corresponding to 48 Nm. We chose this level given the recommendation of the builder with respect to the weight to be handled. The reactivity as well as the softness were set at 50% (default settings). The support level and the assistance at the end were set at 20% (default settings). The exoskeleton was adjusted to each participant's morphology.

A-EXO2: this active exoskeleton is the Cray X (2019) from German Bionic (Germany). It weighs 11 kg and is made up of a dorsal box, integrating the hardware and the battery, and of two electric motors placed at the hip level. Its rigid structure comprises one joint (the axis of the motor) and support points at thigh and chest levels. This exoskeleton has different morphological adjustments and technical settings: dynamic and static modes; assistance level provided during the trunk extension; sensitivity and reaction of the system; and counter force (corresponding to the support level of the trunk during its flexion). For this study, the dynamic mode with an assistance set to 40% was selected, which corresponded to 48 Nm and was comparable to A-EXO1. The sensitivity, the reaction and the counter force were set to 5 (default settings on a 0 to 10 scale). The exoskeleton was adjusted to each participant's morphology.

2.4. Data recording

Oxygen uptake ($\dot{V}O_2$, expressed in ml/kg/min) and heart rate (HR, expressed in beats per minute (bpm)) were measured breath-by-breath during the experimentation using a portable respiratory gas analyzer (K4b2,

Cosmed, Italy). Prior to the experimental lifting task, resting parameters were recorded during a period of 15 minutes with the participant lying in a quiet room and in the dark. The average $\dot{V}O_2$ and HR during the last 5 minutes of this period were considered as resting values.

For each experimental condition, $\dot{V}O_2$ and HR were averaged during the last 2 minutes of the lifting task and were considered as working values. Given the submaximal intensity of the exercise (estimated to be $\approx 36\%$ of $\dot{V}O_2$ max for FREE, with $\dot{V}O_2$ max values being extrapolated from norms based on participants' age, sex and weight (Myers et al. 2017)), the first 3-minute period prior to the recording ensured a stabilization of the cardiorespiratory parameters. Oxygen consumption rate (expressed in ml/kg/min) and cardiac costs (expressed in bpm) associated with the task were then calculated for each experimental condition by subtracting resting values from the working ones.

In order to check that rest values returned to baseline before starting a new effort, $\dot{V}O_2$ was measured during the last 2 minutes of each rest period between lifting tasks. The initial rest value (i.e. 15 minutes lying in a quiet room and in the dark) was 2.93 ± 0.64 ml/kg/min and rest values between lifting tasks were 2.79 ± 0.60 , 2.75 ± 0.79 and 2.72 ± 0.69 ml/kg/min, respectively before the tasks 2, 3 and 4. These values were not statistically different ($p > 0.05$).

2.5. Statistical analysis

The results are presented as means \pm standard deviations. A generalized linear mixed model was used to analyse the main effects of exoskeleton (FREE, P-EXO, A-EXO1 and A-EXO2) and sex (men and women) on oxygen consumption rate and cardiac costs, as well as their interaction effect. These independent variables were set as fixed effects and the participant as a random effect. In case of non-significant interaction, it was removed from the model. Significant effects were analysed using post hoc Bonferroni pairwise comparison tests. Residual normality was verified. The significance level was 5% ($p < 0.05$). Effect size was evaluated by partial eta squared (η_p^2) for main effects, and by means of Cohen's d values for post hoc pairwise comparison. Effect size was considered small ($\eta_p^2 \geq 0.02$; $d \geq 0.20$), medium ($\eta_p^2 \geq 0.15$; $d \geq 0.50$), or large ($\eta_p^2 \geq 0.35$; $d \geq 0.80$) according to Cohen (Cohen 1992). All analyses were performed with STATA software (Stata 16, StataCorp, USA).

3. Results

Initial statistical model indicated that the interaction effect between exoskeleton and sex was not significant either for the oxygen consumption rate ($p = 0.75$) or the cardiac cost ($p = 0.39$). The interaction was therefore removed from the model in order to keep only the main effects. Then, a significant exoskeleton effects ($p < 0.05$) on oxygen consumption rate and cardiac costs, and sex effect only on the cardiac cost were reported (Table 1).

Main Effects	Oxygen consumption rate		Cardiac cost	
	p	η_p^2	p	η_p^2
Exoskeleton	< 0.001	1.78	< 0.001	1.18
Sex	0.13	0.003	< 0.001	0.03

Table 1: Main effects of exoskeleton and sex on cardiorespiratory parameters from the general linear mixed model. Significant effects ($p < 0.05$) are presented in bold type. η_p^2 : effect size partial eta squared.

3.1. Exoskeleton effect

For all participants (women and men), the oxygen consumption rate was significantly lower with P-EXO (11.8 ± 2.4 ml/kg/min; $p = 0.04$, $d = 0.37$), A-EXO1 (9.1 ± 1.8 ml/kg/min; $p < 0.001$, $d = 1.76$) and A-EXO2 (11.0 ± 1.8 ml/kg/min; $p < 0.001$, $d = 0.82$) compared to without equipment (FREE: 12.6 ± 2.2 ml/kg/min) (Figure 2). In addition, the oxygen consumption rate was significantly lower for A-EXO1 than for P-EXO ($p < 0.001$, $d = 1.26$) and A-EXO2 ($p < 0.001$, $d = 1.05$). Concerning the cardiac cost, it was significantly lower with A-EXO1 (45.1 ± 11.5 bpm) compared with FREE (59.7 ± 12.9 bpm; $p < 0.001$, $d = 1.19$), P-EXO (57.4 ± 12.9 bpm; $p < 0.001$, $d = 1.01$) and A-EXO2 (59.1 ± 10.7 bpm; $p < 0.001$, $d = 1.26$) (Figure 3). No significant difference was observed between FREE and P-EXO or A-EXO2.

Insert figure 2

Insert figure 3

3.2. Sex effect

During the task, the oxygen consumption rate (all exoskeletons combined) did not significantly differ ($p = 0.13$, $d = 0.40$) between men (11.6 ± 2.7 ml/kg/min) and women (10.6 ± 2.0 ml/kg/min). Statistical analyses revealed a significant sex effect on the cardiac cost ($p < 0.001$, $d = 1.09$), with a higher value for women (61.7 ± 10.6 bpm) than for men (49.0 ± 12.7 bpm).

4. Discussion

The influence of different back-support exoskeletons on the cardiorespiratory parameters during a repetitive lifting task was analysed in the present study. The possible effect of sex was also tested here. The primary findings showed that using passive and active exoskeletons could significantly reduce cardiorespiratory responses compared to a control condition performed without equipment, and this regardless of the sex.

4.1. Exoskeleton effect

To our knowledge, the present study was the first to compare the effects of passive and active back-support exoskeletons on cardiorespiratory parameters during an identical lifting task. Our results firstly showed that oxygen consumption rate was significantly decreased with all three exoskeletons used compared to the control condition. The amount of reduction was dependent on the exoskeleton design.

The use of the passive exoskeleton (P-EXO, BackX model) reduced the oxygen consumption rate by approximately 7% during our repeated lifting task. Although significant, this reduction was slightly lower in comparison with previous studies using the same exoskeleton, which reported a 13–14% reduction in energy expenditure with lighter loads, respectively 6.8 kg load (Alemi et al. 2020) and 10% of body weight (≈ 7.2 kg) (Madinei et al. 2020). Inversely, Poon et al. (2019) reported a lack of influence on the oxygen consumption rate when wearing the BackX during a lifting task performed with a heavier load (18 kg). Together, these results suggested that beneficial effects of a passive exoskeleton on the metabolic cost seem to be reduced with the increment of the load to be handled. In practice, this highlights the importance of matching the exoskeleton characteristics to those of the working task (such as the weight to be handled) in order to maximize beneficial effects.

The use of active exoskeletons also resulted in a decrease in the oxygen consumption rate of 28% for the A-EXO1 (Exoback) and 13% for the A-EXO2 (Cray X) compared to the condition without equipment. In their study, Wei et al. (2020) evaluated another active exoskeleton (prototype MeBot-EXO) and reported an 18% reduction in metabolic cost, even if only three participants were evaluated.

The wide range of oxygen uptake reduction observed among passive and active assistive devices could be partly related to the design of the exoskeleton used. First, although the P-EXO proposes a lighter weight than the A-EXO1 (4.5 versus 8.4 kg), this maximal assistive torque was lower (≈ 41 versus 48 Nm), which could explain its smaller reduction in the oxygen consumption rate. In addition, without having been able to measure it, it is possible that the torque of the passive exoskeleton, depending on the spring deformation and related to the joint angle, might not be evenly distributed over the range of motion, as shown for another passive exoskeleton

(Koopman et al. 2019a). This would be in line with discrepancies in trunk extensor activation with respect to the trunk inclination, observed among different passive exoskeletons (Schwartz et al. 2021). In contrast, it is assumed that an active exoskeleton provides a more constant torque throughout the whole range of motion because the motor can generate a steady torque. Last, but not least, the need for a passive system to be actively constrained thanks to both muscle contraction and gravity in order to store energy within springs to be released afterwards, probably reduces its efficiency in terms of the metabolic cost.

In the present study, the use of the two active exoskeletons also yielded different reductions in the oxygen consumption rate, despite an identical task and a similar assistive torque (48 Nm). Differences could be explained by the weight discrepancy, the A-EXO2 being heavier than the A-EXO1 (11 versus 8.4 kg, respectively). Accordingly, the real assistance provided to the user could be weaker for the A-EXO2 due to the loss of energy to compensate for the extra weight of the system, therefore influencing the oxygen uptake. A second hypothesis concerns their level of anthropomorphism. Indeed, the A-EXO1 has been designed with two joints, one at the lower-back level and another at the hip level. The A-EXO2 has only one joint at the hip level. Considering the relative contribution of hip and back joints to the trunk flexion/extension, the A-EXO1 appears to be more anthropomorphic than the A-EXO2. As participants performed the lifting task with the stoop technique in the present study, the mobilization of both joints over large ranges of motion was required. It is thus possible that the two joints design (A-EXO1) was less disruptive to natural movement and therefore a lower energy consumption. Finally, it is possible that other adjustment parameters (reactivity and softness of the system, for example), set at the factory values in the present study, could also partly affect the differences observed between the two active exoskeletons.

Results dealing with the cardiac cost, the use of the P-EXO (BackX) did not show any changes compared to the condition without an exoskeleton. This result is in agreement with most of the previous studies on other passive systems (Luger et al. 2021; Erezuma et al. 2021; Ziaei et al. 2021). Surprisingly, the use of the A-EXO2 (Cray X) did not induce significant changes in the cardiac cost compared to the control condition, whereas the use of the A-EXO1 (Exoback) did, with a 15 bpm reduction (45 versus 60 bpm, for A-EXO1 and FREE, respectively). Previous studies that evaluated the effect of using active exoskeletons on the cardiac cost also found either a positive influence (Yin et al. 2019) or no change (von Glinski et al. 2019) compared to without equipment. Therefore, the effects of back-support exoskeletons on the cardiac cost could depend on their characteristics, as mentioned earlier for the oxygen consumption rate. Moreover, it is worth noting that the present results, based on heart rate values, do not seem as sensitive as based on oxygen uptake in order to highlight differences in the

cardiorespiratory response between exoskeletons. Heart rate and oxygen uptake generally evolve in a similar way during a prolonged physical effort. However, some factors could specifically modulate the cardiovascular response. This could be due to environmental factors (ambient noise, temperature...) (Schnell et al. 2013; Yamamoto et al. 2007) or individual factors (age, sex, stress...) (Friedman 2007; Melillo et al. 2011). As environmental factors were similar in all experiments performed in the laboratory, these would likely not explain the difference between heart rate and oxygen uptake results. With regard to individual factors, as all participants were young people, the age factor can be ruled out. Since the effect of sex has been considered in the statistical model, it can also be discarded. An explanation could be related to a possible discomfort perceived with some exoskeletons, causing potential stress. Indeed, it has been observed that some exoskeletons could generate discomfort at the chest level (Alemi et al. 2020; Kim et al. 2020; Madinei et al. 2020), due to a point of force application in this area. As both P-EXO (BackX) and A-EXO2 (Cray X) involved a chest support that could possibly create discomfort during our repeated lifting task, this could influence heart rate responses in another manner than oxygen uptake measures. However, as discomfort was not evaluated in the present study, it remains difficult to relate this parameter to differences between heart rate and oxygen uptake. Future studies are needed to answer this hypothesis and to clearly define which parameter should be used to discriminate exoskeletons in terms of overall physical workload.

To conclude, it appears that the use of both passive and active back-support exoskeletons can reduce the physical workload of a handling task. Nevertheless, active exoskeletons are not necessarily more effective than passive ones, contrarily to our hypothesis. It rather seems that the operating mode (passive versus active), the exoskeleton design (number of joints, weight...) and the level of assistance influence the cardiorespiratory responses and should be considered by the companies with respect to the task to be performed. Accordingly, these different parameters, related to the exoskeleton design, would need to be further investigated in future researches to clarify which must be considered in priority for the prevention of work-related accidents and occupational diseases.

4.2. Sex effect

In order to assess whether the cardiorespiratory consequences of wearing an exoskeleton are identical between men and women, the effect of sex on the oxygen consumption rate and cardiac costs was studied. No main sex effect was reported for the oxygen consumption rate, suggesting that the lifting task induced the same absolute physical workload for both men and women. Erezuma et al. (2021), while evaluating a passive back-support

exoskeleton (Laevo), also showed no significant differences in metabolic cost between men and women. However, this is in contradiction to Madinei et al. (2020), who reported a decrease in the energy expenditure for women but not for men with the use of the passive BackX exoskeleton. These differences could be due to the heterogeneity of the protocols, such as, for instance, the weight to be handled during the lifting task. Indeed, Madinei et al. (2020) used a smaller load for women (~ 6.3 kg) and for men (~ 8.1kg) compared to the present study (10 kg for both sexes). As discussed earlier, the relative beneficial effect of wearing the BackX exoskeleton on the metabolic cost could be more important when handling lighter loads. Therefore, smaller relative beneficial effects with heavy loads could minimize a potential difference in metabolic cost between men and women.

Regarding the cardiac cost, our results showed that women had higher values than men (61.7 bpm versus 49.0 bpm). An explanation for this difference in absolute cardiac cost, while the oxygen consumption rate was identical, could be the fact that women would work at a higher percentage of their physiological capacity than men, resulting in a higher heart rate (Barnes and Fu 2018). This heart rate increase would compensate for a lower stroke volume in women (mainly attributed to a smaller heart size) to yield adequate cardiac output.

In conclusion, the present study highlights that passive and active back-support exoskeletons have beneficial effects on overall physical workload for both men and women. This is encouraging for the deployment of exoskeletons to all workers to reduce their physical workload. However, future investigations seem necessary to better understand the potential effect of the handled load on the cardiorespiratory consequences of using an exoskeleton.

5. Limitations

A first limitation of our study was the use of a standardized protocol carried out in the laboratory. For example, the task performed was only in the sagittal plane. This is not representative of all the tasks done by workers in ecological conditions, which may involve various movements in several planes. However, laboratory experimentations allow controlling the environment and limiting as much as possible measurement biases.

Another limitation was our participant sample. In order to reduce individual heterogeneity and to exclude volunteers with medical restrictions, our sample consisted of healthy young adults. This sample did not represent the general worker population. Our results could then not be extrapolated – for example, to the problem of job retention for elderly or pathological employees through the use of exoskeletons. Nevertheless, unlike most studies assessing occupational exoskeletons, both men and women were evaluated in the present study in order

to expand the knowledge about a wider population. Further studies are needed to consider all potential sources of individual variability.

6. Conclusions

The use of back-support exoskeletons demonstrated beneficial effect on cardiorespiratory consequences during a repeated lifting task. Oxygen consumption rate and cardiac cost reduction depended on the exoskeleton design. The assistance modality (passive versus active), the exoskeletons weight as well as their anthropomorphism level (single or multiple joints) could modulate the cardiorespiratory responses. The cardiorespiratory benefits associated with the use of back-support exoskeletons have also been shown to be similar for men and women. To conclude, the back-support exoskeletons tested in this study appear to reduce the overall physical workload of the users during a repetitive lifting task and could therefore make it possible to limit work-related accidents and occupational diseases induced by strenuous handling tasks.

7. Declarations

Funding:

No funding was received for conducting this study.

Conflicts of interest/Competing interests:

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval:

The experimental protocol received approval from the national ethical committee (n° IDRCB 2019-A02901-56).

Consent to participate:

Participants gave their written consent after receiving detailed information about the objectives, protocol, and possible risks involved.

Availability of data and material:

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable.

Code availability:

Not applicable.

Authors' contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kévin Desbrosses and Mathilde Schwartz. The first draft of the manuscript was written by Mathilde Schwartz and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figure 1: The three exoskeletons used; (A) passive exoskeleton (P-EXO) (BackX, Suit X, USA), (B) active exoskeleton (A-EXO1) (Exoback, RB3D, France), and (C) active exoskeleton (A-EXO2) (CrayX, German Bionic, Germany). Joints of the exoskeletons and support points of the assistance are represented by the white circles and the white arrows, respectively.

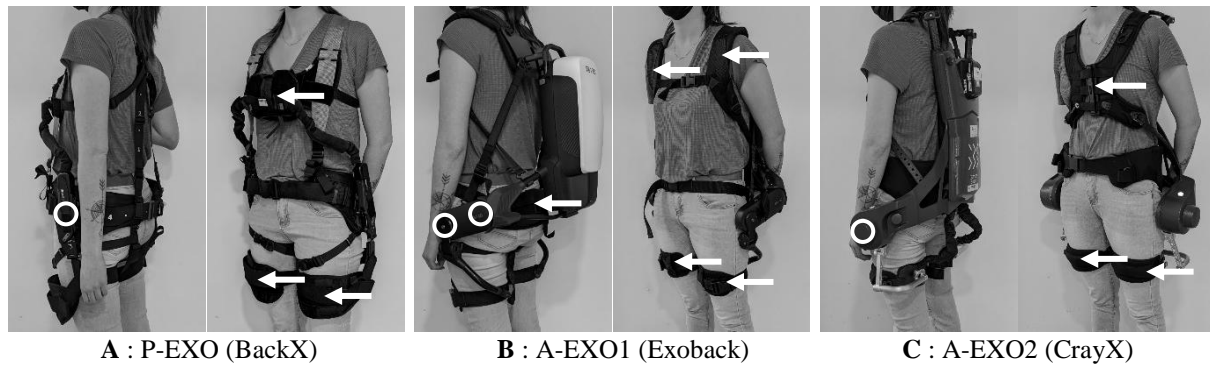


Figure 2: Mean oxygen consumption rate (ml/kg/min) and standard deviation obtained with the use of the passive exoskeleton (P-EXO, light grey), both active exoskeletons (A-EXO1, dark grey; A-EXO2, dark), and without equipment (FREE, white). *: significant differences between exoskeletons ($p < 0.05$).

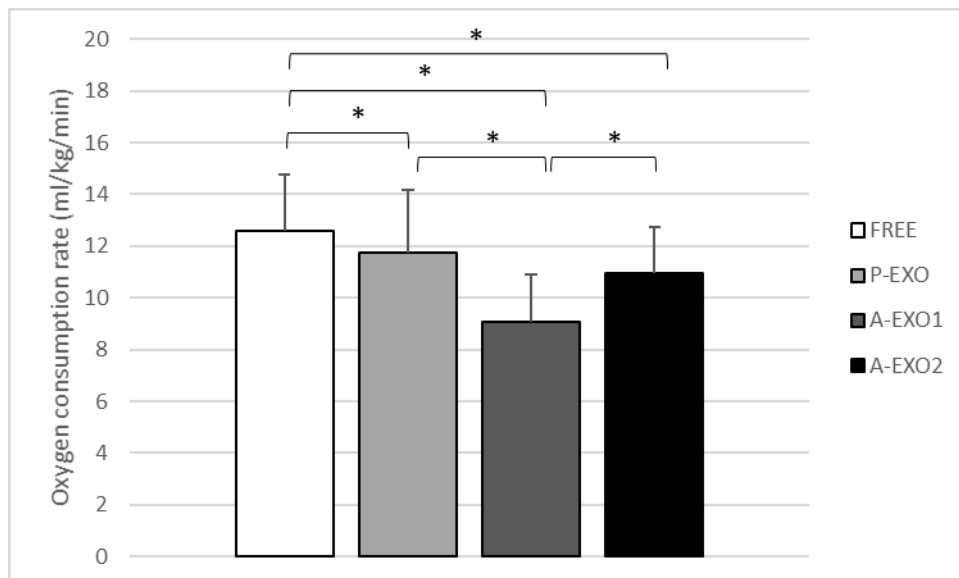


Figure 3: Mean cardiac cost (bpm) and standard deviation obtained with the use of the passive exoskeleton (P-EXO, light grey), both active exoskeletons (A-EXO1, dark grey; A-EXO2, dark), and without equipment (FREE, white). *: significant differences between exoskeletons ($p < 0.05$).

