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Physiological consequences of using an upper limb exoskeleton during manual handling tasks

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ABSTRACT

This study aimed to assess the physiological consequences of using an upper limb exoskeleton during manual handling task, as muscle activity, upper limb kinematics, postural balance and cardiac cost. Participants performed three tasks (load lifting (LIFT), carrying (WALK) and stacking-unstacking (STACK)) with (EXOS) and without (FREE) an exoskeleton. During LIFT and STACK, the activity of the deltoid anterior muscle was significantly lower for EXOS than for FREE. During LIFT, the activity of the triceps brachii (TB) and tibialis anterior muscles significantly increased for EXO. The TB muscle activity significantly decreased for EXOS during WALK. The cardiac cost tended to increase with the use of the exoskeleton during LIFT, compared to FREE. The upper limb kinematics significantly differed between the EXOS and FREE conditions for all tasks. The benefits of the upper limb exoskeleton to reduce shoulder flexor muscle activity has been demonstrated, while broader physiological consequences have also been evidenced as increased antagonist muscle activity, postural strains, cardiovascular demand, and modified kinematics.

1. Introduction

Manual handling activities are known to expose individuals to considerable biomechanical strains and risks of musculoskeletal disorders (MSD) (Ayoub, 1982; Cole and Grimshaw, 2003; Rempel, 1992; Straker, 1999). Despite the development of modern technology, many jobs still require manual handling tasks so that more than 40% of workers in the European Union continue to suffer from back and shoulder pains (Eurofound, 2012). To deal with this prevalence of MSDs in handling tasks, research is now focusing on new issues, such as the use of exoskeletons (de Looze et al., 2016). Defined as wearable, mechanical structures that enhance the strength of a person, occupational exoskeletons have been designed to physically assist workers in performing their tasks, and thus reduce their exposure to the associated physical demand.

Previous studies have examined the benefits of these new technologies on musculoskeletal strains, focused in particular on devices specifically developed to assist spine erection during trunk bending. The use of back exoskeletons appears to efficiently reduce the activity of low back muscles (Abdoli et al., 2006; Bosch et al., 2016; Frost et al., 2009; Whitfield et al., 2014), local muscular fatigue (Godwin et al., 2009; Lotz et al., 2009), and the internal forces applied to the lumbar spine (Abdoli-Eramaki et al., 2007; Graham et al., 2009) during handling tasks. However, little information is known on the potential benefits of upper-limb exoskeletons regarding the biomechanical strains associated with manual handling tasks. These tasks are also commonly incriminated in the occurrence of shoulder MSD, particularly due to the combination of heavy load carrying, shoulder solicitations in flexion and abduction, and overhead work (OHW) (Frost et al., 2002; Miranda et al., 2005; Roquelaure et al., 2011; Silverstein et al., 2008; van Rijn et al., 2010). Designed to reduce the physical strains placed on the shoulders, upper limb exoskeletons commonly features one or two mechanical arms, fixed on a rigid jacket. A spring system designed to raise the arms provides physical assistance. To our knowledge, these exoskeletons have been specifically assessed during OHW (Rashedi et al., 2014; Sylla et al., 2014). In both studies, the experimental task consisted to a simulated intermittent OHW, in a standing position, where the participants had to holding and handling different tools or payloads (from approximately 1 to 8 kg) over the head. The first results nonetheless demonstrated the potential of the assistive devices to reduce the perceived exertion, shoulder flexor muscle activity (Rashedi et al., 2014), and shoulder joint torque (Sylla et al., 2014).

Therefore, it is interesting to examine the impacts of using these technologies on shoulder biomechanical strains during other handling activities than OHW. It is essential to ensure that upper limb exoskeletons also provide a real advantage for shoulder MSD prevention, without causing other biomechanical strains. For example, previous studies have demonstrated that the use of similar devices could involve

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significant postural changes during OHW (Sylla et al., 2014) and kinematics stains (Ulrey and Fathallah, 2013). Moreover, increased lumbar muscle activity has been observed during OHW with a customised upper limb exoskeleton, compared to an identical task, performed without assistance (Rashedi et al., 2014). The inertial characteristics (i.e. mass and balance) of upper limb exoskeletons could partly explain the latter observations. It can also be expected that the postural changes resulted to modifications in the motor pattern of the upper limbs (i.e. focal muscular chain), due to kinematics strains. Furthermore, the increase of postural strains associated to the increase of muscle activity could have significant repercussions on metabolic responses.

The present study aimed to assess the impact of using an upper limb exoskeleton on focal and postural muscle activity, upper arm kinematics and cardiac cost during handling tasks.

2. Materials and methods

2.1. Participants

Four women (31 ± 2 years, 166 ± 4 cm, 62 ± 10 kg) and four men (33 ± 3 years, 179 ± 3 cm, 78 ± 3 kg), right-handed, without back or shoulder pathologies, volunteered to participate in this study. Their usual work tasks mainly consisted in the manual handling of different boxes. They were trained (97 ± 18 min) to perform the experimental tasks during 4 sessions, with and without an exoskeleton. They had given their written consent after receiving detailed information on the objectives, protocol and possible risks. The experimental protocol received approval from the ethical committee of the company, including the medical staff and union representatives. Each volunteer participated in the present study after a medical examination.

2.2. Experimental tasks

The participants had to perform three modalities of handling tasks according to the present protocol, each of them with (EXOS) and without (FREE) an exoskeleton, in random order. These experimental tasks consisted successively in load lifting in the sagittal plane (LIFT), walking while carrying a load (WALK), and manual load handling with a 90°-rotation in the longitudinal axis (STACK) (Fig. 1). The two conditions (EXOS and FREE) were separated by a recovery period of 20 min, in a sitting position.

2.2.1. Exoskeleton

The EXHAUSS Stronger® exoskeleton (EXHAUSS, France) was used in this study. It weighs 9 kg and consists of two mechanical arms activated by springs. The arms are linked to a rigid wearable jacket, with joints, allowing free 3D movements. The distal extremities of the mechanical arms have short belts used to strap the user's hand (Fig. 1). This exoskeleton provides non-linear arm lift assistance over an angular range from 0° to 135° of the shoulder anterior flexion. The assistive torque can be adjusted by prestressing the springs. In this study, we adjusted the system so that the exoskeleton provided a force assistance of ≈9 kg for men and ≈5 kg for women at the arm end of the exoskeleton for a 90° shoulder anterior flexion. These values were in accordance with the loads handled by each group during the LIFT condition. The participants had to handle routine materials (toolboxes) during the WALK and STACK tasks. The exoskeleton was adjusted to the anthropometric characteristics of the subjects.

2.2.2. Load lifting and lowering task (LIFT)

The LIFT task was a standardized task consisting in load lifting from a low platform to a high one, and vice versa for 3 min at an imposed rate, using a rhythmic beep (ten cycles/minute). One full cycle included both load lifting and lowering actions. The two platforms faced the participant so as to limit the movement in the sagittal plane. These platforms were adjusted to the anthropometric characteristics of the workers, at knee and shoulder height, respectively. The high platform was positioned behind the low one, so as to obtain a complete elbow extension in the sagittal plane (Fig. 1, A). The load was adjusted to 9 kg for men and 5 kg for women, respectively. This difference was related to the maximum strength of the men and women observed for anterior shoulder flexion during the pre-tests (100% vs. 56%). A recovery period of five minutes was provided after the task.

2.2.3. Walking with load carrying task (WALK)

WALK consisted in walking over a distance of 30 m at a free chosen (as usual working tasks) speed, carrying a two-handled toolbox (Fig. 1, B). For each experimental condition (EXOS vs. FREE), the task was repeated four times and a break of 10 s was given between each repetition, done by releasing the toolbox. The toolbox weight was adjusted to 15 kg for the men and 8 kg for the women. A 5-min recovery period was provided after the entire task.

2.2.4. Box unstacking and stacking task (STACK)

STACK consisted in unstacking and stacking 4 boxes (≈80 cm wide and 35 cm high) with a 90° rotation of the operator on its longitudinal axis (Fig. 1, C). The full unstacking and stacking of the 4 boxes was considered as a cycle. The subjects had to perform eight full cycles to complete this experimental task. Contrary to LIFT, the workers were not subjected to any imposed pace (as usual working tasks). The free pacing advised was defined as “normal for a 5 min work period”. The boxes weighed 15 kg for the men and 8 kg for the women.

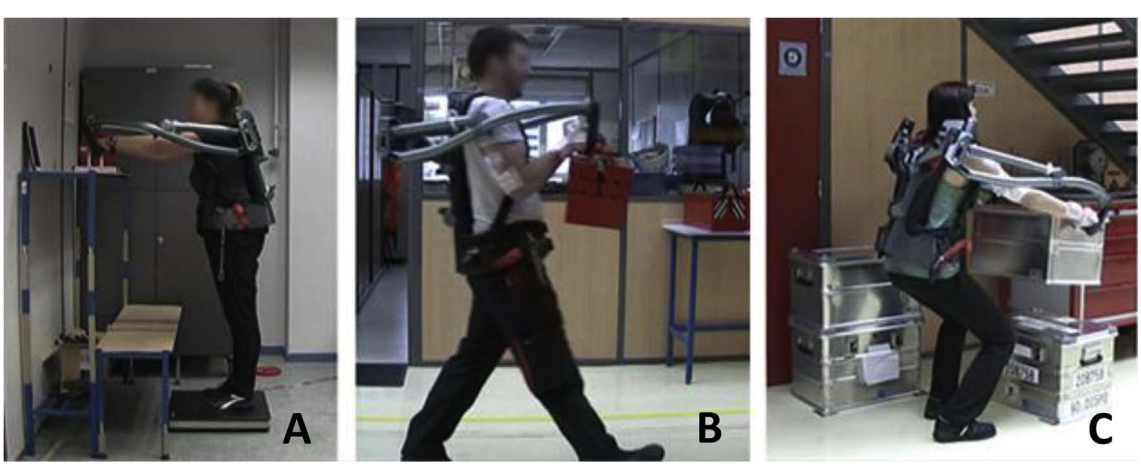

Fig. 1. Experimental tasks. Each participant performed a LIFT task (A), a WALK task (B) and a STACK task (C), with and without an upper limb exoskeleton.

2.3. Data recording

2.3.1. EMG

The electromyographic activity (EMG) of the anterior deltoid (AD), the long head of the triceps brachii (TB), the erector spinae longissimus (ES) and the tibialis anterior (TA) muscles was continuously recorded on the right side (Cometa, Wave Plus™, Italy). Two single-use surface electrodes (BlueSensor N-00-S, Ambu) were placed on the skin in accordance with SENIAM recommendations (Hermens and Freriks, 1997). Inter-electrode distance was 20 mm. Skin preparation allowed an impedance lower than 5 kΩ. EMG signals were recorded at 2000 Hz, amplified (x1000) and filtered at 10–500 Hz bandpass. Then the RMS (Root Mean Square) value was calculated over successive periods of 100-ms sliding windows in 10-ms steps.

Before the first task, two isometric voluntary maximal contractions were performed successively for AD, TB and TA muscles. For ES muscles, two isometric submaximal voluntary contractions were performed. In a standing posture, the participants had to hold a load (9 kg for men and 5 kg for women) with arms extended at 90° of shoulder anterior flexion. All contractions were maintained for 5 s and separated by at least 1 min recovery. For each muscle, the highest 100-s RMS value was used as the reference value (RMSref). Then, for the three tasks, RMS values were expressed in percentage of RMSref.

For LIFT, an average RMS value was computed during the last 5 cycles, in their entirety. For WALK, an average RMS value was computed over 10 footsteps during the last repetition (between 5 and 25 m distance). For STACK, an average RMS value was computed during the last 2 cycles, in their entirety. EMG was computed at the end of each task in order to ensure that subjects were fully immersed in the work situation.

2.3.2. Upper limb kinematics

Right upper limb movements were recorded using four wireless magneto-inertial measurement units (MIMU, version firmware 2.0.8, Xsens, Enschede, Netherlands). Each MIMU is a small and light device (34.5 × 57.8 × 14.5 mm, 27 g) that consists of a 3D linear accelerometer, a 3D rate gyroscope and a 3D magnetometer. The MIMU technical coordinate system linked to an earth-based global coordinate system was provided as an output, using the Xsens fusion algorithm.

For an appropriate estimation of upper arm movement, the four sensors were placed in specific positions on each upper limb body segment and on the trunk (Bouvier et al., 2015) on the flat portion of the sternum, on the central third of the upper arm, laterally and slightly posterior, dorso-distally on the forearm and dorsally on the hand (Fig. 1). After MIMU positioning each subject performed a calibration posture: upper arm along the body, elbow flexed at 90°, in neutral forearm pronosupination, fingers pointing forward. MIMU data were recorded at 50 Hz and synchronized with all the other recorded data and video-recordings.

Following a previous study procedure (Bouvier et al., 2015), a non-orthonormal segment representation was associated with all of the MIMU sensor-to-segment calibrations in order to calculate joint angles (Dumas and Chèze, 2007). In accordance with ISB (International Society of Biomechanics) recommendations, the wrist (flexion (+)/extension (−) and adduction (+)/abduction (−)), elbow (flexion (+)/extension (−)) and internal-external rotation (pronation (+)/supination (−)) and shoulder (flexion (+)/extension (−), adduction (+)/abduction (−)) and internal -external rotation (internal (+)/external (−)) angles were calculated (Wu et al., 2005).

Prior to angle data analysis, a qualitative analysis of the magnetic sensors was realized. This analysis did not identify any MIMU perturbation. The mean and standard deviation of each joint angle were analysed independently for all 3 tasks.

2.3.3. Heart rate

Heart rate (HR) was continuously recorded during the three experimental tasks (PolarTeam2 system, Polar, Finland). For each condition (FREE vs. EXOS), a 5-minute recovery period was observed before LIFT to record the HR at rest (the average of the lowest data acquired over a continuous period of 30 s). We computed the mean HR value for the last 30 s for LIFT and STACK and for the last 30 meters for WALK. For each condition and task, the heart rate was expressed as the absolute cardiac cost (CC) which was obtained by subtracting rest HR from work HR. Measurements were performed under normal temperature and relative humidity conditions (20.5 ± 1.4 °C and 49 ± 5%, respectively).

2.3.4. Perceived exertion

Perceived exertion was recorded using the Rating of Perceived Exertion (RPE) scale (Borg, 1998). The participants were questioned at the end of each task, in both experimental conditions (FREE vs. EXO).

2.3.5. Postural balance

During LIFT, a stabilometric platform (SATEL, France) was placed under the feet of the participants to assess the displacements of centre of pressure (CoP). The signal was recorded at 40 Hz over a period of 51.2 s at the end of the task. The CoP displacement was analysed using the area of the confidence ellipse (mm^2) and the maximal oscillation in the antero-posterior direction (mm) (Marcolin et al., 2016).

2.3.6. Work duration

For WALK and STACK, the times taken to walk 20 m (5–25 m) during the last repetition and the last 2 handling cycles, respectively, were recorded.

2.4. Statistics

The results are presented as means ± standard deviations (SD). For each task (LIFT, STACK and WALK), the data were analysed using a general linear model including the subject as a random effect and the condition (FREE, EXOS) as a fixed effect. Residual normality was verified and a 5% significance level adopted ($p < 0.05$). Commercial software was used for the analyses (Statgraphics Centurion XVI).

3. Results

3.1. LIFT

The EMG activity of AD was significantly ($p < 0.01$) lower for EXOS than for FREE. TB and TA activities were significantly ($p < 0.01$ and $p < 0.001$) higher when LIFT for EXOS than for FREE (Fig. 2). No statistical difference in EMG activity was reported for ES between conditions.

Regarding upper limb kinematics, EXOS did not present significant wrist joint angle modifications in comparison with FREE (Fig. 3). EXOS induced a significantly ($p < 0.05$) higher averaged elbow flexion angle in comparison with FREE ($p < 0.05$). EXOS was accompanied by smaller ($p < 0.05$) averaged flexion and external rotation angles of the shoulder.

The area of the confidence ellipse was significantly ($p < 0.05$) higher for EXOS (6870 ± 2380 mm^2) than for FREE (4076 ± 997 mm^2). Similar results were found for the maximal oscillation in the antero-posterior direction (182 ± 38 mm vs. 136 ± 11 mm; $p < 0.05$). RPE was similar between conditions (Table 1). Finally, a strong trend ($p = 0.058$) towards a higher CC was observed for EXOS in comparison to FREE (Table 1).

3.2. WALK

TB activity was significantly lower for EXOS than for FREE ($p < 0.05$; Fig. 1). No significant difference between conditions was observed for the other muscles studied.

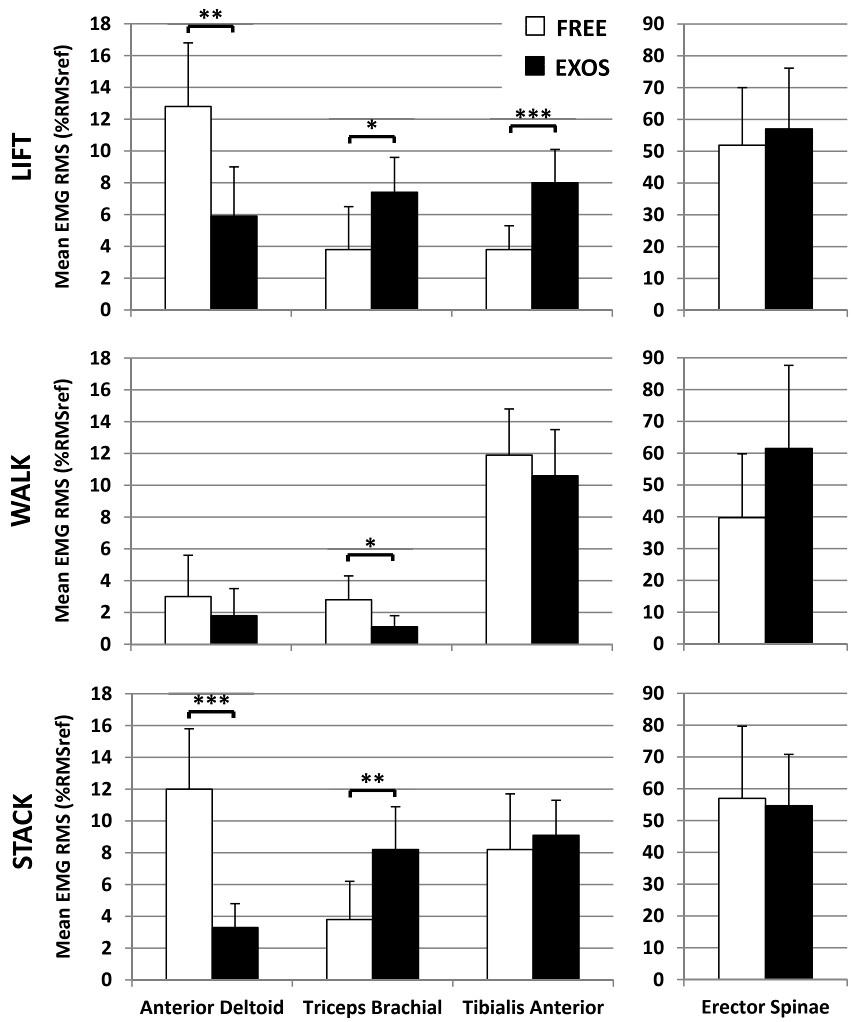

Fig. 2. Electromyographic activities (EMG) during LIFT, WALK and STACK. The tasks were performed without (FREE, empty bars) and with the exoskeleton (EXOS, filled bars). RMS values are expressed in percentage of RMSref obtained during maximal contractions for the *anterior deltoid*, *triceps brachial* and *tibialis anterior*, and during submaximal contractions for the *erector spinae longissimus*. For statistical differences between FREE and EXOS: * = $p < 0.05$; ** = $p < 0.01$ and *** = $p < 0.001$.

With regard to upper arm kinematics, EXOS involved a significantly ($p < 0.05$) higher averaged flexion angle of the elbow and a higher averaged abduction angle of the shoulder (Fig. 2), in comparison with FREE.

The CC was similar between EXOS and FREE and the RPE was significantly ($p < 0.05$) lower for EXOS than for FREE (Table 1). In addition, the time taken to perform the 10 steps was similar between conditions (Table 1).

3.3. STACK

AD activity was lower for EXOS than for FREE ($p < 0.001$). The EMG activity of TB was higher ($p < 0.01$; Fig. 1) with the exoskeleton than without it. No statistical difference between either condition was observed for ES and TA muscle activity.

Both the averaged flexion angle of the elbow and the averaged abduction angle of the shoulder were significantly ($p < 0.05$) lower for EXOS in comparison to FREE (Fig. 3). The movement direction and angular motion of the shoulder internal rotation were significantly ($p < 0.05$) different between both conditions.

Finally, RPE and CC were similar between EXOS and FREE while a significant ($p < 0.05$) longer time to handle the last 8 boxes was recorded for EXOS (Table 1).

4. Discussion

The present research aimed to evaluate the impact of an upper limb exoskeleton on physiological responses during common handling tasks.

Our results showed that the use of an upper limb exoskeleton led to significant reduction of AD muscle activity during load lifting and stacking/unstacking tasks. The extent of these decreases respectively corresponded to 54% and 73% of the EMG activity recorded during the same tasks performed without equipment. These data are in accordance with Rashedi et al. (2014) that also reported a reduction of the EMG activity of the AD muscle when using a similar wearable assistive device during overhead work. In the study of Rashedi et al. (2014), workers had to complete 10 min of simulated intermittent overhead work consisting in holding a tool, with and without an upper limb exoskeleton. The drop in AD muscle activity with the exoskeleton ranged from 36 to 56%, depending on the mass of the tool. The relative decrease of AD muscle activity with the exoskeleton was more important when the mass of the object handled was heavy. In the present study, similar observations can be made, where the relative impact of the assistive device on shoulder muscle solicitation was greater ($p < 0.05$) during the stacking/unstacking task, in which the boxes handled weighed 15 and 8 Kg, than during the lifting task, in which the experimental loads weighed 9 and 5 kg, for men and women, respectively. The principle of the assistive devices, examined by Rasheidi et al. (Rashedi et al., 2014) and by the present study, was to facilitate the sagittal flexion of the shoulder, a movement for which the AD muscle act. These work modalities, involving an arm elevation, thus proved favourable for demonstrating the benefits of upper limb exoskeletons on the shoulder muscle studied. In contrast, when participants had to carry a heavy toolbox while walking, the exoskeleton did not have any significant

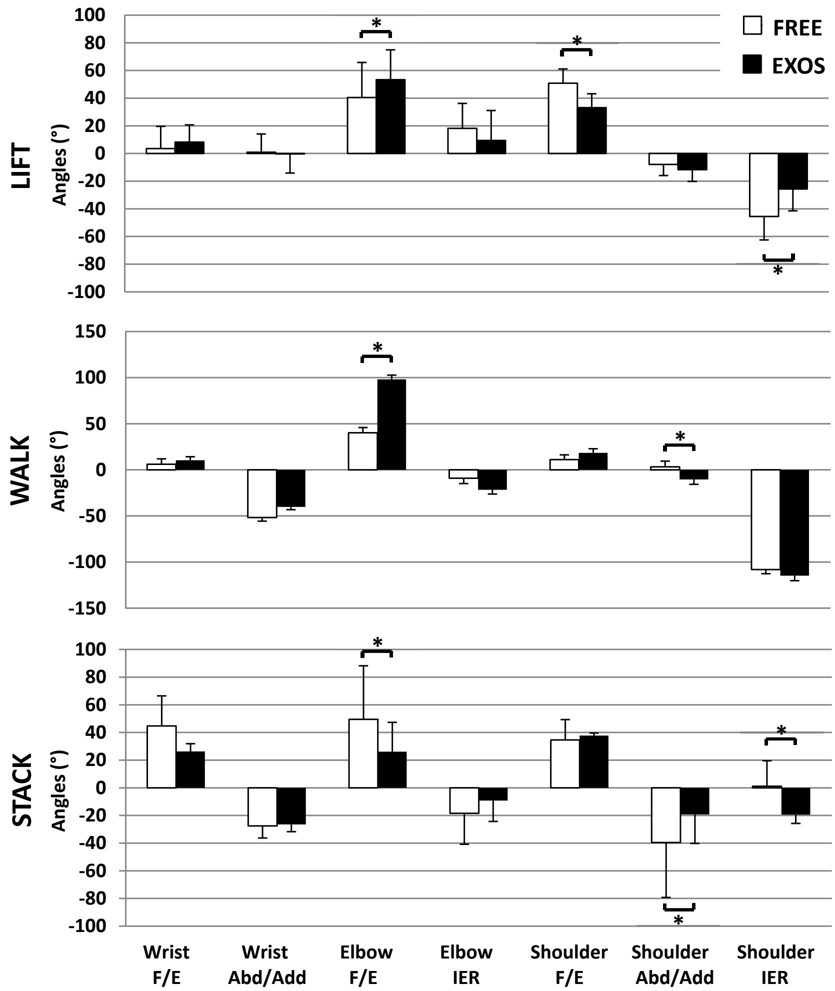

Fig. 3. Average joint angles for wrist flexion (+)/extension (−) (F/E), wrist adduction (+)/abduction (−) (Abd/Add), elbow flexion (+)/extension (−), elbow internal (+)/external (−) rotation (IER), shoulder flexion (+)/extension (−), shoulder adduction (+)/abduction (−), shoulder internal (+)/external (−) rotation (IER) during LIFT, WALK and STACK. Tasks were performed without (FREE, empty bars) and with the exoskeleton (EXOS, filled bars). For statistical significant differences between FREE and EXOS: * = $p < 0.05$.

effect on shoulder muscular strain compared to the FREE condition. Indeed, the relative activation of the AD muscle in this case was very low, even when this task was performed without assistance (3% of RMS max). Based on the kinematic data recorded during this last experimental task, it seems probable that the main muscular demand, placed on the upper limb, mainly concerned the elbow flexor muscles and not the shoulder flexor muscles, as was initially supposed (Holewijn et al., 1992). During the present experimentation, the tool box was generally maintained with the upper arm down by the body (10°) and the elbow sufficiently flexed (98°) to maintain the tool box at hip level and not hinder walking. Independently to the task to be carried out, the relative positive impacts of the exoskeleton on shoulder muscular demand depended on the gestural technique adopted by the workers.

In addition, it was also initially expected that the use of the upper limb exoskeleton during handling tasks could have broader implications on the activity of shoulder antagonist muscles in the assisted movement. Indeed, the design of the devices (passive exoskeleton, (de Looze et al., 2016)) assessed here, entailed that the energy delivered during arm elevation (i.e., shoulder flexion) had to be stored previously via the compression of springs (i.e. shoulder extension). As a result, the use of this exoskeleton in the present study increased the average workload in the TB muscle during LIFT (+95%) and STACK (+116%). Regarding this point, the present results contradict the observation of Rashedi et al. (2014) on overhead work. These authors reported that muscular demand decreased by approximately 40% in the TB with the use of an exoskeleton. Although it is possible to compare the functions of both the exoskeletons discussed here, we assume that the role of the TB muscle in the action considered in our study differed from that of Rashedi et al. (2014). During overhead work, the TB can act for the elbow extension, in order to raise the hands, or to exert an upwards force. In this case, the moments of both forces developed by the TB on the one hand, and by the exoskeleton, on the other hand, act jointly in

Table 1
Duration, rate of perceived exertion (RPE) and cardiac cost during LIFT, WALK and STACK without (FREE) and with the exoskeleton (EXOS). A 3 min duration was imposed for LIFT and corresponds to a 20 m distance in the middle of the last 30 m and to the last 2 cycles for WALK and STACK, respectively. RPE was evaluated on a scale of 6–20 (Borg, 1998). Cardiac cost was computed during the last 30s for LIFT and STACK, and during the last 30 m for WALK. For statistical differences between FREE and EXOS: * = $p < 0.05$; ** = $p < 0.01$ and *** = $p < 0.001$.

	LIFT		WALK		STACK	
	FREE	EXOS	FREE	EXOS	FREE	EXOS
Duration (s)	–	–	14.0 ± 1.2	14.7 ± 1.1	36.9 ± 6.7	47.6 ± 7.1 **
RPE (a.u.)	13.4 ± 1.1	12.9 ± 1.4	13.6 ± 1.5	11.2 ± 2.2 *	13.3 ± 1.2	12.8 ± 1.7
Cardiac cost (bpm)	52.1 ± 5.4	59.3 ± 8.2	49.3 ± 9.7	46.0 ± 4.5	66.6 ± 5.2	67.0 ± 7.4

arm extension, thereby reducing the muscular effort required by the task. In contrast, in the present study, during the load lifting task and the load stacking/unstacking task, the TB muscle mainly acted in shoulder extension to seize or place the load or the box in low position. The moments of force developed by the exoskeleton and the TB muscle thus acted in opposition, thereby explaining our present results. These observations point out that the physical assistance delivered by this type of exoskeleton is not dedicated to a specific joint or to a specific muscular group, but to a specific action (here, the sagittal elevation of the arms). The impact of the exoskeleton on muscular workload (positive or negative) and the joint concerned by the physical assistance also seem to depend on the kinematic configuration of the movement.

Furthermore, considering that the muscular strains associated with the work task are closely linked to the gestural kinematics adopted to perform it, we also envisaged characterizing the potential modifications that the use of an assistive device during handling tasks could involve in the upper limb kinematics. Indeed, the exoskeleton may lead to kinematic constraints due to its mechanical design (e.g., rigid arms, wrist belt, rigid jacket, additional mass, etc.). In this study, biomechanical analyses showed several modifications in the upper limb kinematics when using the exoskeleton, whatever the experimental task. Specifically, the use of the exoskeleton induced significant changes in the averaged flexion-extension angle of the elbow for all the tasks analysed. This could be explained by the ability of the exoskeleton to support the load carried. Thus, for LIFT and WALK the subject kept the box in more extended postures for the elbow than in the FREE condition. For the shoulder joint, significant changes were also identified in the averaged angle and in the direction of the movement. For WALK, the slight increase of shoulder adduction was accompanied by a higher averaged angle in the F/E angle of the elbow. These differences could be explained by the kinematic strains involved by the exoskeleton structure and its ability to assist the box load carried by the workers. The results are consistent with the works of Jarrasse et al. (2010) and Sylla et al. (2014), who also proved that modifications of arm kinematic are induced by the use of an upper limb robotic exoskeleton.

Associated with the kinematic constraints, it was also expected that probable changes in force transmission, in movement inertia and/or in body balance entailed by the use of the exoskeleton during the manual handling task, would have significant repercussions on the preservation of postural balance and thus on the activity of postural muscles, such as ES and TA muscles. Indeed, Sylla et al. (2014) previously reported significant modifications in the postural strategy of the users of a unilateral upper limb exoskeleton. In this study, the participants had to perform a representative overhead screwing task, with or without an assistive device. The analyses of ground reaction forces on the mediolateral and antero-posterior planes during this task revealed that workers lean slightly to one side or bend forward to maintain their balance when wearing the exoskeleton. Here, during the load lifting task (LIFT), the stabilometric analyses also demonstrated an increase of the oscillations of the centre of pressure when using the exoskeleton, particularly in the anterior-posterior plane, in comparison with the control task. These observations thus confirm that using the exoskeleton tends to increase postural strains. Moreover, the EMG analyses also revealed that the TA muscle activity was significantly higher when the lifting task was performed with assistance. However, although the activity of this muscle could have been increased by the additional mass supported in the EXOS condition, compared to the FREE one, this muscle is also strongly implicated in anterior-posterior balance regulation (Colebatch et al., 2016). Thus, based on the stabilometric analyses, it seems legitimate to presume that this observation is in this case due to the increase of postural strains. Rashedi et al. (2014) also revealed increased postural muscles stress when using an upper limb exoskeleton. More particularly, they reported an increase of the physical demands on the low back when using assistive devices. Compared to the same task, performed without equipment, this increase of ES EMG activity (iliocostalis lumborum) reached 31–88%, depending on the payload condition. In the latter study, only the right side of the lumbar muscles was involved in this increase of ES muscle activity. Thus the authors pointed to the imbalance of the exoskeleton studied, which resulted in an asymmetric fixation (on the left side) of the mechanical arm delivering the physical assistance. In the present study, ES muscle activity was not significantly affected by the use of the exoskeleton, whatever the tasks examined (i.e., LIFT, WALK and STACK). Indeed, although ES muscle activity increased strongly (+55%, $p = 0.08$) with the upper limb exoskeleton during the walking task with load carrying, this result was not confirmed by the statistical analyses. Considerable inter-subject variability regarding ES muscle activity associated with a low number of participants could partly explain the lack of statistical significance. Contrary to both previous works, the device studied here had two bilateral mechanical arms, and no asymmetrical moment, thus loading of the torso could be envisaged. Nevertheless, based on our kinematics analyses, which showed an exaggerated extension of the arms during load carrying with the exoskeleton, an increase of the workload placed on the low back would have been expected, resulting from the lengthening of the distance between the load and the body (i.e. lever arm). Further investigations may be necessary to eliminate this doubt. Indeed, there is no question of involving additional efforts on back muscles already heavily solicited during the handling task.

Carrying on from the above, to prevent potential negative impacts of using upper limb exoskeletons, the present study evaluated the cardiovascular responses during each experimental task examined. Due to the additional mass (approximately 9 kg in the present study) involved in wearing a mechanical structure, and to the kinematic strains which it imposes, the use of an upper limb exoskeleton was expected to require greater energetic demand, despite the fact that it limited muscular activity locally. To our knowledge, no previous study has investigated this issue with the use of an upper limb exoskeleton. Oxygen consumption did not seem affected during a prolonged lifting and lowering task with a back exoskeleton (Whitfield et al., 2014). The present results show, on the contrary, that the averaged absolute cardiac cost was increased (+14%) by the use of an exoskeleton during LIFT but not during STACK or WALK. During the load lifting task, a work rate was imposed on the participants, which was not the case for the two other tasks. During LIFT, the stabilometric and kinematics measures showed that wearing the exoskeleton involved muscular (TB and TA muscles), gestural and postural constraints that could partly explain the increase in cardiac cost, despite the reduction of AD muscle activity. The cardiac cost was similar with and without the exoskeleton during STACK. Nevertheless, the time taken to complete the tasks was lengthened with the assistance devices by approximately 30% in comparison with the condition without equipment. This adaptation to reduce the intensity of work had probably prevented an increase in the participants' cardiovascular stress, as observed during LIFT. Nevertheless, it appears more surprising that cardiovascular responses was not affected by the use of the exoskeleton during walking, therefore walking speed was seen to be identical between the FREE and EXO conditions. Indeed, the impact of the mass carried is known to increase the energetic cost of locomotion (Holewijn et al., 1992). In this study, it could be imagined that the muscular assistance provided by the exoskeleton to the upper limb muscles (biceps brachii, for example) offsets the negative effect of the additional mass worn on locomotion efficiency.

According to the type of handling tasks, the upper limb exoskeleton used in the present study had global physiological repercussions for the workers, reducing or aggravating the physiological demand. Thus it was interesting to know how users perceived their effort in these different work situations with the exoskeleton, compared to without equipment. It appeared that the participants did not perceive real improvement when using the assistive device during the lifting and stacking tasks, while they perceived a decrease in the effort required during the load carrying task. AD muscle activity was not affected by the exoskeleton during this task, contrary to two other experimental tasks. During full body exercise like manual handling tasks, the perceived effort may depend mainly on the intensity of metabolic demand (Sutherland et al., 1999). Questions on the perceived local muscular effort would probably have been more relevant for estimating the effect of the exoskeleton on the perceived muscular shoulder strains.

5. Conclusion

To conclude, the use of the Exhauss® exoskeleton seemed to be beneficial for reducing the workload of shoulder flexor muscles, in particular during the load lifting, lowering, and boxes stacking/unstacking tasks. Nevertheless, the benefits induced by this device did not appear without broader physiological consequences, such as increased antagonist muscle activity, postural strains, cardiovascular demand and even changes in upper limb kinematics. More technological developments thus appear essential to limit the negative repercussions of this category of assistive device. Moreover, the advantages and disadvantages of this device do not manifest themselves in the same way, according to the occupational task studied, and more exactly to the movements performed by the workers. In practical terms, these results underline the need for companies to thoroughly and specifically analyze each work situation in which an exoskeleton is intended to protect a worker against muscular over-solicitation to ensure that its contribution is perfectly well-adapted. Companies that consider purchasing this type of exoskeleton should also be advised not to focus their attention on the joints or on the muscle groups to be relieved, but on the external forces to which workers are exposed in the their tasks. Thus it will be essential to be particularly vigilant regarding cases where the use of the exoskeleton is intended for various tasks, as there is a risk of that the benefits expected for over-solicited muscles will not be obtained.

Declaration of interest

The authors report no conflicts of interest in this work.

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