New active exoskeleton reduces muscle activity and metabolic cost during repetitive lifting tasks

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Highlights

ExoBack reduces back muscles activity by 21-24% during repetitive lifting tasks

ExoBack reduces hip extensors activity by 26-39% during repetitive lifting tasks

Exoback reduces metabolic cost by 16-26 % during repetitive lifting tasks

ExoBack reduces exertion perception by 30-41% during repetitive lifting tasks

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Abstract

Manual-handling tasks, such as repetitive load lifting, put workers particularly at risk for low back pain. Exoskeletons are increasingly investigated as a promising strategy to relieve back muscles and passive tissues from excessive load. The present study investigated the effect of a novel exoskeleton on muscle activity and metabolic cost. Twenty-one healthy male participants, equipped with retro-reflective markers, electromyography sensors and a portable breathing gas analyzer, performed 40 lifting cycles both with and without exoskeleton using stoop and squat techniques. Exertion perception and users' impressions were also collected. The ExoBack reduced hip extensors activity by 26-39%, back muscles activity by 21-24%, metabolic cost by 16-26% and exertion perception by 30-41%. Other subjective outcomes suggested a fair acceptability among users. In conclusion, the present study suggested the ExoBack was helpful at relieving back load and fatigue and thus could be efficient at reducing the risk of LBP among manual-handling workers.

Keywords: Active exoskeleton; Metabolic cost; Muscle activity

1. Introduction

Low back pain (LBP) is a musculoskeletal disorder (MSD) affecting millions of people worldwide (Wu et al. 2020). As the leading cause of years lived with disability globally (Wu et al., 2020), and an economic burden of billions of dollars (Maher et al., 2017; Hartvigsen et al., 2018), it is acknowledged as a major public health issue. The patho-anatomical cause of LBP is often difficult to establish since many factors are involved in LBP incidence and recurrence (Maher et al., 2017; Hartvigsen et al., 2018; Vlaeyen et al., 2018), in addition to the complexity of the lumbar area. However, specific mechanical loadings may compromise the trunk stability (Jin, 2018) and endanger lumbar structures (McGill, 1997; Adams et al., 2004; Marshall and McGill, 2010; Petit and Roquelaure, 2015). In particular, some occupational activities, including heavy load carrying, repetitive lifting, and frequent bending, have been identified as risks factors (Marras, 1993; Ozguler, 2000; Coenen et al., 2014; Petit and Roquelaure, 2015; Ramon-Roquin et al., 2015; Amorim et al., 2019), thereby explaining that manual-handling workers are particularly exposed to LBP (Hartvigsen et al., 2018). Indeed, the prevalence of LBP in the workplace lasting at least 1 week in the US, 1 day and 30 days in France was 25% (Ferguson et al., 2019), 43% and 17% (Ozguler, 2000) respectively. According to the French Institute in charge of the security and health in the workplace, LBP represents 20% of work-related injuries and 7 % work-related diseases, resulting in 11,5 million days of work lost per year, and it is the third cause for invalidity admission (INRS, Low back pain statistics, 2018).

Prevention strategies aim at reducing the exposure to risk factors, however occupational interventions (Sowah et al., 2018) may not always be applicable or may overly hamper the productivity. Moreover, existing literature suggests they have only minor effect on LBP incidence (Sowah et al., 2018; Vlaeyen et al., 2018) although solid evidence is lacking. Those disappointing facts elicited a growing interest in exoskeletons, defined as "wearable device that augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body" (Del Ferraro et al., 2020). In the workplace, occupational exoskeletons intend to alleviate work done by the upper body (Theurel et al., 2018; Huysamen et al., 2018a), legs (LegX®) or lower back (Atoun Model Y®, CrayX®, BackX®) while performing demanding handling tasks. The present work focuses on exoskeletons designed to assist the lower back while lifting loads.

Recently, an increased number of back-assist exoskeletons have been investigated and/or commercialized (De Looze et al., 2016; Toxiri et al., 2019; Del Ferraro et al., 2020; Kermavnar et al., 2021), with the expectations that they would decrease the risk of LBP by reducing metabolic load, muscle fatigue and spinal compression. They may be passive if they use elastic materials (springs, carbon fiber beams (Näf et al., 2018)) to release elastic energy stored during part of the movement, or they are called active if powered actuators provide the user with additional torque (De Looze et al., 2016). In both cases, the mechanism of action is an increased extension moment by applying forces either parallel (Whitfield et al., 2014) or perpendicular (Näf et al., 2018) to the body.

Most of the commercialized exoskeletons are passive because they may be lighter, faster to develop and simple to use. Moreover, they were shown to decrease back muscle activity during assembly (Bosch et al., 2016; Madinei et al., 2020a) and holding tasks (Bosch et al., 2016). However, even though a decrease in metabolic cost of lifting was shown (Baltrusch et al., 2019; Baltrusch et al., 2020a), the results of muscle activity were conflicting (Baltrusch et al., 2019; Koopman et al., 2020b). In addition, passive exoskeletons exhibited limits when other tasks were considered (Baltrusch et al., 2018), suggesting they might be task-specific and may hinder the user during other activities. The lack of versatility is also explained by the limited and non-adaptive assistance. Moreover, a recent review showed back muscle activity was reduced by 25% (range -6% -48%) on average with active exoskeletons compared to 18% (range -6% -35%) with passive systems, similarly spinal compression and trunk flexion were reduced to a larger extent with active machines, even though caution is needed to compare studies (Kermavnar et al., 2021).

Promoting a better versatility, active exoskeletons have been gaining popularity, as shown by some major projects described in the literature such as Robo-Mate (Huysamen et al., 2018b; Koopman et al., 2019b; Lazzaroni et al. 2019; Poliero et al., 2019), HAL (Cyberdyne, Ibaraki, Japan) (Miura et al., 2018, 2020; Tan et al., 2019; von Glinski et al., 2019), H-WEX (Ko et al., 2018), APO (Chen et al., 2018) and other recent works (Nakamura et al., 2017; Wei et al., 2020). Active exoskeletons have already shown promising results since a decrease in back muscle activity of 6-48% has been measured, depending on the exoskeleton's design and lifting protocol (Kermavnar et al., 2021). Moreover, beneficial effects on performance parameters (Miura et al., 2018; Tan et al., 2019), and exertion perception (Huysamen et al., 2018) have been reported.

However, weight and control strategy are critical for active exoskeletons' efficiency as they ought to deliver the right assistance at the right time without interfering with the user's motion and intention. Their growing complexity, such as EMG-based control strategy systems requiring muscle activity monitoring (Poliero et al., 2019; Tan et al., 2019, van Glinski et al., 2019; Miura et al., 2020), may be counterproductive since it demands more developing time and may result in systems difficult to use in the field. Similarly, control strategy based on angular acceleration might better follow intention but require additional IMU and may not entail significant result compared to a simple inclination-based strategy (Lazzaroni et al. 2019). Therefore, a single actuator system using a simple inclination-based strategy might be the right trade-off between efficiency and acceptability.

Most studies investigating exoskeletons 'efficiency measured back muscles activity but only a few passive (Whitfield et al., 2014; Baltrusch et al., 2019; Baltrusch et al., 2020a, Del Ferraro et al., 2020; Madinei et al., 2020b; Kermavnar et al., 2021) and only one active (Wei et al., 2020) exoskeletons, investigated metabolic cost, although it provides valuable insight about fatigue induced by repetitive tasks, previously shown to increase the risk of LBP (McGill, 1997). The present study investigated a novel active exoskeleton undergoing the final stage of development. The ExoBack provides assistance adapted to the user using an inclination-based control strategy. The purpose of this study was to assess the effects of the ExoBack on muscle activity and metabolic cost during repetitive lifting tasks using two commonly used or recommended lifting techniques, i.e. stoop and squat. Muscle activity of the lower back and legs and metabolic cost were measured by surface electromyography (sEMG) and indirect calorimetry respectively. In addition, trunk flexion angle and angular speed and extension moment were calculated using cinematic data. Finally, participants' impressions were collected in order to get a sense of acceptability. It was hypothesized that 1) the exoskeleton would efficiently reduce muscular and metabolic fatigue during repetitive lifting using both stoop and squat techniques and 2) the exoskeleton, illustrating a trade-off between control strategy and simplicity, would show a good acceptability. To our knowledge, it is the first time such a comprehensive study, including muscle activity and metabolic cost measurements, as well as subjective outcomes assessment, on twenty one participants, is performed on the ExoBack, an active exoskeleton in final stage of development.

2. Material and Methods

2.1 Participants

Twenty one healthy males voluntarily enrolled in the study. They were free from LBP or any other musculoskeletal condition and did not have any back or lower limb pain in the previous 6 months. The age, height, weight of the participants were 23±3 yrs, 176±8 cm and 72±9 kg respectively. They were orally instructed, and with a written note, of the design, and potential risks of the study. All participants provided a signed informed consent before starting the experiments. The study was approved by the Est-II research ethics committee (# 20.12.07.60216).

2.2 Study design

All participants were appointed to come to the biomechanics lab at the Institut Regional de Médecine et d'Ingénierie du Sport (IRMIS) on two separate occasions. During the training session they familiarized with the exoskeleton and the lifting techniques, stoop (flexion extension with quasi straight legs) and squat (flexion extension with legs flexed 90 degrees). In particular, they practiced the execution technique with a load gradually increased until 25% of body mass at a metronome pace. The training session lasted approximately 45 minutes.

During the experimental session, each participant was equipped with the sEMG sensors, the retro-reflected markers and a portable breathing gas analyzer to measure muscle activity, trunk inclination, and oxygen consumption, respectively. Care was taken to avoid any contact with the exoskeleton at any time. Each subject performed stoop and squat activities for both conditions (with and without exoskeleton) in a randomized order. The randomization determined first the with/without condition and then the stoop/squat condition for each, in order to avoid several exoskeleton donning/doffing. Positioned on force plates, each participant performed 40 repetitions of each symmetric lifting cycle with a frontal load of 25% of body mass at a pace of 10 cycles/minute imposed by a metronome. A lifting cycle started by a flexion without load, followed by an extension with load, a flexion with load and an extension without load. Three to five minutes of rest, required for the oxygen consumption to go back to rest levels, were observed between activities and conditions to avoid fatigue. The second session lasted approximately two hours.

2.3 The active exoskeleton

The exoskeleton tested in the present study was the Exoback (RB3D, France) (fig.1) developed to assist hip extension without hampering the movement. This novel active exoskeleton is composed of a single actuator unit providing a maximum theoretical torque of 73 Nm. The actuation architecture consists of a brushless motor with an ultra-reversible reduction and a cable connecting right and left hip joints. Thanks to the inertial control unit, the actuator adapts the assistance to the user's intention of bending or load lifting providing resistant or driving torques accordingly. Torque amplitude is proportional to the sine of the inclination angle and can be adapted to the user's need, although a standard setting was used in the present study. Walking and climbing stairs are free thanks to a differential inserted on the cable route between the two hips. There are two additional actuated articulations in the back to support motion while avoiding contact with the rigid back structure. The exoskeleton's attachment to the user has been designed in order to maximize comfort. The mass of the exoskeleton is 8.4 kg.

[insert figure 1, color should be used]

Figure 1. A subject wearing the ExoBack and all the measuring equipment.

2.5 Surface electromyography

Muscle activity data were collected during the last minute using 10 Trigno (Delsys, Natick, MA, USA) wireless sensors. Skin was shaved, gently abraded/scrubbed and cleaned with alcohol before all sEMG sensors were placed bilaterally on 5 muscle pairs following SENIAM recommendations (Seniam recommendations): Longissimus (LGI), Multifidus (MLTI), Gluteus Maximus (GL), Biceps Femoris (BF) and Rectus Femoris (RF). All signals were recorded at a rate of 1000 Hz.

Data processing was performed using custom routines in Octave free software (GNU Octave version 5.2.0©). All data were band pass filtered (Butterworth 2nd order 20-500Hz), full-wave rectified and low-pass filtered (Butterworth 4th order 2.7Hz) to extract the linear envelop. Five cycles over the last 40 seconds of each trial were averaged to obtain an ensemble curve, later used to calculate the area under the curve (iEMG in uV.s) over the whole cycle and during separated flexions and extensions.

2.6 Motion analysis

Motion analysis was performed using a 12 cameras (4-Raptor) motion capture system (Motion Analysis, Rohnert Park, CA, USA) to record retro-reflective markers position (100 Hz) in Cortex software (Motion Analysis, Rohnert Park, CA, USA). Markers were placed on anatomical landmarks using a Helen Hayes markerset (Collins et al., 2009), replacing the shank and thigh wand markers with medial epicondyles and malleoli. A static trial was acquired at the beginning of each condition.

Cinematic data (trunk angles), synchronized with EMG data, were exported and Octave custom routines were used to derive total trunk inclination normalized to the flexion extension cycle. Angular speeds and accelerations were calculated, and the total flexion moment at the hip was derived.

2.7 Metabolic cost

A portable breathing gas analysis system (Metamax 3B, Cortex, Leipzig, Germany) was used to measure metabolic cost by analyzing inhaled and exhaled gases. Data were recorded in the associated software (MetaSoft Studio) and exported in .xlsx format. The change in oxygen consumption rate due to the different tasks, defined as metabolic cost in the present study, was calculated on the plateau detected during the last 30 seconds of exercise.

2.8 Extension moment

Total extension moment ($\sum M$) was calculated for both tasks using a simple model (fig.2).

[insert figure 2]

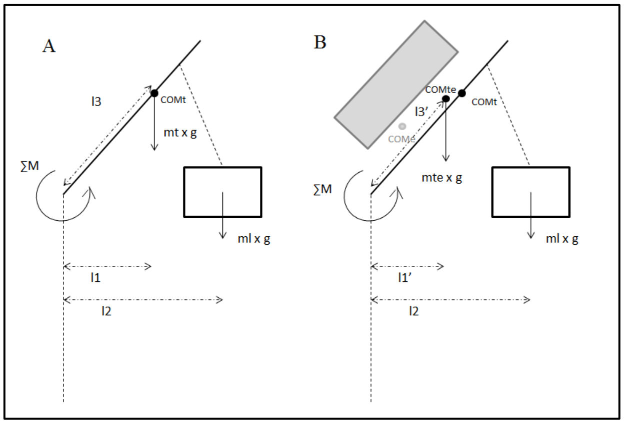

Figure 2. Model used to calculate extension moment. A. without exoskeleton. B. With exoskeleton.

The balance of moments was used at the hip: $\sum M = I\alpha$ (eq.1)

Where $\sum M$ is the sum of all moments involved in the trunk extension, I is the moment of inertia of the trunk at the hip, and α is the angular acceleration at the hip derived from the inclination measured by motion analysis.

Considering that the trunk's weight, the load and the muscle activity contribute to the total moment of extension, eq.1 can be written: $M_{muscle} = - M_{com} - M_{load} + I\alpha$ (eq.2)

With $M_{com} = m_t \times g \times l1$ (eq.3), m_t the mass of the trunk, g the gravity acceleration constant (9.81 m/s^2) and $l1$ the lever arm between the center of mass and the hip center of rotation.

And $M_{load} = m_l \times g \times l2$ (eq.4), m_l the load mass, g the gravity acceleration constant (9.81 m/s^2) and $l2$ the lever arm between the load and the hip center of rotation.

All variables were adapted when stoop with exoskeleton was considered, and the moment of extension due to muscle or to muscle + exoskeleton was compared between both conditions. Considering that the moment provided by the exoskeleton was saturated at 0.8*72 N.m during the peak total extension moment, the rest was due to muscle and was compared to the extension moment applied in the condition without exoskeleton.

2.9 Subjective outcomes

A questionnaire was used to collect exertion perception using a Borg scale (CR10) after each activity, to compare conditions with and without exoskeleton.

For the trials with exoskeleton, a body map with a similar scale was used to assess local discomfort, and questions using 100 mm visual analog scales (VAS) were asked to the participant to assess back relief, interference as well as ease to don/doff/adjust/use and usefulness of the machine.

2.10 Statistical analysis

The statistical analysis was performed using Statistica© (version 7, StatSoft Inc., Tulsa, OK, USA). Normality of the data was tested using a Shapiro-Wilk test. In case of normal distribution, a student test was performed to compare the without/with conditions for each lifting technique separately. Otherwise, a non-parametric Wilcoxon test was preferred. The threshold for significance was $p<0.05$.

3. Results

3.1 Trunk angle and angular speed

Peak trunk angle was significantly reduced when using the exoskeleton for stoop (136.5±9.7 deg vs. 140.7±9.3 deg, -3%, p=0.008) and squat (136.1±9.3 deg vs. 141.7±8.7 deg, -4%, p=0.005) tasks. However, the angular speed was not significantly affected by the exoskeleton's wear neither for stoop (132.2±22.9 deg/s vs. 124.4±20.7 deg, p=0.07) nor for squat (133.7±19.8 deg vs. 130.4±18.1 deg, p=0.493) tasks.

3.2 Surface electromyography

The areas under the curve (iEMG) of the whole ensemble curve and of each cycle part are presented in figure 3.

[insert figure 3]

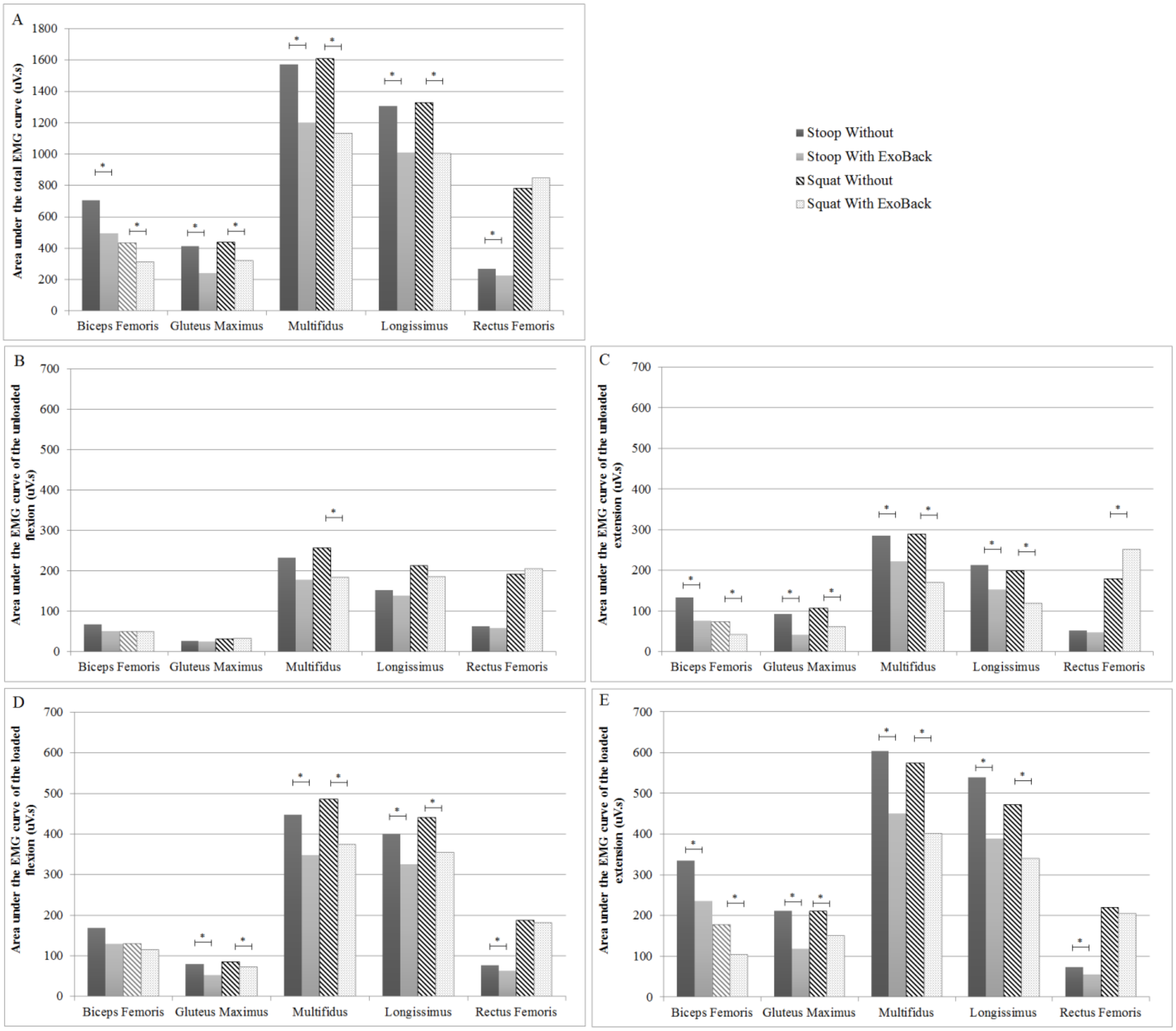

Figure 3. Integrated EMG (uV.s) for A. the whole lifting cycle B. the unloaded flexion C. the unloaded extension D. the loaded flexion E. the loaded extension. * p<0.05

For the stoop activities the area under the curve of the total cycle was significantly higher without the exoskeleton for BF (704±381 uV.s vs 493±208 uV.s, p=0.002), GL (411±183 uV.s vs 239±95 uV.s, p<0.001), MLTI (1571±624 uV.s vs 1201±417 uV.s, p=0.005), LGI (1305±666 uV.s vs 1008±496 uV.s, p=0.001) RF (265±117 uV.s vs 225±91 uV.s, p=0.043). The decreases due to the exoskeleton were 26±20%, 39±16%, 21±23%, 22±18%, 10±37% for the BF, GL, MLTI, LGI and the RF respectively.

Regarding the flexions and extensions separately, the results were similar except that the decreases were not significant for all muscles during the unloaded flexion, for BF during the loaded flexion and RF during the unloaded extension.

For the squat activities the area under the curve of the total cycle was significantly higher without the exoskeleton for the biceps femoris (434±157 uV.s vs 310±137 uV.s, p<0.001), the gluteus maximus (434±146 uV.s vs 317±194 uV.s, p<0.001), the multifidus (1608±543 uV.s vs 1131±369 uV.s, p=0.004), the longissimus (1324±665 uV.s vs 1000±609 uV.s, p=0.006) but not for the rectus femoris (p=0.269). The decreases due to the exoskeleton were 27±20%, 30±21%, 24±23%, 21±26%, 11±25% for the BF, GL, MLTI, LGI and the RF respectively.

Regarding flexions and extensions separately, the results were similar except that the decreases were not significant for BF, GL, LGI and RF during the unloaded flexion, for BF and RF during the loaded flexion and for RF during the loaded extension. It is worth noticing that the area under the unloaded extension for RF is significantly increased with the exoskeleton.

3.3 Metabolic cost

The changes in oxygen consumption rate due to the stoop and squat tasks are presented in figure 4.

[insert figure 4]

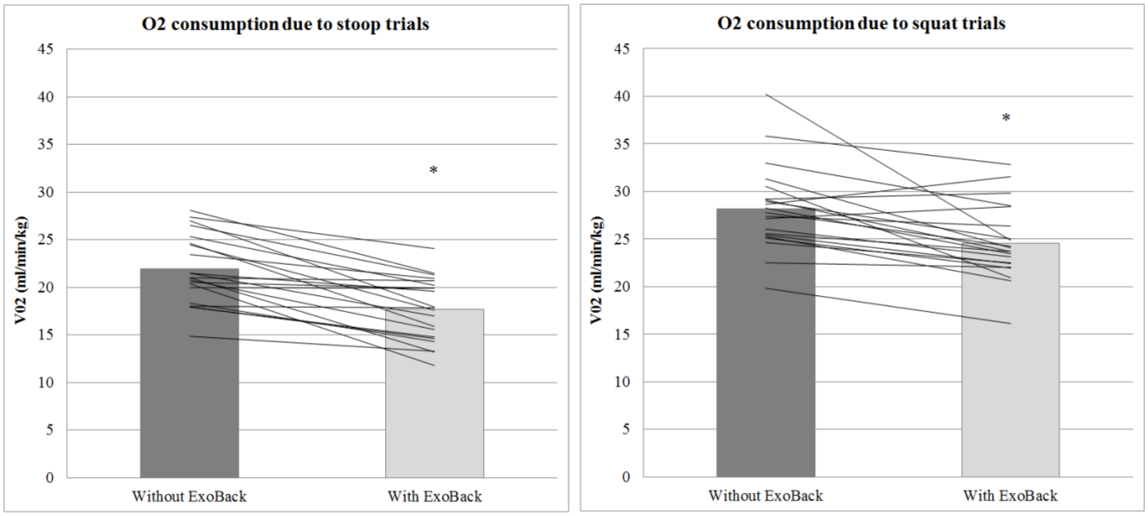

Figure 4. Oxygen consumption rates due to stoop (A) and squat (B) activities. * p<0.05

The oxygen overconsumption due to exercise was significantly lower with the exoskeleton for both lifting techniques, i.e. stoop (17.7±3.3 ml/min/kg vs 21.9±3.6 ml/min/kg, p<0.001) and SQUAT (24.6±3.9

ml/min/kg vs 28.2±4.5 ml/min/kg, $p<0.001$). Oxygen consumption rate decreased by 26±20% and 16±16% for the stoop and squat techniques, respectively.

3.4 Extension moment

The moment due to muscle work was significantly lower with the exoskeleton for stoop (244±65 N.m vs 284±54 N.m, $p<0.001$) and squat (207±69 N.m vs 246±62 N.m, $p<0.001$). Maximum moment due to muscle work decreased by 15±9% and 16±13% for the stoop and squat techniques, respectively.

3.5 Subjective outcomes

Exertion perception for stoop and squat tasks for both without and with conditions are presented in figure 5.

[insert figure 5]

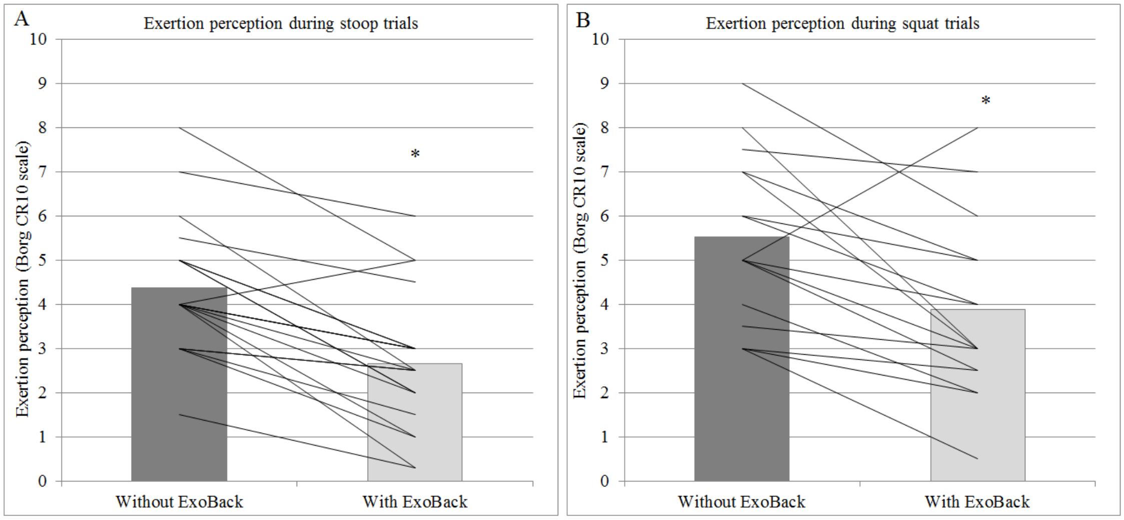

Figure 5. Exertion perceptions without and with exoskeleton for A. stoop and B. squat tasks. * $p<0.05$

The exertion perception was significantly lower with the exoskeleton for both stoop (2.6±1.5 vs. 4.4±1.5 $p<0.001$) and squat (3.9±1.7 vs. 5.5±1.7 $p<0.001$), which was a decrease of 41±27% and 30±28% for stoop and squat, respectively.

A very light to light discomfort was felt by 9 participants for stoop (score 2.4±1.4) and 13 for squat (score 2.3±1.7) mainly at the shoulders and side of the hip respectively.

The participants' impressions about the exoskeleton are presented in table 1. On the overall the participants felt a back relief, particularly with stoop task (score 79 and 63 for stoop and squat respectively, p=0.009), with only little interference with the tasks they were doing (17 and 24 for stoop and squat respectively). The exoskeleton was quite easy to use (score 84) even though it appeared less easy to don/doff and adjust (score 60) for some participants. However, the participants thought that the machine could be useful to workers that handle heavy loads frequently (score 81).

Table 1. Participants' impressions about the machine using both lifting techniques. They were asked to answer on a 100 mm visual analog scale where the limits min and max were specified.

Questions	Score (mean±sd)
Did you feel a back relief during stoop tasks? (Not at all=0 to a lot=100)	79±20
Did you feel a back relief during squat tasks? (Not at all=0 to a lot=100)	63±27
Did the machine interfere with the stoop task you were doing? (Not at all=0 to a lot=100)	17±14
Did the machine interfere with the squat task you were doing? (Not at all=0 to a lot=100)	24±21
How easy was the use of the machine? (Not easy at all=0 to very easy=100)	84±13
How easy was the don/doff and adjustment of the machine? (Not easy at all=0 to very easy=100)	60±27
Do you think the machine could be useful to workers that handle heavy loads frequently? (Not usefull at all=0 to very usefull=100)	81±17

4 Discussion

The present work aimed to assess a novel active exoskeleton in its final stage of development during repetitive lifting tasks using surface electromyography and indirect calorimetry to measure its effect on muscle activity and metabolic cost respectively. Motion analysis was used to assess the extension moment required by each task and the participants' impressions were collected. The objective of this comprehensive study was to assess the effect of the Exoback on mechanical and metabolic parameters during repetitive lifting tasks. The major finding was that lower back and leg muscle activity and oxygen consumption rate were significantly decreased with the exoskeleton for both stoop and squat lifting techniques, thereby confirming our first hypothesis. So was the second hypothesis, since the participants reported good general impressions explained by the exoskeleton's efficiency to relieve back load and assist them in the tasks with only limited interference.

In the present study, muscle activity significantly decreased on the overall lifting cycle, in particular back muscles decreased by 21-22% and 21-24% on average for stoop and squat respectively, suggesting that the muscular fatigue was alleviated by the assistance provided by the exoskeleton. Previous studies on exoskeletons showed also a decrease in lumbar activity of 6-48% and 6-35% for active and passive exoskeletons respectively (Kermavnar et al., 2021). In particular for active exoskeletons, Ko et al. found 10.5% and 23.5% decreases in erector spinae activity for stoop and semi-squat respectively using H-WEX

(4.5 kg, single actuator) with an assistance of 45 N.m to lift a 15 kg load 10 times (Ko et al., 2018). Similarly, Koopman et al. asked ten male participants to lift a box of 15kg three times using Robo-Mate, a double-actuators exoskeleton of 11kg providing a maximum assistance of 40N.m. They found a significant decrease in lumbar activity of 16.2% and 23.3% for stoop and squat respectively using the inclination mode (Koopman et al., 2019b). Above results from (Ko et al., 2018) and (Koopman et al., 2019b) for stoop were lower than the decreases measured in the current study but they were similar for squat, suggesting that the provided assistance had the greatest effect for stoop, however, the machine's weight was no longer compensated when the task was squatting. Similarly, a recent study using a maximum assistance of 80 N.m to lift 10/20 kg found similar decreases (18.3/18.7% and 25.5/24.7% for the thoracic and lumbar erector spinae respectively) using a pneumatic back exoskeleton (Kermavnar et al., 2021). However, our protocol included some muscle fatigue which was shown to have an impact on muscle activity (Tan et al., 2019). Therefore, it is worth mentioning that comparisons with other studies need caution, indeed the large range of muscle activity decrease described in (Kermavnar et al., 2021) can be explained by differences in protocol, processing and calculation techniques (Butterworth filter, RMS, MVC normalisation, comparison of mean, peak or integrated EMG, reporting of mean or median values, …). For instance, only a few studies reported integrated EMG, but Chen et al. compared only the transparent and assistive modes of APO (Chen et al., 2018), and von Glinski et al. reported a decrease of 14% of integrated EMG at the right lumbar erector spinae with HAL but the participants used a freestyle technique (von Glinski et al., 2019).

Muscle activity measured on other muscles involved in trunk extension showed similar results since GL and BF activity decreased by 39% and 26% for stoop and 30% and 27% for squat. Similarly to the comparisons made for back muscles, Ko et al. found with H-WEX a decrease of 15.8% and 10.1% for stoop and 18.6% and 30% for semi-squat (Ko et al., 2018). They also looked at antagonist muscles and measured no significant difference for RF, unlike the results observed in this study for stoop where a 10% significant decrease was measured. Although the result was not significant for squat, the exoskeleton seemed to increase their activity, suggesting that the exoskeleton's weight might have a slight negative effect explained by the fact that RF worked harder to raise the COM of the system (participant + exoskeleton). However, the exoskeleton's mass seemed to have no effect during the stoop tasks, confirming our earlier comments. Interestingly, when the loaded and unloaded flexions and extensions were taken separately, we observed only one significant difference for the unloaded flexion suggesting that the exoskeleton offered no assistance, and did not interfere neither, in this first part of the cycle. However, the back muscle activity was significantly decreased during flexion holding the load, suggesting that the exoskeleton helped the back resisting the torque added by the load. Designed as assistance for hip extension, the loaded and unloaded extensions presented all significant decrease of muscle activity as expected, except for RF, which, besides being not significant for squat during loaded extension, was significantly increased during unloaded extension, in agreement with our previous comment about the negative impact of the exoskeleton's inertial characteristics during squat. However, this potential side effect was not as high as reported by others (Kermavnar et al., 2021; Lanotte et al., 2020) and is expected to further decrease with the weight reduction forseen in the next version of the ExoBack.

In line with the muscle activity results, the metabolic cost decreased significantly with the exoskeleton as the oxygen consumption rate due to exercise was decreased by 26% and 16% for stoop and squat respectively. In the literature, to our knowledge only one active exoskeleton was shown to reduce the metabolic rate (in Kcal/min*kg) (by 18%) but it was only on 3 subjects (Wei et al., 20). On the contrary, several studies on passive exoskeletons reported decrease in metabolic cost (Del Ferraro, et al., 2020), however results were very different possibly due to differences in protocol and design, as well as in equations used to calculate metabolic cost (Del Ferraro et al., 2020). For instance, Baltrusch et al. showed a 18% decrease with SPEXOR (Baltrusch et al., 2020a) and 17% with high-cam LAEVO (but not significant with low-cam) (Baltrusch et al., 2019), VT Lowe's decreased the metabolic cost by 7.9% (Alemi et al., 2019), and finally (Madinei et al., 2020b) measured a decrease of 8-9% and 13-14% for Laevo and BackX respectively.

In the current study, the extension moment caused by the muscles significantly decreased by 15% and 16% on average for stoop and squat respectively. In the literature, very few studies calculated the extension moments, Koopman et al. measured decreases of 13.7% and 12.4% in the subject moment for stoop and squat respectively using Robo-Mate, although they insisted it was both due to the assistance provided and a change in lifting behaviour (Koopman et al., 2019b). Unlike Koopman et al., although there was a small significant decrease of the trunk angle (-3% and -4% for stoop and squat respectively), the angular speed was not affected, suggesting that the participants bent a little less but without changing dramatically their lifting behaviour. Moreover, the decreased flexion angle might be considered as a beneficial effect of the exoskeleton protecting the passive tissues taking most of the load during maximum bending (McGill, 1997).

The perceived exertion was significantly decreased with the exoskeleton for both stoop and squat techniques, by 40% and 30% respectively. In the literature on active exoskeletons, only a few assessed subjective outcomes. Huysamen et al. investigated several subjective outcomes after Robo-Mate use and observed a significant decrease in perceived exertion for the trunk of 11.4% when lifting the 15kg box (Huysamen et al., 2018b). However, participants perceived local pressure, particularly on the thighs, and six participants out of ten rated the exoskeleton's usability above acceptable. In the present study, the participants assessed the machine as moderately easy to don/doff and adjust but easy to use. Participants felt very light to light local discomfort, particularly on the side of the hip during squat tasks, as well as a strong back relief with only little interference, particularly using stoop technique. Some studies investigating passive exoskeletons reported users' impression and results depended highly on the tasks performed, the exoskeleton and the population tested (Baltrusch et al., 2018; Kermavnar et al., 2021). For instance, a first study with Laevo and 18 young healthy participants resulted in an increase in perceived difficulty for most of the tasks, including lifting, and a general discomfort median between 3.5 and 4 out 10 for this same task (Baltrusch et al., 2018) whereas a similar study using SPEXOR in a population of workers and some with a history of LBP, the perceived task difficulty of lifting was greatly decreased, so did the general low back discomfort (Kermavnar et al., 2021). However, both pointed out a mitigated impression on efficacy. In the present study, the participants assessed the exoskeleton as useful for workers with a score of 81, suggesting that not only the weight, but also the design, have a great importance on acceptability, and participants' opinion should be part of all exoskeleton's assessment.

Potential limitations should be acknowledged in the present study. Despite the great care taken by the investigators and the participants to avoid touching the sensors, some EMG data were lost during the experiments, however this was a minority and did not impact the conclusions. The actual extension moment provided by the exoskeleton was not measured although actual and commanded moments could differ as shown elsewhere (Koopman et al., 2019b). Moreover, the passive structures (tendons, ligaments,…) at maximum flexion was not taken into account, and may have resulted in overestimated peak muscle moment. Further measurements of actual machine assistance during the whole flexion/extension cycle should be performed to confirm the strong effect of the exoskeleton on the muscle moment. The present study used laboratory settings with a homogeneous population performing simple standardized tasks, as we considered this step necessary to collect reliable objective measurements. Further investigations should focus on real-life situations to assess actual workers' impressions. A longitudinal study might also account for the effect of chronic ExoBack's use on the long-term risk of LBP.

5 Conclusion

In conclusion, the here presented exoskeleton allowed to significantly reduce the metabolic cost and back muscle activity of twenty-one healthy participants performing repetitive lifting task using both stoop and squat techniques, without changing dramatically their lifting behavior. The exoskeleton's inertial aspect had a slight negative impact on the antagonist leg muscles although it was not reflected by the metabolic cost measurements. However, further refinement ought to sort this out as the weight is expected to greatly decrease. In line with the decrease in muscle activity, the extension moment applied by the subject was significantly reduced during stoop and squat tasks, which should be further assessed by monitoring the actual machine assistance. Perceivable improvements were reported by the participants regarding the exertion of each task. Despite some light local discomfort and slight interference, participants described the assistance as efficient to relieve back load, particularly during stoop lifting. They mostly thought the exoskeleton would be useful to workers, which will be further investigated by works addressing this need for real-life situations. Based on muscular and metabolic measurements, this study suggested the ExoBack was helpful at relieving back load and fatigue and thus the risk of LBP among manual-handling workers.

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