A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting

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ABSTRACT

The VT-Lowe's exoskeleton is a novel passive lift-assistive device designed to offload the back muscles during repetitive lifting. In this study, the effect of the exoskeleton on electromyographic (EMG) signals was investigated in four different lifting types (stoop, squat, freestyle and asymmetric) and two box weights (0% and 20% of body weight). Twelve young healthy adults ages 18–31 years (mean = 22.75, SD = 4.35) were participants. The EMG signals for twelve muscles (iliocostalis erector spinae (IL), longissimus erector spinae (LT), multifidus (MF), bicep femoris (BF), vastus lateralis (VL) and abdominal external oblique (AEO) muscles) were measured. The exoskeleton significantly decreased the peak and mean activity of back muscles (IL and LT) by 31.5% and 29.3%, respectively, for symmetric lifts and by 28.2% and 29.5%, respectively, for asymmetric lifts. The peak and mean EMG of leg muscles were significantly reduced by 19.1% and 14.1% during symmetric lifts, and 17.4% and 14.6% during asymmetric lifts. Although the exoskeleton reduced the activation of back and leg muscles, it slightly increased the activity of external oblique muscles, although this was not statistically significant. In conclusion, the exoskeleton is promising as a lift-assist device for manual material handlers and workers performing repetitive lifting.

1. Introduction

Work related musculoskeletal disorders (WMSDs) are one of the most prevalent causes of nonfatal occupational injuries, and these affect a significant portion of industrial workers and manual material handlers (Bosch et al., 2016). According to the Bureau of Labor Statistics (BLS), in 2015 WMSDs accounted for 31% (356,910 cases) of the total cases of injuries for all industrial workers, with the primary type of injuries being sprains, strains, or tears (426,792 cases resulting in 421,610 days-away-from-work) (BLS, 2016). Among all types of WMSDs, injuries due to lower back pain (LBP) accounted for about 17.3% of cases with median of 7 days away from work (BLS, 2016). Rubin and colleagues report that almost 80% of workers experience injuries due to WMSDs at least once in their life (Rubin, 2007). Some of these injuries, such as soreness during work, resolve in the short-term. Other injuries, such as lower back strain, can be more persistent. This is especially problematic for workers whose duties involving repetitive lifting. Compounding the problem, WMSDs from LBP have the potential to alter body posture by changing the kinematics of motion; compensating with different parts of the body increases the probability of injury and re-injury, and decreases worker effectiveness (Marras 2003; Marras and Granata, 1995; Ayoub, 1992; Park and Chaffin, 1974; Kuiper et al., 1999; Garg and Herrin, 1979). One possibility for relieving these types of WMSDs is to use an exoskeleton that will create a torque around the hip and back during lifting. By reducing the loads on the muscles and back, exoskeletons can in principle reduce injury risk and fatigue (Treaster, 2018).

Exoskeletons are generally classified into two groups: "passive" and "active." Active exoskeletons are powered by electromechanical actuators (Yang et al., 2008; Bogue, 2009; Anam and Al-Jumaily, 2012; Asbeck et al., 2015; Li et al., 2015; Islam et al., 2017). In comparison, passive exoskeletons (Zhang et al., 2015; Lamers et al., 2017; Frost et al., 2009; Wehner et al., 2009; Hasegawa and Muramatsu, 2013; Bosch et al., 2016, Kazerooni et al., 2017; Kim et al., 2018a; 2018b; Chang et al., 2019) work by storing energy in a spring or elastic element; as their wearer bends forward, their potential energy is stored in the spring, it is then returned as they stand up again. Recently, a novel, passive, wearable exoskeleton was developed at Virginia Tech in

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Fig. 1. Front and back views of the VT-Lowe's exoskeleton.

collaboration with Lowe's Inc. (Chang et al., 2019), shown in Fig. 1.

The exoskeleton consists of carbon fiber beams running along the center of the back and along the backs of the legs, and they are held together with a mounting block at the back of the waist. Soft components, including a waist belt, shoulder straps, and thigh pads, connect the exoskeleton frame to the body. The carbon fiber beams (42 beams along the back, and 14 at the back of each leg) flex when the wearer bends forward, storing energy, and return > 95% of it to the wearer when they return to a standing posture. The shoulder harness and thigh pads are connected to the carbon fiber beams through low-friction sliders, so they can move to accommodate different heights of wearer and can accommodate the kinematic difference between the exoskeleton and body during lifting. Nominally, the exoskeleton should offset the weight of the wearer's torso during lifting, but in practice, the torque-versus-angle relationship was not optimized. A detailed explanation of exoskeleton's components and behavior is available in Chang et al. (2019).

A summary of several passive lift-assistive exoskeletons follows. For more details, a comprehensive review of exoskeletons for industrial applications is available in de Looze et al. (2016). In 2006, the PLAD (Personal Lift-Assistive Device) was developed and extensively studied (Abdoli et al., 2006; Frost et al., 2009; Whitfield, 2014). The PLAD lowers the lumbar moment during lifting tasks using elastic bands/elements (Abdoli et al., 2006; Frost et al., 2009). Abdoli et al. (2006) reported that PLAD significantly reduced the integrated muscle activity of lumbar and thoracic erector spinae by 14.4% and 27.6%, respectively, with no significant changes in the activation level of the abdominal muscles. In 2009, Frost et al. modulated the elastic stiffness of the PLAD. They found that the condition that was most beneficial to the back reduced the activity of erector spinae muscles (average of lumbar and thoracic) for stoop and freestyle lifts by 37% and for squat lifting by 38%, but increased external oblique activity during stoop lifting by up to 138% and increased rectus femoris activity during freestyle and squat lifting by 29–83%. In 2008, Abdoli et al. tested the PLAD during asymmetric lifting for three different loads (5 kg, 15 kg and 25 kg) and reported that ensemble average of integrated electromyography (EMG) amplitudes lowered by 23.9% for lumbar erector spinae and 24.4% for thoracic erector spinae (Abdoli and Stevenson, 2008).

Ulrey et al. tested another personal weight transfer device called the BNDR (Bending Non-Demand Return) (Ulrey and Fathallah, 2012). They demonstrated that in static stooped postures, BNDR could lower the muscle activity of bicep femoris by 17% and the lumbar flexion could also be lowered by 12%.

Bosch et al. evaluated a recent lift-assistive exoskeleton which is currently being marketed as the Laevo (Bosch et al., 2016). The paper describes two experiments performed: the first study was a simulated assembly task with the trunk held in bent-forward position, while in the second study the trunk was held statically in a similar posture without any additional activity. They found that the low back muscle activity reduced by 35–38% during the first task, and that users had increased discomfort in the chest but lower discomfort in the back. They also found out that the users' endurance time increased from 3.2 min to 9.7 min on average during static holding tasks (Bosch et al., 2016). Similar EMG results were reported by Koopman for similar tasks with the same exoskeleton (Koopman et al., 2019).

In 2017, Lamers et al. proposed a new passive lift-assistive garment which was similar to PLAD except the elastic bands were directly against the body (Lamers et al., 2017). The EMG results demonstrated that the device could lower the mean and peak erector spinae muscle activity by 14–16% and 19–23% for squat lifting tasks (two box weights: 12.7 kg and 24 kg) and 23–43% for static leaning tasks.

In comparison to the other exoskeletons described here, our device provides a higher peak torque to the wearer. It pushes perpendicularly to the chest and legs, whereas the PLAD and lift-assistive garment pull down on the shoulders to some extent. Its uses carbon fiber, which has a much higher energy return than gas springs such as used in the Laevo (typically ~ 85%). Our exoskeleton also permits torso rotations and arbitrary lifting kinematics due to its flexible structure.

In the current study, we measured the peak and mean muscle activities of 12 muscles during four different types of dynamic lifting (stoop, squat, freestyle and asymmetric) and two box weights (0% and 20% of bodyweight) both with and without the exoskeleton. We hypothesized that the normalized peak and mean muscle activities of back and leg muscles would be reduced when the VT-Lowe's exoskeleton was worn.

2. Materials and methods

2.1. Participants

A convenience sample of 12 young and healthy male participants were recruited for in-lab experiments from the university and local community. Their average (SD) ages, heights, body weights and BMIs were 22.75 (4.35) years, 178.92 (6.05) cm, 80.41 (5.59) kg and 25.16 (1.91) kg/m^2, respectively. The study was approved by the Institutional Review Board (IRB) of Virginia Tech and all participants signed consent forms at the beginning of the study session. None of participants had any history of musculoskeletal disorders or low back pain in the past year and all of them were capable of lifting at least 25% of their body weight.

2.2. Preparation

All of the participants were trained for around half an hour during which time they wore the exoskeleton and conducted 15–25 practice lifts (stoop, squat, freestyle, asymmetric) with boxes containing 0% and 20% of their bodyweight. During this time, the exoskeleton was adjusted for each participant based on their verbal feedback until they felt comfortable with it and no further modifications were necessary.

2.3. Instrumentation

To quantify the muscle activity, electromyographic signals were recorded using a wireless Delsys Trigno™ (Delsys Inc., Boston, MA, USA) system (differentially amplified with a gain of 1000 and a bandwidth of 20–450 Hz). The EMG data were sampled at a frequency of 1925.93 Hz. For proper placement of EMG electrodes, the steps provided in SENIAM (for back muscles), Barbero et al. (for leg muscles) and Abdoli et al. (for abdominal external oblique muscles), were followed
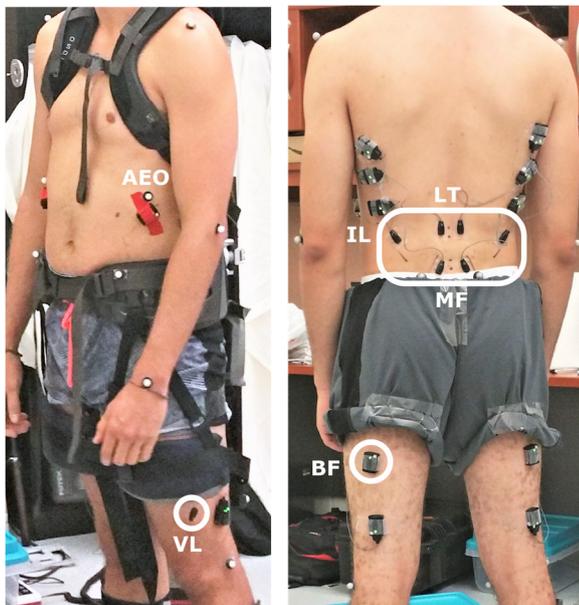
Fig. 2. EMG electrode placement locations.

(SENIAM (http://www.seniam.org/ and Hermens et al., 1999), Barbero et al., 2012; Abdoli et al., 2006). The palpation technique was also utilized in advance to find the spinal bones, anterior superior iliac crest (ASIS), posterior superior iliac crest (PSIS) and other important joints to determine the exact placement of the muscles. A total of twelve EMG electrodes (six on the back (bilaterally), two in front (bilaterally) and four electrodes on the legs) were placed on the Abdominal External Oblique (AEO), Longissimus Erector Spinae (LT), Iliocostalis Erector Spinae (IL), Multifidus (MF), short head Bicep Femoris (BF) and Vastus Lateralis (VL) muscles. Electrode placements are shown in Fig. 2.

2.4. Experimental procedures

A full lifting cycle for symmetric lifting types was defined as bending down, grasping a $0.43 \times 0.31 \times 0.2\,m^3$ plastic box on the floor, lifting the box up to a standing posture, pausing for a moment, lowering the box down to the floor again, and finally returning to the original standing posture.

The experimental session proceeded with the following steps. After fitting and lifting training with the exoskeleton, the EMG electrodes were placed carefully on all 12 muscles described above. Then, all participants were asked to perform a series of isometric maximum voluntary contraction (MVC) tasks to isolate the specific muscles so the peak muscle activity could be found for further EMG normalization. The MVC was used because it allows a comparison of the task demands between subjects, and it allows for normalization of EMG data for each subject. At the end of each MVC trial, enough rest was provided for participants so their heart rates and muscle activities returned to normal. After finishing all MVC trials, participants rested for 15–20 min.

The stoop, squat and freestyle lifting trials were all performed in the sagittal plane. All participants were asked to perform these three lifting types plus asymmetric lifts for 0% and 20% of their bodyweights, both with and without exoskeleton, in a randomized order. The order was randomized to assure that experimental confounding effects due to fatigue and other unknown effects would be minimized. For stoop lifting, the participants used their own back and hips to lift a box. While in this type of lifting the knees should not be bent, during the experiment a small amount of knee bending was allowed, especially for tall subjects. For squat lifting, the subject used their own legs to lift a box (i.e. lifting with neutral spine). In this case, the knees became bent and the
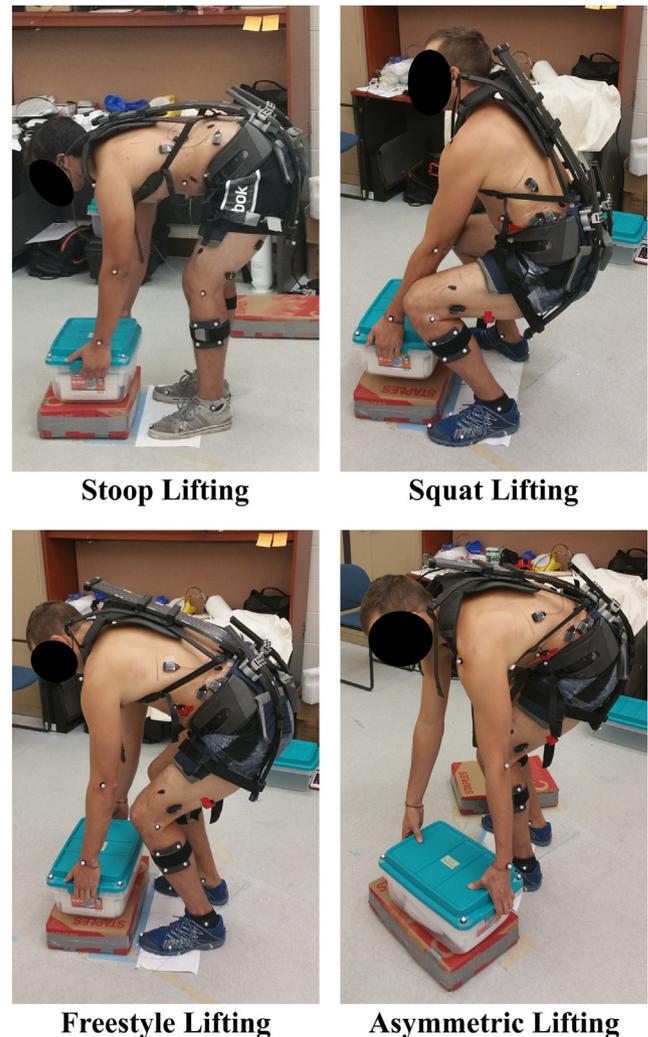

Fig. 3. Photos of the four different lifting types in the experiment.

participants tried to keep their trunk as straight as possible. For freestyle lifting, there were no restrictions on lifting style and the participants chose their own desired lifting method. The lift height was kept constant across all symmetric lifting types.

In contrast to symmetric lifts, asymmetric lifts started at 60 degrees to the left side of sagittal plane (starting point) and ended at 60 degrees to the right side of the sagittal plane (ending point). As such, the participant's trunk rotated clockwise by 120 degrees during the lifting task. The participants moved directly between these two poses, only bringing the box around 0.5 m high above the floor; they did not stand up fully or pause as with the symmetric lifts. At the end of each asymmetric lift, an experimenter returned the box to the starting point, so participants only lifted the box from left to right. During asymmetric lifting, the feet were kept stationary so that the majority of the rotation occurred at the waist and trunk. Fig. 3 depicts the different lifting types in the study.

In every trial, the subject started in standing position and performed the complete lifting cycle four times per minute (once every 15 s). A narrative script was built using MATLAB (The MathWorks, Inc., Natick, MA) and the subject lifted and returned the box as narrator commanded. Before start of lifting tasks, the participants were asked to perform assorted lifting trials to find the foot position relative to the box which felt most comfortable during lifting. This position was recorded by tracing on the floor around the participant's foot, and it was used for all lifts during the remainder of the experiment. Each participant performed 64 different trials including 16 different conditions ($4 \times 2 \times 2$). Rest was provided after each trial to the participant's preference. At the

end of the experiment, the subject was asked to provide ratings of possible discomfort for each part of their body and to propose any suggestions that could improve the exoskeleton's design.

2.5. Data processing

To process and filter the raw EMG signals (both in lifting trials and during Maximum Voluntary Contraction (MVC) tasks), first the mean of the signal was subtracted. Next, the resulting signal was band-pass filtered (20–450 Hz, 6th-order Butterworth filter, bidirectional) and subsequently full-wave rectified. Then, to smooth the EMG signals, root-mean-square (RMS) envelopes were computed using a moving window of 400 ms.

All EMG signals during lifting sessions were normalized based on the peak muscle activity obtained during the MVC trials. To report the normalized EMG values for stoop, squat and freestyle conditions, the average peak and average mean values of muscle activities of right and left muscles were averaged for all participants. For asymmetric lifting conditions, the average peak and average mean values of the EMG for each muscle were averaged across all participants and reported separately.

2.6. Statistical analysis

As discussed in the experimental procedures section, there are three independent variables in this study: A: lifting type (4 levels), B: exoskeleton intervention (2 levels) and C: box weight (2 levels). To report the normalized (with respect to MVC) EMGs, normalized muscle activities were averaged for left and right sides for symmetric lifts (stoop, squat and freestyle) while for asymmetric lifting, the normalized muscle activities for each side are presented separately. The two dependent variables in this study are: 1. normalized averaged peak muscle activity for all muscles (averaged over up to 4 lifting cycles in a trial), and 2. normalized averaged mean muscle activity for all muscles (averaged over up to 4 lifting cycles in a trial). For statistical analysis of EMG data, initially a *t*-test was performed to study if there were any significant differences between right and left muscles for all symmetric lifts (stoop, squat and freestyle). Next, a three-way ANOVA of repeated measures was performed using JMP Pro 11 (SAS, Cary, NC) assuming that the minimum level of significance was 0.05. In addition to investigating the fixed effects of independent variables on dependent variables, the interaction effects were considered and the significant interaction effects were reported.

3. Results

Tables 1 and 2 represent the descriptive statistics for normalized average peak and mean muscle activities respectively. Standard deviations are presented in parentheses. In each table, percent changes in muscle activity between the with-exoskeleton and no-exoskeleton trials across all conditions were also provided. The last column (total reduction) in Tables 1 and 2 reports the ensemble average of the EMG reduction for all four different lifting types.

The p-values and effect sizes (η_p^2) of three-way ANOVA test for normalized average peak and mean muscle activities for all 12 muscles are shown in Table 3. Results of three-way ANOVA showed that the exoskeleton significantly reduced the averaged peak muscle activation in all conditions except for abdominal external oblique muscles. Although the peak muscle activation increased for AEO muscles, the increase was not statistically significant for LAEO (p = 0.37) and RAEO (p = 0.17). For averaged mean muscle activities, the exoskeleton had significant effects on EMG reduction of all muscles except RAEO (p = 0.064) and LAEO (p = 0.069). Lifting type had also significant effect on peak EMG on all muscles except the right illiocostalis lumborum (RIL: p = 0.673). For averaged mean muscle activity, lifting type

effect was significant on EMG reduction for all back and leg muscles. Box weight also showed a significant effect on averaged peak and mean muscle activation for all back muscles. Regarding the interaction effects, results revealed that there were no interaction effects for "Lifting Type × Exo Intervention", "Box Weight × Exo Intervention" and "Lifting Type × Box Weight × Exo Intervention" for all muscles studied.

Figs. 4–6 represent the graphical display of ensemble average of normalized peak and mean muscle activities for stoop, squat, freestyle and asymmetric lifting types for both box weights. For symmetric lifts, the normalized EMGs of left and right muscles were averaged and reported in Figs. 4 and 5. However, for asymmetric lifts, the EMG results of all muscles were reported separately. All of these graphs demonstrated that VT-Lowe's exoskeleton significantly lowered the averaged peak and mean of back and leg muscle activities during all types of lifts across all conditions.

The peak and mean muscle activity reductions averaged across back muscles (IL and LT muscles) and all symmetric lifting types were 31.5% and 29.3%, respectively. In the back (IL and LT), the peak and mean EMG reductions for squat (peak: 35.4%, mean: 31.4%) and freestyle (peak: 32.3%, mean: 30.5%) lifts were close to each other but greater than stoop lifting (peak: 27%, mean: 25.9%). In the legs, stoop lifting had higher peak and mean EMG reductions compared to squat and freestyle lifts (stoop: peak: 22.8%, mean: 18.9%; squat: peak: 16.5%, mean: 9% and freestyle: peak: 18.1%, mean: 14.4%).

For asymmetric lifting, the IL and LT muscles had an average EMG reduction of 28.2% for the peak (lower than the average of symmetric lifting types) and an EMG reduction of 29.5% for the average mean muscle activity (slightly larger than the average of symmetric lifts). Asymmetric lifts also showed 17.4% and 14.6% EMG reduction for peak and mean leg muscles' activities, respectively. Therefore, symmetric lifts had a higher peak EMG reduction for leg muscles on average.

4. Discussion

As discussed in introduction, Abdoli et al showed that the EMG activity of lumbar and thoracic erector spinae (for symmetric lifts) could be reduced by 14.4–27.6% while using the PLAD. In comparison, the VT-Lowe's exoskeleton showed higher peak and mean EMG reductions on average across all symmetric lifting types. Additionally, for asymmetric lifts, Abdoli and Stevenson (2008) reported the reduction of 23.9% and 24.4% across all subjects for lumbar and thoracic erector spinae muscles, respectively. The VT-Lowe's exoskeleton, however, showed on average higher EMG reduction (by ~5%) for asymmetric lifts (peak: 28.2% and mean: 29.5% for IL and LT muscles).

In Lamers study, the mean EMG of erector spinae muscles reduced by 14–16%, whereas, the peak erector spinae muscle activity reduced by 19–23% for squat lifting tasks (Lamers et al., 2017). However, for symmetric lifting tasks with VT-Lowe's exoskeleton, the average peak and mean of IL and LT muscles' activity reduced by 31.5% (peak) and 29.3% (mean). The VT-Lowe's exoskeleton thus resulted in a higher mean and peak EMG reduction compared to the device in the Lamers study by a factor of almost two.

The only muscles where the average EMG did not decrease with the VT-Lowe's exoskeleton were the external oblique muscles, where the peak and mean EMGs increased by 16–39%. These relatively large percentages are due to the fact that the normalized peak and mean muscle activations across all conditions were quite small relative to the other muscles, so a small absolute increase corresponds to a large percentage (see Tables 1 and 2). In addition, during lifting, for a number of participants the stomach EMG electrodes were very close to the waist belt which resulted in weak signals with a high signal-to-noise ratio. Furthermore, it is likely that many of the participants were not fully adapted to wearing the exoskeleton before the test was completed, as they only had a small amount of training time at the beginning of the experimental session. The magnitude of peak EMG for AEO muscles was subject to high inter-subject variability independent of bodyweight or

Table 1
Normalized average peak muscle activity, standard deviations and % change in muscle activity (with versus without the exoskeleton) across all conditions.

Muscle names	Box weights	Stoop			Squat			Freestyle			Asymmetric			Total reduction (%)
		Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	
Right Illiocostalis Lumborum	0%	0.225 (0.132)	0.153 (0.073)	−25.9	0.253 (0.155)	0.141 (0.091)	−42.8	0.230 (0.116)	0.136 (0.071)	−39.6	0.236 (0.169)	0.148 (0.091)	−35.4	−36.0
	20%	0.372 (0.186)	0.254 (0.125)	−30.5	0.422 (0.216)	0.251 (0.134)	−40.4	0.384 (0.204)	0.237 (0.143)	−39.1	0.324 (0.203)	0.261 (0.201)	−24.7	−33.7
Left Illiocostalis Lumborum	0%	0.305 (0.185)	0.169 (0.077)	−34.4	0.314 (0.202)	0.187 (0.146)	−39.7	0.298 (0.175)	0.148 (0.071)	−42.7	0.298 (0.157)	0.171 (0.087)	−35.7	−38.1
	20%	0.466 (0.247)	0.316 (0.160)	−30.1	0.610 (0.365)	0.350 (0.202)	−32.3	0.519 (0.281)	0.287 (0.135)	−30.9	0.381 (0.212)	0.278 (0.203)	−26.7	−30.0
Right Longissimus Thoracis	0%	0.477 (0.129)	0.350 (0.118)	−27.1	0.529 (0.127)	0.337 (0.123)	−37.2	0.478 (0.135)	0.326 (0.125)	−31.8	0.411 (0.117)	0.291 (0.107)	−30.2	−31.6
	20%	0.783 (0.196)	0.628 (0.168)	−20.0	0.831 (0.186)	0.604 (0.180)	−27.7	0.745 (0.154)	0.576 (0.155)	−22.8	0.546 (0.124)	0.440 (0.106)	−19.4	−22.5
Left Longissimus Thoracis	0%	0.396 (0.144)	0.274 (0.109)	−27.0	0.427 (0.170)	0.278 (0.091)	−39.2	0.391 (0.146)	0.264 (0.129)	−31.5	0.371 (0.176)	0.248 (0.110)	−31.3	−32.3
	20%	0.674 (0.262)	0.537 (0.214)	−20.6	0.693 (0.251)	0.528 (0.201)	−23.5	0.627 (0.234)	0.480 (0.158)	−20.0	0.412 (0.166)	0.313 (0.125)	−22.4	−21.6
Right Multifidus	0%	0.484 (0.241)	0.366 (0.187)	−19.6	0.420 (0.185)	0.307 (0.159)	−29.6	0.371 (0.142)	0.307 (0.148)	−28.7	0.381 (0.183)	0.318 (0.185)	−16.8	−23.7
	20%	0.669 (0.328)	0.554 (0.273)	−20.7	0.626 (0.224)	0.449 (0.210)	−20.9	0.573 (0.219)	0.494 (0.234)	−17.0	0.449 (0.221)	0.399 (0.213)	−18.1	−19.2
Left Multifidus	0%	0.491 (0.169)	0.363 (0.151)	−24.7	0.462 (0.143)	0.341 (0.134)	−24.2	0.405 (0.145)	0.309 (0.157)	−27.1	0.454 (0.192)	0.377 (0.140)	−22.8	−24.7
	20%	0.713 (0.291)	0.597 (0.238)	−15.7	0.675 (0.207)	0.533 (0.219)	−22.9	0.638 (0.198)	0.462 (0.160)	−23.7	0.504 (0.200)	0.416 (0.201)	−19.1	−20.3
Right Vastus Lateralis	0%	0.188 (0.057)	0.151 (0.050)	−20.0	0.580 (0.190)	0.509 (0.152)	−8.8	0.387 (0.130)	0.344 (0.088)	−6.5	0.171 (0.085)	0.135 (0.075)	−22.7	−14.5
	20%	0.162 (0.076)	0.120 (0.052)	−19.6	0.581 (0.189)	0.507 (0.175)	−8.1	0.443 (0.184)	0.346 (0.130)	−24.4	0.196 (0.087)	0.165 (0.094)	−18.0	−17.5
Left Vastus Lateralis	0%	0.121 (0.088)	0.086 (0.054)	−23.1	0.550 (0.253)	0.443 (0.225)	−17.8	0.392 (0.221)	0.324 (0.153)	−11.9	0.162 (0.101)	0.107 (0.065)	−27.7	−20.1
	20%	0.115 (0.065)	0.087 (0.046)	−28.5	0.537 (0.238)	0.434 (0.224)	−20.1	0.403 (0.199)	0.298 (0.150)	−25.2	0.196 (0.129)	0.149 (0.074)	−21.7	−23.9
Right BF	0%	0.261 (0.095)	0.197 (0.078)	−24.9	0.200 (0.094)	0.158 (0.079)	−20.7	0.225 (0.080)	0.177 (0.064)	−20.5	0.263 (0.106)	0.213 (0.085)	−17.3	−20.8
	20%	0.409 (0.133)	0.321 (0.120)	−21.9	0.302 (0.134)	0.238 (0.089)	−19.2	0.306 (0.100)	0.250 (0.078)	−17.6	0.301 (0.116)	0.242 (0.108)	−20.1	−19.7
Left BF	0%	0.208 (0.059)	0.160 (0.043)	−21.5	0.129 (0.076)	0.100 (0.046)	−18.9	0.150 (0.072)	0.116 (0.046)	−20.0	0.221 (0.067)	0.199 (0.070)	−9.5	−17.5
	20%	0.343 (0.059)	0.263 (0.041)	−22.7	0.221 (0.084)	0.182 (0.075)	−18.1	0.236 (0.072)	0.192 (0.060)	−18.6	0.351 (0.088)	0.337 (0.090)	−2.3	−15.4
Right AEO	0%	0.064 (0.052)	0.124 (0.127)	46.1	0.068 (0.057)	0.110 (0.063)	59.4	0.052 (0.035)	0.081 (0.064)	33.9	0.129 (0.112)	0.131 (0.097)	36.7	44.0
	20%	0.089 (0.066)	0.130 (0.144)	26.9	0.088 (0.054)	0.135 (0.080)	43.8	0.072 (0.040)	0.108 (0.072)	26.4	0.213 (0.163)	0.267 (0.212)	35.7	33.2
Left AEO	0%	0.081 (0.049)	0.109 (0.089)	21.0	0.089 (0.073)	0.112 (0.082)	19.7	0.069 (0.051)	0.086 (0.098)	22.2	0.125 (0.093)	0.154 (0.112)	26.6	22.4
	20%	0.112 (0.065)	0.135 (0.087)	6.0	0.122 (0.102)	0.150 (0.111)	32.3	0.097 (0.074)	0.113 (0.105)	9.5	0.191 (0.109)	0.240 (0.191)	22.7	17.6

Table 2

Normalized average mean muscle activity, standard deviations and % change in muscle activity (with versus without the exoskeleton) across all conditions.

Muscle names	Box weights	Stoop			Squat			Freestyle			Asymmetric			Total reduction (%)
		Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	Without Exo	With Exo	% Difference	
Right Illiocostalis Lumborum	0%	0.083 (0.050)	0.060 (0.032)	−23.8	0.084 (0.045)	0.055 (0.035)	−35.3	0.080 (0.041)	0.052 (0.030)	−33.9	0.069 (0.045)	0.050 (0.028)	−29.4	−30.6
	20%	0.121 (0.064)	0.090 (0.050)	−24.9	0.132 (0.067)	0.088 (0.050)	−33.8	0.115 (0.063)	0.077 (0.043)	−32.2	0.092 (0.056)	0.068 (0.048)	−28.6	−29.9
Left Illiocostalis Lumborum	0%	0.104 (0.060)	0.061 (0.036)	−34.9	0.098 (0.055)	0.065 (0.046)	−35.5	0.094 (0.052)	0.055 (0.037)	−37.4	0.080 (0.046)	0.051 (0.034)	−31.5	−34.8
	20%	0.141 (0.076)	0.100 (0.054)	−28.9	0.166 (0.086)	0.103 (0.055)	−29.9	0.155 (0.080)	0.088 (0.048)	−29.8	0.100 (0.058)	0.063 (0.038)	−31.3	−30.0
Right Longissimus Thoracis	0%	0.164 (0.055)	0.119 (0.049)	−26.9	0.167 (0.039)	0.111 (0.051)	−35.2	0.159 (0.041)	0.108 (0.046)	−33.3	0.124 (0.042)	0.083 (0.038)	−33.3	−32.2
	20%	0.241 (0.066)	0.195 (0.064)	−19.8	0.255 (0.057)	0.192 (0.071)	−25.8	0.233 (0.058)	0.178 (0.055)	−23.9	0.160 (0.049)	0.117 (0.051)	−25.8	−23.8
Left Longissimus Thoracis	0%	0.138 (0.068)	0.092 (0.047)	−26.6	0.137 (0.064)	0.099 (0.045)	−33.1	0.128 (0.057)	0.089 (0.049)	−30.2	0.094 (0.041)	0.062 (0.029)	−32.1	−30.5
	20%	0.208 (0.096)	0.165 (0.078)	−21.4	0.211 (0.092)	0.165 (0.084)	−22.5	0.198 (0.091)	0.149 (0.070)	−23.2	0.114 (0.050)	0.084 (0.039)	−24.4	−22.9
Right Multifidus	0%	0.178 (0.081)	0.142 (0.069)	−11.4	0.157 (0.071)	0.132 (0.075)	−22.1	0.148 (0.062)	0.128 (0.069)	−25.0	0.123 (0.061)	0.101 (0.054)	−19.3	−19.4
	20%	0.226 (0.104)	0.194 (0.091)	−17.6	0.234 (0.087)	0.172 (0.093)	−20.6	0.215 (0.081)	0.182 (0.089)	−19.7	0.151 (0.066)	0.130 (0.070)	−22.8	−20.1
Left Multifidus	0%	0.174 (0.060)	0.136 (0.054)	−15.4	0.156 (0.046)	0.132 (0.062)	−15.5	0.151 (0.051)	0.127 (0.063)	−21.0	0.133 (0.049)	0.108 (0.043)	−22.7	−18.6
	20%	0.239 (0.080)	0.206 (0.080)	−14.1	0.236 (0.070)	0.200 (0.096)	−17.0	0.230 (0.073)	0.174 (0.071)	−20.9	0.159 (0.059)	0.133 (0.043)	−16.6	−17.1
Right Vastus Lateralis	0%	0.079 (0.042)	0.059 (0.030)	−23.4	0.154 (0.037)	0.141 (0.033)	−6.8	0.114 (0.045)	0.102 (0.032)	−6.1	0.056 (0.039)	0.050 (0.036)	−10.9	−11.8
	20%	0.058 (0.027)	0.048 (0.026)	−12.8	0.157 (0.040)	0.147 (0.046)	−3.1	0.117 (0.038)	0.103 (0.037)	−16.2	0.060 (0.036)	0.060 (0.042)	−3.1	−8.8
Left Vastus Lateralis	0%	0.045 (0.033)	0.028 (0.017)	−28.9	0.137 (0.054)	0.121 (0.050)	−8.6	0.101 (0.055)	0.087 (0.039)	−7.8	0.041 (0.029)	0.032 (0.018)	−15.1	−15.1
	20%	0.036 (0.020)	0.031 (0.013)	−14.0	0.134 (0.051)	0.128 (0.063)	−3.8	0.105 (0.053)	0.082 (0.038)	−19.9	0.047 (0.031)	0.038 (0.022)	−19.9	−14.4
Right BF	0%	0.077 (0.036)	0.061 (0.034)	−22.4	0.065 (0.033)	0.0656 (0.035)	−16.3	0.077 (0.039)	0.060 (0.033)	−23.1	0.086 (0.047)	0.066 (0.040)	−21.9	−20.9
	20%	0.110 (0.042)	0.092 (0.042)	−17.5	0.100 (0.043)	0.082 (0.040)	−17.2	0.098 (0.037)	0.081 (0.033)	−16.1	0.097 (0.047)	0.072 (0.039)	−23.3	−18.5
Left BF	0%	0.060 (0.027)	0.046 (0.019)	−21.3	0.041 (0.023)	0.045 (0.016)	−9.8	0.046 (0.026)	0.036 (0.016)	−17.7	0.055 (0.020)	0.045 (0.018)	−16.5	−16.3
	20%	0.083 (0.030)	0.073 (0.023)	−11.0	0.066 (0.030)	0.061 (0.030)	−6.4	0.069 (0.030)	0.062 (0.025)	−8.2	0.067 (0.022)	0.064 (0.030)	−5.9	−7.9
Right AEO	0%	0.019 (0.009)	0.031 (0.021)	35.6	0.024 (0.021)	0.034 (0.022)	35.5	0.021 (0.018)	0.024 (0.018)	15.8	0.029 (0.018)	0.033 (0.021)	18.9	26.5
	20%	0.028 (0.016)	0.035 (0.024)	22.3	0.031 (0.025)	0.039 (0.025)	30.0	0.026 (0.018)	0.033 (0.020)	25.1	0.036 (0.021)	0.050 (0.025)	35.6	28.2
Left AEO	0%	0.025 (0.014)	0.030 (0.019)	17.9	0.031 (0.020)	0.033 (0.023)	15.4	0.031 (0.019)	0.028 (0.023)	14.6	0.033 (0.018)	0.035 (0.021)	11.7	14.9
	20%	0.036 (0.021)	0.040 (0.021)	4.6	0.039 (0.028)	0.043 (0.030)	28.4	0.033 (0.021)	0.037 (0.030)	23.7	0.043 (0.027)	0.048 (0.028)	11.6	17.1

Table 3
The p-values (the effect sizes) of fixed and interaction effects in three-way ANOVA for all 12 muscles.

Normalized averaged peak EMGs	RIL	RLT	RM	RVL	RBF	RAEO	LIL	LLT	LM	LVL	LBF	LAEO
Exo Intervention	< 0.0001 (0.413)	< 0.0001 (0.537)	< 0.0001 (0.274)	0.001 (0.067)	< 0.0001 (0.263)	0.1748 (0.057)	< 0.0001 (0.313)	< 0.0001 (0.427)	< 0.0001 (0.314)	0.0001 (0.092)	< 0.0001 (0.187)	0.3659 (0.031)
Lifting Type	0.6734 (0.010)	< 0.0001 (0.397)	< 0.0001 (0.227)	< 0.0001 (0.711)	< 0.0001 (0.228)	< 0.0001 (0.261)	0.0427 (0.051)	< 0.0001 (0.308)	< 0.0001 (0.178)	< 0.0001 (0.637)	< 0.0001 (0.591)	< 0.0001 (0.193)
Box Weight (% BW)	< 0.0001 (0.500)	< 0.0001 (0.748)	< 0.0001 (0.489)	0.9981 (1e-6)	< 0.0001 (0.449)	0.0014 (0.072)	< 0.0001 (0.462)	< 0.0001 (0.636)	< 0.0001 (0.455)	0.6234 (0.002)	< 0.0001 (0.636)	0.0045 (0.065)
Lifting Type×Exo Intervention	0.1562 (0.033)	0.0716 (0.065)	0.414 (0.018)	0.8291 (0.006)	0.6838 (0.009)	0.8682 (0.006)	0.2069 (0.029)	0.3081 (0.022)	0.5615 (0.014)	0.4221 (0.018)	0.0883 (0.039)	0.7671 (0.010)
Box Weight×Exo Intervention	0.1317 (0.015)	0.5636 (0.002)	0.9718 (5e-6)	0.4808 (0.003)	0.3191 (0.006)	0.7926 (4e-4)	0.1752 (0.012)	0.9416 (3e-5)	0.8008 (4e-4)	0.8869 (1e-4)	0.4056 (0.004)	0.9236 (5e-5)
Lifting Type×Box Weight	0.9184 (0.003)	< 0.0001 (0.136)	0.0035 (0.084)	0.3527 (0.020)	0.0001 (0.121)	0.0496 (0.054)	0.0398 (0.053)	< 0.0001 (0.211)	0.0007 (0.107)	0.7433 (0.009)	0.0045 (0.077)	0.3619 (0.027)
Lifting Type×Box Weight×Exo Intervention	0.4161 (0.018)	0.7399 (0.008)	0.9399 (0.003)	0.8654 (0.005)	0.9715 (0.002)	0.9294 (0.003	0.59 (0.012)	0.8219 (0.006)	0.9744 (0.001)	0.9544 (0.002)	0.7249 (0.008)	0.9524 (0.003)
Normalized Averaged Mean EMGs	**RIL**	**RLT**	**RM**	**RVL**	**RBF**	**RAEO**	**LIL**	**LLT**	**LM**	**LVL**	**LBF**	**LAEO**
Exo Intervention	< 0.0001 (0.475)	< 0.0001 (0.542)	< 0.0001 (0.304)	0.0017 (0.061)	< 0.0001 (0.253)	0.0644 (0.137)	< 0.0001 (0.441)	< 0.0001 (0.382)	< 0.0001 (0.262)	0.0026 (0.058)	< 0.0001 (0.104)	0.0689 (0.078)
Lifting Type	< 0.0001 (0.142)	< 0.0001 (0.529)	< 0.0001 (0.443)	< 0.0001 (0.769)	0.0345 (0.053)	< 0.0001 (0.170)	< 0.0001 (0.235)	< 0.0001 (0.465)	< 0.0001 (0.422)	< 0.0001 (0.691)	< 0.0001 (0.154)	0.0004 (0.144)
Box Weight (% BW)	< 0.0001 (0.534)	< 0.0001 (0.684)	< 0.0001 (0.516)	0.9624 (1e-5)	< 0.0001 (0.385)	< 0.0001 (0.140)	< 0.0001 (0.511)	< 0.0001 (0.568)	< 0.0001 (0.518)	0.7236 (0.001)	< 0.0001 (0.473)	< 0.0001 (0.187)
Lifting Type×Exo Intervention	0.3039 (0.023)	0.2503 (0.025)	0.7357 (0.008)	0.5898 (0.012)	0.6384 (0.011)	0.7265 (0.010)	0.247 (0.027)	0.4995 (0.015)	0.7179 (0.009)	0.7968 (0.007)	0.5755 (0.012)	0.8582 (0.007)
Box Weight×Exo Intervention	0.1241 (0.015)	0.6809 (0.001)	0.4055 (0.004)	0.5607 (0.002)	0.4548 (0.004)	0.2311 (0.011)	0.073 (0.021)	0.7046 (0.001)	0.6201 (0.002)	0.6615 (0.001)	0.3513 (0.005)	0.835 (4e-4)
Lifting Type×Box Weight	0.1282 (0.036)	< 0.0001 (0.141)	0.0368 (0.053)	0.1258 (0.035)	0.0023 (0.088)	0.2957 (0.027)	0.0041 (0.083)	0.0005 (0.103)	0.0026 (0.091)	0.7804 (0.008)	0.1722 (0.30)	0.767 (0.10)
Lifting Type×Box Weight×Exo Intervention	0.7876 (0.007)	0.9817 (0.001)	0.9705 (0.002)	0.7481 (0.008)	0.9043 (0.004)	0.7091 (0.010)	0.8492 (0.005)	0.9465 (0.002)	0.9193 (0.003)	0.7025 (0.009)	0.9609 (0.002)	0.8372 (0.007)

height. This seems to imply that some individuals were co-contracting their muscles as compared to letting the exoskeleton support their torso's weight during lifting. It should also be noted that increasing stomach muscle activity may actually be beneficial because it will stabilize the trunk even if the back muscles' activation decreases (Granata, 2001; Stokes, 2011). If the exoskeleton was weaker, then we would not expect to see an increase in the stomach muscles' activity but there would be smaller reductions in back muscle activity.

At the end of the experiments, each participant was asked to rate the discomfort level (at any location on the body) during the lifting trials. Participants rated the discomfort level using a 0–10 Borg scale where 0 corresponds to no discomfort and 10 to extreme discomfort. According to discomfort survey, none of the participants declared any discomfort at upper arms, elbows, lower arms, back (thoracic region), upper chest and abdomen. The summary of discomfort ratings for different regions of the body is presented in Table 4. Based on Table 4, the average discomfort level for every segment was smaller than 0.3 except for the thigh (0.94 on average). The slight discomfort on thighs felt by some participants was due to the leg straps and pads tending to move upward a little bit during lifting; this issue could be mitigated by positioning the exoskeleton on the wearer in a different location during the fitting period. Written comments by participants revealed that all of them favored the exoskeleton especially because it was easy to use and that it provided support during lifting tasks. Participants also reported that the exoskeleton was more supportive in symmetric lifting compared to asymmetric lifting.

For comparison, with the PLAD, almost 20% of the participants commented that they would not like to wear the PLAD again and 50% of participants replied "maybe" about the prospect of using the PLAD in a subsequent lab experiment. However, in the current study, all the participants were willing to use the VT-Lowe's exoskeleton again and all

of them commented that they felt how supportive the device was during lifting.

Several limitations should be acknowledged for this study. First, the number of carbon fiber beams was fixed for all participants, and this may have created too much force for some of the lighter participants, causing them to work against the exoskeleton while bending forward. Ideally, the number of carbon fiber beams could be optimized for each participant to obtain a force matched to their weight and height, which would minimize any adverse effects when bending forward. A second limitation was that all participants underwent a brief training experience, which might have caused smaller muscular reductions compared to what they could have shown with a longer training period. A study conducted by Wiggin (2012) suggested that adaptation to exoskeletons during walking may take up to four days. Therefore, a longer training period could have resulted in lower activations of the abdominal muscles while wearing the exoskeleton.

5. Conclusions

In this study, the effect of the VT-Lowe's exoskeleton on peak and mean muscle activation of 12 different muscles was fully examined. The EMG muscle activation was recorded and processed for four different lifting types at two box weights (0% and 20%). Results demonstrated that the exoskeleton could reduce the average peak and mean muscle activation of back and leg muscles regardless of different levels of box weights and lifting types. The exoskeleton had a significant effect on EMG reductions for all back (longissimus thoracis, illiocostalis lumborum and multifidus) and leg muscles (bicep femoris and vastus lateralis), but not for the external oblique muscles. Averaging across all symmetric conditions, the exoskeleton was able to successfully reduce the peak and mean muscle activation of IL and LT muscles by 31.5%
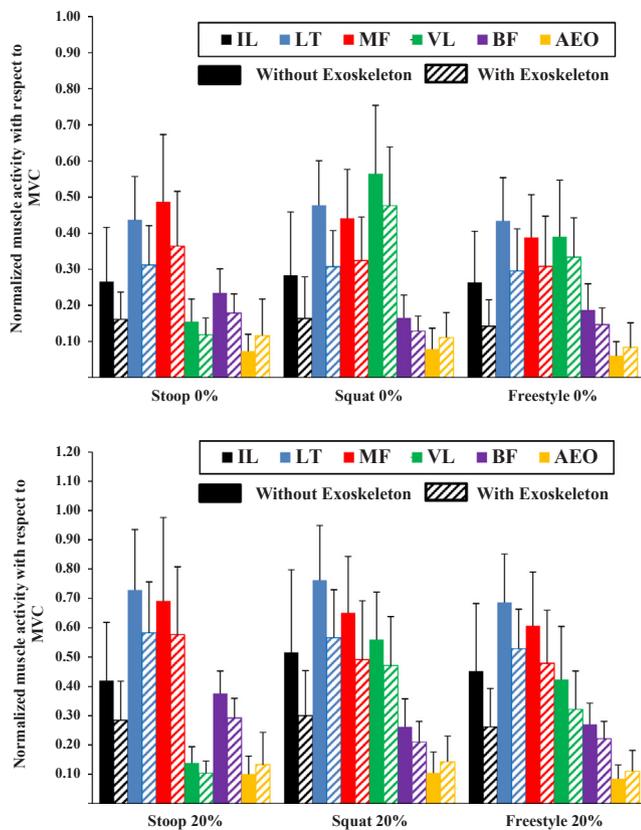
Fig. 4. Ensemble average of normalized peak muscle activity for stoop, squat and freestyle lifts for 0% (top) and 20% (bottom) of body weight.
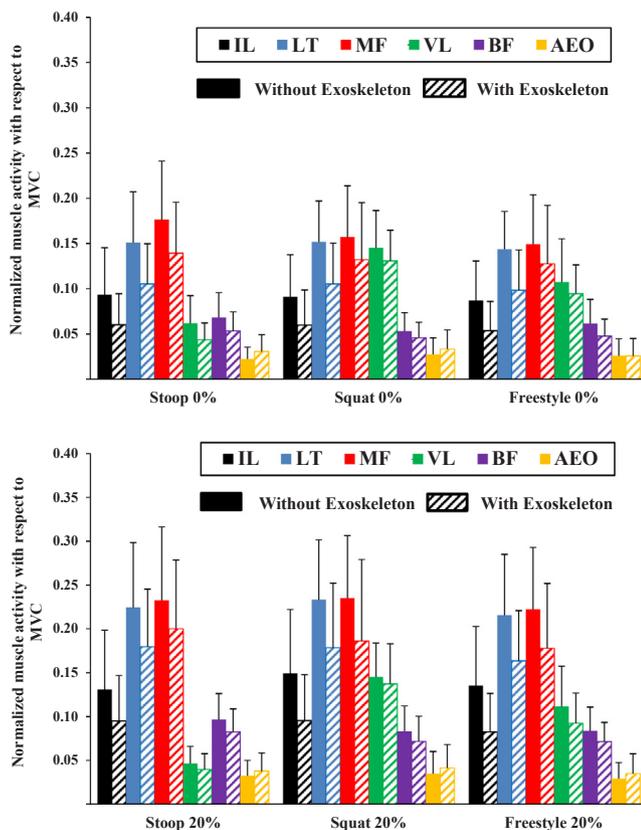

Fig. 5. Ensemble average of normalized mean muscle activity for stoop, squat and freestyle lifts for 0% (top) and 20% (bottom) of body weight.
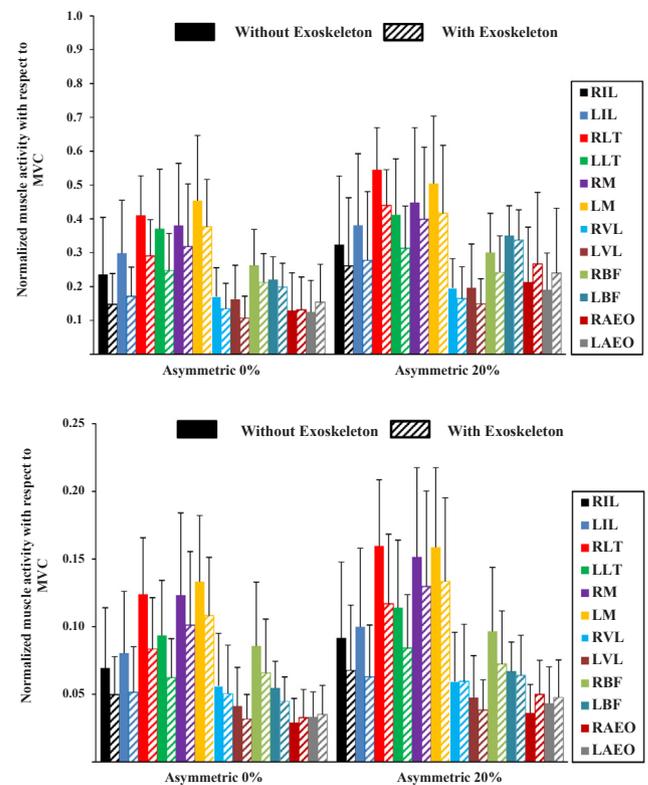

Fig. 6. Ensemble average of normalized peak (top) and mean (bottom) muscle activity for asymmetric lifts for 0% and 20% of body weight.

and 29.3%, respectively. The exoskeleton reduced back muscle activity (peak and mean) the most during squat lifting, followed by freestyle and asymmetric lifting, and finally, during stoop lifting. Additionally, the activity of leg muscles reduced by 19.1% and 14.1% for peak and mean, respectively, while wearing the exoskeleton. For asymmetric lifts, back muscles (IL and LT) had smaller peak EMG reduction but slightly higher mean EMG reduction compared to symmetric lifts (peak: 28.2% and mean: 29.5%). This was the same for leg muscles in asymmetric lifts where lower peak EMG reduction (17.4%) and higher mean EMG reductions (14.6%) were recorded.

Contrary to back and leg muscles, on average, there were slight increases in normalized peak and mean EMGs of AEO muscles in all lifting types and box weights. This is likely due to imperfect adaptation to the exoskeleton, since participants were only familiarized with the device for 20–30 min just before the data collection began. For further lab studies, the behavior of other abdominal muscles could be potentially investigated, with longer adaptation times. However, for sagittal lifting types, they might have the same responses (Abdoli et al., 2006).

In addition to EMG results, the discomfort survey (Table 4) showed that except for the thigh which had an average discomfort of 0.94 in the Borg scale, participants experienced either no discomfort or an average discomfort of less than 0.3. In summary, the VT-Lowe's exoskeleton significantly reduced the peak and mean muscle activity of erector spinae, bicep femoris and vastus lateralis muscles for all different lifting types regardless of box weights, all without producing any significant discomfort. As such, this exoskeleton is a promising passive lift-assistive device.

Conflict of interest statement

S. E. Chang, J. Geissinger, and A. T. Asbeck are co-authors on a patent for the exoskeleton which is currently licensed to Lowe's Inc.

M. M. Alemi and A. A. Simon have no conflicts of interest.

Table 4
Summary of discomfort ratings for different body segments (12 participants).

Body Segment	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	Average discomfort (Std)
Neck	0.5	0	0	0	0	0	0	0	0	0	0	0	0.042 (0.144)
Shoulder	0	0	0	1	0	0	0	0	0	0	0	0	0.083 (0.289)
Upper Arms	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Elbows	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Lower Arms	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Hand	0	0	0	0	0	0	0	0	0.75	0	0	0	0.062 (0.217)
Upper Chest	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Abdomen	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Back (Thoracic)	0	0	0	0	0	0	0	0	0	0	0	0	0 (0)
Back (Lumbar)	0	0	0	0	0	2	0	0	0	0	0	0	0.167 (0.577)
Groin and Buttocks	0	0	0	1.5	0	0	0	0	0	0	0	0	0.125 (0.433)
Thigh	0	2.25	1.5	2	1.5	1.5	0.5	0	1	0	1	0	0.937 (0.827)
Knee	0	0	0	0	0	0	0	0	1	0	0	2	0.250 (0.622)
Shank	0	0	0	0	0	0	0	0	1	0	0	0	0.083 (0.289)
Foot and ankle	0	0	0	0	0.5	0	0	0	0	0	0	0	0.042 (0.144)

References

Abdoli-E, M., Agnew, M.J., Stevenson, J.M., 2006. An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of erector spinae during lifting tasks. Clin. Biomech. 21 (5), 456–465. https://doi.org/10.1016/j.clinbiomech.2005.12.021.

Abdoli-E, M., Stevenson, J.M., 2008. The effect of on-body lift assistive device on the lumbar 3D dynamic moments and EMG during asymmetric freestyle lifting. Clin. Biomech. 23 (3), 372–380. https://doi.org/10.1016/j.clinbiomech.2007.10.012.

Anam, K., Al-Jumaily, A.A., 2012. Active exoskeleton control systems: state of the art. Procedia Eng. 41 (Iris), 988–994. https://doi.org/10.1016/j.proeng.2012.07.273.

Asbeck, A.T., Schmidt, K., Galiana, I., Wagner, D., Walsh, C.J., 2015. Multi-joint soft exosuit for gait assistance. In: Proceedings – IEEE International Conference on Robotics and Automation, 2015–June(June), pp. 6197–6204. https://doi.org/10.1109/ICRA.2015.7140069.

Ayoub, M.M., 1992. Problems and solutions in manual materials handling: the state of the art. Ergonomics 35 (7–8), 713–728. https://doi.org/10.1080/00140139208967358.

Barbero, M., Merletti, R., Rainoldi, A., 2012. Atlas of Muscle Innervation Zones. Springer Milan, Milano. https://doi.org/10.1007/978-88-470-2463-2.

Chang, S., Pesek, T., Pote, T., Alemi, M., Geissinger, J., Hall, J., Asbeck, A., 2019. Design and preliminary evaluation of a flexible exoskeleton to assist with lifting. J. Biomech. Eng [in press].

Bogue, R., 2009. Exoskeletons and robotic prosthetics: a review of recent developments. Indus. Robot: Int. J. 36 (5), 421–427. https://doi.org/10.1108/01439910910980141.

Bureau of Labor Statistics, U.S. Department of Labor, 2016. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2015. Report USDL-16-2130. https://www.bls.gov/news.release/pdf/osh2.pdf.

Bosch, T., van Eck, J., Knitel, K., de Looze, M., 2016. The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. Appl. Ergon. 54, 212–217. https://doi.org/10.1016/j.apergo.2015.12.003.

de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O'Sullivan, L.W., 2016. Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics 59 (5), 671–681. https://doi.org/10.1080/00140139.2015.1081988.

Delia Treaster, 2018. The Exoskeletons are coming here Industrial Exoskeleton Workshop. In: Ohio BCW.

Frost, D.M., Abdoli-E, M., Stevenson, J.M., 2009. PLAD (personal lift assistive device) stiffness affects the lumbar flexion/extension moment and the posterior chain EMG during symmetrical lifting tasks. J. Electromyogr. Kinesiol. 19 (6). https://doi.org/10.1016/j.jelekin.2008.12.002.

Garg, A., Herrin, G.D., 1979. Stoop or squat: a biomechanical and metabolic evaluation. AIIE Trans. 11 (4), 293–302. https://doi.org/10.1080/05695557908974474.

Granata, K.P., Orishimo, K.F., 2001. Response of trunk muscle coactivation to changes in spinal stability. J. Biomech. 34 (9), 1117–1123. https://doi.org/10.1016/S0021-9290(01)00081-1.

Hasegawa, Y., Muramatsu, M., 2013. Wearable lower-limb assistive device for physical load reduction of caregiver on transferring support. In: 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics: Mechatronics for Human Wellbeing, AIM 2013, 1027–1032. https://doi.org/10.1109/AIM.2013.6584229.

Hermens, H.J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C., Hägg, G., 1999. European Recommendations for Surface ElectroMyoGraphy. Roessingh Research and Development 8–11.

Stokes, I.A.F., Gardner-Morse, M.G., S.H., 2011. Abdominal muscle activation increase lumbar spinal stability: analysis of contributions of different muscle groups. Clin. Biomech. 26 (8), 797–803. https://doi.org/10.1016/j.clinbiomech.2011.04.006.ABDOMINAL.

Islam, M.R., Spiewak, C., Rahman, M.H., Fareh, R., 2017. A brief review on robotic exoskeletons for upper extremity rehabilitation to find the gap between research porotype and commercial type. Adv. Robot. Autom. 06 (03). https://doi.org/10.4172/2168-9695.1000177.

Kazerooni, H., Tung, W., Rempel, D., 2017. Trunk Supporting Exoskeleton and Method of Use, US Patent US9655762B2.

Kim, S., Nussbaum, M.A., Mokhlespour Esfahani, M.I., Alemi, M.M., Alabdulkarim, S., Rashedi, E., 2018a. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – "Expected" effects on discomfort, shoulder muscle activity, and work task performance. Appl. Ergon. 70 (December 2017), 315–322. https://doi.org/10.1016/j.apergo.2018.02.025.

Kim, S., Nussbaum, M.A., Mokhlespour Esfahani, M.I., Alemi, M.M., Jia, B., Rashedi, E., 2018b. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II – "Unexpected" effects on shoulder motion, balance, and spine loading. Appl. Ergon. 70 (December 2017), 323–330. https://doi.org/10.1016/j.apergo.2018.02.024.

Koopman, A.S., Kingma, I., Faber, G.S., de Looze, M.P., van Dieen, J.H., 2019. Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks. J. Biomech. 83, 97–103. https://doi.org/10.1016/j.jbiomech.2018.11.033.

Kuiper, J.L., Burdorf, A., Verbeek, J.H.A.M., Frings-Dresen, M.H.W., van der Beek, A.J., Viikari-Juntura, E.R.A., 1999. Epidemiologic evidence on manual materials handling as a risk factor for back disorders: a systematic review. Int. J. Ind. Ergon. 24, 389–404. https://doi.org/10.1016/S0169-8141(99)00006-2.

Lamers, E.P., Yang, A.J., Zelik, K.E., 2017. Biomechanically-assistive garment offloads low back during leaning and lifting. In: 41st Annu. Meeting of the American Society of Biomechanics.

Li, N., Yan, L., Qian, H., Wu, H., Wu, J., Men, S., 2015. Review on lower extremity exoskeleton robot. Open Automat. Control Syst. J. 7, 441–453. https://doi.org/10.2174/1874444301507010441.

Marras, W.S., 2003. The case for cumulative trauma in low back disorders. Spine J. 3 (3), 177–179. https://doi.org/10.1016/S1529-9430(03)00032-9.

Marras, W.S., Granata, K.P., 1995. A biomechanical assessment and model of axial twisting in the thoracolumbar spine. Spine 20 (13), 1440–1451.

Park, K.S., Chaffin, D.B., 1974. A biomechanical evaluation of two methods of manual load lifting. AIIE Trans. 6 (2), 105–113. https://doi.org/10.1080/05695557408974941.

Rubin, D.I., 2007. Epidemiology and risk factors for spine pain. Neurol. Clin. 25 (2), 353–371. https://doi.org/10.1016/j.ncl.2007.01.004.

Ulrey, B.L., Fathallah, F.A., 2012. Evaluation of a personal device in reducing the risk of low back disorders during stooped work. Work 41 (SUPPL.1), 2381–2383. https://doi.org/10.3233/WOR-2012-0469-2381.

Wehner, M., Rempel, D., & Kazerooni, H., 2009. Lower extremity exoskeleton reduces back forces in lifting. In: ASME 2009 Dynamic Systems and Control Conference, Volume 2, (October 2009), pp. 49–56. https://doi.org/10.1115/DSCC2009-2644.

Whitfield, B.H., Costigan, P.A., Stevenson, J.M., Smallman, C.L., 2014. Effect of an on-body ergonomic aid on oxygen consumption during a repetitive lifting task. Int. J. Ind. Ergon. 44 (1), 39–44.

Wiggin, M.B., Collins, S.H., Sawicki, G.S., 2012. A passive elastic ankle exoskeleton using controlled energy storage and release to reduce the metabolic cost of walking. In: Proceedings 7th Annual Dynamic Walking Conference, pp. 24–25.

Yang, C.-J., Zhang, J.-F., Chen, Y., Dong, Y.-M., Zhang, Y., 2008. A review of exoskeleton-type systems and their key technologies. Proc. Inst. Mech. Eng. C: J. Mech. Eng. Sci. 222 (8), 1599–1612. https://doi.org/10.1243/09544062JMES936.

Zhang, H., Kadrolkar, A., Sup, F.C., 2015. Design and preliminary evaluation of a passive spine exoskeleton. J. Med. Dev. 10 (1), 011002. https://doi.org/10.1115/1.4031798.

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