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# Biomechanical assessment of two back-support exoskeletons in symmetric and asymmetric repetitive lifting with moderate postural demands

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ABSTRACT

Two passive back-support exoskeleton (BSE) designs were assessed in terms of muscular activity, energy expenditure, joint kinematics, and subjective responses. Eighteen participants (gender-balanced) completed repetitive lifting tasks in nine different conditions, involving symmetric and asymmetric postures and using two BSEs (along with no BSE as a control condition). Wearing both BSEs significantly reduced peak levels of trunk extensor muscle activity (by ~9–20%) and reduced energy expenditure (by ~8–14%). Such reductions, though, were more pronounced in the symmetric conditions and differed between the two BSEs tested. Participants reported lower perceived exertion using either BSE yet raised concerns regarding localized discomfort. Minimal changes in lifting behaviors were evident when using either BSE, and use of both BSEs led to generally positive usability ratings. While these results are promising regarding the occupational use of BSEs, future work is recommended to consider inter-individual differences to accommodate diverse user needs and preferences.

## 1. Introduction

Low back disorders (LBDs) continue as the leading cause of work-related disability, accounting for ~40% of all work-related musculoskeletal disorders (WMSDs) and ~38% of cases in the U.S. involving days away from work (BLS, 2019). The development of LBDs has been directly associated with "physical" risk factors including overexertion, repetitive lifting, bending, and prolonged/sustained non-neutral trunk postures (Punnett et al., 2005; da Costa and Vieira, 2010; Griffith et al., 2012). Engineering controls that re-design tools or workspace (Silverstein and Clark, 2004; Lavender et al., 2013), use of mechanical aids (Westgaard and Winkel, 1997; Nussbaum et al., 1999), and/or worker training (Daltroy et al., 1997; Burke et al., 2006) have each been proposed as potential ergonomic interventions to minimize the risks of work-related LBDs. However, evidence of their efficacy, sustainability, and/or usability remains limited in practice (Hignett, 2003; Clemes et al., 2009), and in some working scenarios one or more of these intervention approaches can be infeasible, impractical, or excessively costly.

Back-support exoskeletons/exosuits (BSEs) are designed to support, augment, and/or assist with the back and hip muscles, by producing restorative torques, passively by the means of springs and/or elastic materials, or actively through use of powered actuators (Lee et al., 2012). BSEs have emerged recently as an alternative and promising intervention to reduce physical demands on the spine, while retaining the mobility that manual work requires. While the development of active BSEs is still in progress (Toxiri et al., 2017, 2019; Huysamen et al., 2018), multiple passive devices are already commercially available and are being tested and adopted in the workplace due to their cost-efficiency and ease of implementation (De Looze et al., 2016; Hensel and Keil, 2019).

Previous studies have evaluated the efficacy of passive BSEs, specifically during static trunk bending and repetitive lifting. In many of these studies, the potential benefits of passive BSEs were quantified in terms of a reduction in back muscle demands. Passive BSEs were found to reduce trunk extensor muscle activity during static trunk bending, by up to 57% during symmetric tasks (Barrett and Fathallah, 2001; Graham et al., 2009; Ulrey and Fathallah, 2013; Bosch et al., 2016; Lamers et al., 2018; Koopman et al., 2019b), and by up to 37% during asymmetric tasks (Madinei et al., 2020). Reductions of up to 54% in trunk muscle activity (or trunk external moment) were found during repetitive, symmetric lifting (Abdoli-e et al., 2006; Abdoli-e & Stevenson, 2008;

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Frost et al., 2009; Godwin et al., 2009; Lotz et al., 2009; Wehner et al., 2009; Lamers et al., 2018; Näf et al., 2018; Alemi et al., 2019a), and by up to 30% during asymmetric lifting (Abdoli-e & Stevenson, 2008; Alemi et al., 2019a; Alemi et al., 2020). Earlier work has also shown that the use of a passive BSE can reduce metabolic demands by up to 17% during symmetric lifting (Alemi, 2019; Baltrusch et al., 2019) and by up to 6% during asymmetric lifting (Alemi et al., 2020). Despite such potential benefits, use of passive BSEs may also impose unintended or adverse consequences on users, such as increased discomfort at the chest (Bosch et al., 2016; Hensel and Keil, 2019) and thighs (Amandels et al., 2018), or adoption of riskier working postures to exploit the device support, such as increased lumbar flexion and knee extension (Frost et al., 2009; Sadler et al., 2011; Bosch et al., 2016; Koopman et al., 2020).

While there is a growing body of literature on the efficacy of passive BSEs in repetitive lifting tasks, most earlier work is limited in three important aspects. First, previous studies often considered only one particular BSE; thus, it is unclear whether there is a preferred BSE design under various working conditions. Additional comparative evaluations of different BSE designs are needed to help guide the selection and application of these devices under diverse conditions, given that the functionality of a BSE appears to be task-specific and dependent on the design approach (Alemi et al., 2020). Such comparisons are especially needed for tasks involving asymmetric postures since these are associated with an increased risk of LBDs (e.g., Punnett et al., 1991; Norman et al., 1998; Punnett et al., 2005). Recently, we examined the efficacy of two passive BSEs during repetitive lifting tasks (Alemi et al., 2020), finding that both BSEs resulted in significant reductions in energy expenditure (by 4–13%) and peak activity of trunk extensor muscles (by 10–28%). Such benefits, though, were task-dependent and differed between the devices tested. Furthermore, the lifting conditions simulated in that study considered the functionality of the BSEs near their extreme operating regions, and thus those findings may not generalize to more moderate working postures. As such, the efficacy of these devices in a range of moderate lifting postures needs further exploration. Second, prior investigations were often focused on trunk muscle activities, however conclusions regarding the actual benefits of using a BSE would be premature without knowledge of trunk kinematics (Koopman et al., 2020). Third, evidence on the efficacy of passive BSEs is rather limited in asymmetric working postures as compared to symmetric postures.

To address these limitations, this exploratory study evaluated the efficacy of two passive BSE designs during repetitive symmetric and asymmetric lifting and lowering involving a range of lifting heights to simulate diverse tasks. The two BSEs tested were both commercially-available: BackX™ model AC (SuitX™, www.suitx.com), and Laevo™ V2.5 (www.laevo.nl). Both of these devices incorporate passive torque generation mechanisms about the hip that are intended to augment the trunk extensor muscles, yet they have distinct design features. The BackX™ AC includes a structural frame that pulls the torso backwards by distributing the pressure to the shoulder straps and chest pad, whereas the Laevo™ transfers the load through pushing against the chest only. Further, support levels and modes can be adjusted easily with the BackX™, while the Laevo™ only provides different engagement angles. We included muscle activity, energy expenditure, and joint kinematics as objective outcome measures, and supplemented these with several subjective assessments including perceived exertion, discomfort, and usability. Based on earlier findings as summarized earlier, we hypothesized that using these BSEs during repetitive lifting activities would reduce muscle activity in the lower back muscles and provide metabolic savings, but that the magnitude of these benefits would vary between the two BSEs and across task conditions.

## 2. Methods

### 2.1. Participants

A convenience sample of 18 gender-balanced participants, recruited from the local student and community populations, completed the study. Respective means (SD) of age, body mass, stature, and body mass index were 26.8 (3.9) years, 178.4 (4.4) cm, 80.9 (5.0) kg, and 25.5 (2.2) kg/m$^2$ among the males, and 25.1 (3.1) years, 165.8 (4.3) cm, 62.5 (5.7) kg, and 22.7 (1.5) kg/m$^2$ among the females. Participants reported no current or recent (i.e., past 12 months) musculoskeletal disorders or injuries. Additional inclusion criteria, related to anthropometry, were adopted from BSE user instructions to ensure a proper fit to the BSEs. The research reported herein complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at Virginia Tech. Informed consent was obtained from each participant prior to any data collection, and compensation was provided at $10/hr.

### 2.2. Experimental tasks and procedures

A repetitive material handling task was simulated in a laboratory environment to examine the effects of two BSEs under several conditions that varied in task symmetry and height. Participants performed trials of repetitive lowering/lifting using a wooden box (40 × 25 × 23 cm, with 4 cm handle clearance diameter), the mass of which was set to 10% of individual participant body mass. Participants were instructed to repetitively lower/lift the box for 4 min in different conditions (see below), at a pace of 10 lower/lift cycles per minute (i.e., 40 lower/lift cycles in each trial). Lifting pace was controlled by a digital metronome. The lifting pace and duration were chosen, similar to earlier work (Graham et al., 2011), to ensure a continuous lifting pattern while minimizing the development of muscular fatigue, and the load mass was standardized to account for differences in body sizes among the participants.

Participants performed the lowering/lifting trials in three conditions, involving different levels of *Height* and *Symmetry* (Fig. 1), which were intended to reflect a range of working postures frequent in the performance of manual material handling tasks, such as in warehouses and distribution centers (Kuorinka et al., 1994). Symmetric lowering/lifting was done to/from two heights set based on individual anthropometry: mid-shank and knee level (respectively referred to as Sym_Ground and Sym_Knee hereinafter). Asymmetric lowering/lifting was done to/from a location 90° to the right of the mid-sagittal plane (referred to as Asy_Knee hereinafter). This latter task was only done at knee height, since reaching to/from mid-shank height was found to be challenging for many participants in pilot work. Note that the initial box location for all lowering/lifting conditions was set at individual waist height (i.e., anterior superior iliac spine), and the mid height of the shank was determined as the mid-point between the patella (knee height) and the lateral malleolus (ankle height). Target locations for placing the box were marked using wooden blocks, and the horizontal distances between the centers of the target locations on the table and on the floor were controlled (symmetric: 25 cm, asymmetric: 50 cm). Each lowering/lifting cycle involved the following in sequence: 1) participant standing in the upright posture facing the box; 2) grasping the box and lowering it down to the target location; 3) lifting the box back to the initial location; and, 4) returning to the original, upright posture. Participants were allowed to freely choose their lifting style and feet location while maintaining a consistent feet location for the entire trial.

Each participant completed a training session (~1 h) followed by an experimental session (~4.5 h) on separate days. In the training session, participants were familiarized with the support levels and functionality of each BSE following manufacturers' manuals. Participants then practiced the lowering/lifting task in each of the three experimental conditions, during which they were also asked to determine their preferred lifting style, as well as exoskeleton support levels (for BackX™) and engagement angles (for Laevo™). Note that the BackX™ has four combinations of support, consisting of two modes (instant vs. standard) and two support levels (low vs. high). The instant mode provides assistive torque immediately after the wearer bends forward, while in the standard mode supportive torque is provided when trunk flexion reaches 30-


**Fig. 1.** Illustrations of the repetitive lowering/lifting task in each of the three experimental conditions.

45°. The Laevo™ allows for an adjustment of the engagement angle with respect to the upright posture. Distributions of preferred support levels for BackX™ and engagement angles for Laevo™ are provided in Appendix A. Participants were familiarized with providing ratings of perceived exertion (RPE), by holding a 1-kg weight in their outstretched arm (i.e., fully extended arm with elbow locked and shoulder flexed at 90°) to the maximum of their endurance and providing intermittent RPE ratings using the Borg (2004) CR-10 scale.

In the experimental session, participants completed a total of nine lowering/lifting trials, involving the factorial combination of three *Interventions* (i.e., BackX™, Laevo™, and Control = no BSE) and the three *Task Conditions.* Presentation orders of *Intervention* and *Task Condition* were each counter-balanced using 3 × 3 Latin squares, and a minimum of 5-min of rest was provided between lifting trials.

### 2.3. Instrumentation and data processing

Surface electromyography (EMG) was recorded bilaterally from five muscle groups in the lower lumbar, thoracic, abdominal, and shoulder regions, with electrode placements based on previous guidelines (Hermens et al., 1996; Cram, 2010). Specific muscle groups were: thoracic erector spinae (TES), iliocostalis lumborum (ILL), rectus abdominis (RA), external oblique (EO), and anterior deltoid (AD). After appropriate skin preparation (abrasion and cleaning with alcohol), pairs of pre-gelled, bipolar Ag/AgCl electrodes with a 2.5 cm inter-electrode spacing were placed over the noted muscle groups. These muscle groups were selected based on relevance to the simulated lifting tasks and accessibility across the devices used (e.g., different exoskeleton contact areas with the body, due to straps, pads, and rod locations).

Following electrode placement, participants completed a series of maximum voluntary isometric contractions (MVICs) for each muscle group, using a commercial dynamometer (Biodex System 3 Pro, Biodex Medical Systems Inc., NY, USA) and a custom frame to isolate the pelvis and lower extremities. For the trunk extensor (TES and ILL) and flexor (RA and EO) muscles, participants stood in the frame (positioned next to the dynamometer) with their trunk flexed 20° and performed trunk flexion, extension, and bidirectional axial rotation (Marras and Mirka, 1993; Jia et al., 2011; Madinei et al., 2018). For the AD muscle, arm flexion was performed with the shoulder flexed at 90° (Boettcher et al., 2008). MVICs were replicated twice for each muscle group, during which non-threatening verbal encouragement was provided. Rest breaks of 30 s or longer were provided between MVICs.

Raw EMG signals were sampled at 1.5 kHz during MVICs and the lowering/lifting trials, using a telemetered system (TeleMyo Desktop DTS, Noraxon, AZ, USA). These signals were band-pass filtered (20–450 Hz, 4th-order Butterworth, bidirectional) and subsequently low-pass filtered (3 Hz cut-off, 4th-order Butterworth, bidirectional) to create linear envelopes. Processed EMG signals were normalized (nEMG) to maximum values collected during MVICs. As in earlier work (Potvin et al., 1990; Frost et al., 2009; Graham et al., 2009; Madinei et al., 2020), four separate metrics were calculated to represent the level of muscular activity. For the first two metrics, peak (95th percentile) levels of the trunk extensor muscles (TES and ILL) were averaged on each side, yielding $TEM_L = \frac{TES_L + ILL_L}{2}$ and $TEM_R = \frac{TES_R + ILL_R}{2}$. The third metric was obtained as the sum of the peak levels of all bilateral trunk muscles (TES, ILL, RA, and EO), and is subsequently referred to as TTM (total trunk muscle activity). The fourth metric was calculated as the sum of the peak levels of the bilateral AD, and is subsequently referred to as SM (shoulder muscles). Each EMG metric was obtained separately for the lowering and lifting phases (see below for phase determination).

Energy expenditure (metabolic cost) was determined through respiratory data collected using indirect calorimetry (CosMed K5, CosMed, Rome, Italy), the accuracy and precision of which has been reported earlier (Perez-Suarez et al., 2018). Prior to each experimental session, a calibration procedure was completed following the manufacturer's guidelines. Breath-by-breath oxygen and carbon-dioxide uptake rates (mL/min) collected from the calorimeter were smoothed using a 4th-order, low-pass, bidirectional, Butterworth filter with a cutoff frequency of 0.33 Hz. The Brockway (1987) equation was used to estimate relative energy expenditure rates (kcal/kg•min), and this approach accounted for both participant body mass and BSE mass (if used). Based on pilot work and earlier evidence (Bilzon et al., 2001; Åstrand et al., 2003), steady-state metabolic rate was determined by averaging relative energy expenditure rates over the last 1.5 min of each trial.

Segmental body kinematics were monitored at 60 Hz using a wearable inertial motion capture system (MVN Awinda, Xsens Technologies B.V., Netherlands). The standard rotation sequence recommended by ISB (ZXY) was used to analyze kinematic data (Wu et al., 2005). Kinematic data were filtered using a 4th-order, low-pass, bidirectional Butterworth filter with a cut-off frequency of 5 Hz. For each trial, peak (95th percentile) triaxial angular velocities – axial rotation (AR), lateral bending (LB), and flexion/extension (FE) – were determined for the trunk and lumbar spine (thorax vs. pelvis). Angular velocities were separated for the lowering and lifting phases. Triaxial ranges-of-motions (ROMs) were also obtained, and mean values were calculated across lowering/lifting cycles. Maximum and minimum trunk inclination angles (with respect to the upright posture) were used to identify the beginning and ending of each lowering/lifting phase. Note that angular velocities and ROMs were used here as outcome measures to capture potential differences in the lifting methods employed between *Interventions*.

After completing each trial, participants reported ratings of perceived discomfort (RPDs) resulting from exoskeleton contact with their body – specifically at the chest, waist, and thighs – using 7-point Likert scales (Kuijt-Evers et al., 2007), where 0 = no discomfort and 6 = extreme discomfort (Appendix B). Subsequently, they reported RPEs for the shoulders, lower back, abdominal region, and legs, using the Borg CR-10 scale. For both RPD and RPE ratings, participants provided a single overall value for bilateral body parts. After completing all three trials with a given BSE, participants provided an overall usability score for that BSE on a continuous scale from 0 (not helpful at all) to 100 (absolutely helpful), and rated exoskeleton fit, comfort, and movement hinderance using separate 7-point Likert scales (Appendix B). Finally, they were asked to select their preferred BSE after completing all lifting trials.

### 2.4. Statistical analyses

Separate three-way, mixed-factor analyses of variance (ANOVAs) were used to assess the effects of *Intervention*, *Task Condition*, and *Gender* on each of outcome measures (EMG metrics, energy expenditure, joint angular velocities and ROMs, RPEs, and RPDs). The presentation orders of *Task Condition* and *Intervention* were included as a blocking effect. For EMG metrics and angular velocities, these ANOVAs were performed separately for results obtained in the lowering and lifting phases. Two-way ANOVAs were used for usability ratings, with independent variables of *Intervention* and *Gender*. Parametric model assumptions were assessed, and in several cases transformations were needed to achieve normally-distributed residuals. All subjective measures and usability ratings were analyzed using parametric analysis, the robustness of which was reported earlier (Rickards et al., 2012; Mircioiu and Atkinson, 2017). Summary outcomes were back-transformed and are reported as least squares means (95% CIs), and effect sizes are reported using eta-squared ($\eta^2$). Significant interaction effects were explored using simple-effects testing, and *post hoc* paired comparisons were completed using the Tukey-Kramer procedure where relevant. Given the study goals, the subsequent presentation of results and the discussion emphasizes the main and interaction effects of *Intervention*. All statistical analyses were performed using JMP Pro 14 (SAS, Cary, NC), using the restricted maximum likelihood (REML) method, with statistical significance concluded when $p < 0.05$.

## 3. Results

### 3.1. Muscle activity

A complete summary of ANOVA results for each outcome measure is provided in Appendix C. ANOVA results for nEMG measures are summarized in Table C1 (see Appendix C). *Intervention* main effects were significant for $TEM_L$, $TEM_R$, and TTM during both the lowering and lifting phases. Using the BackX™ significantly reduced the levels of $TEM_L$, $TEM_R$, and TTM, respectively by 20.0, 18.3, and 17.3% during the lowering phase, and by 11.9, 11.9, and 10.4% during the lifting phase (Fig. 2). Laevo™ use also led to significant reductions in $TEM_L$, $TEM_R$, and TTM, but only during the lowering phase, with respective magnitudes of 9.3, 8.7, and 7.8% (Fig. 2). Further, a significant *Intervention* × *Gender* interaction effect was found for $TEM_L$ during lowering (Fig. 3). All simple effects were significant, with *Intervention* significant for both *Genders* ($p \leq 0.0006$), and *Gender* significant for all *Interventions* ($p \leq 0.0037$). Females experienced a significant reduction when using either BSE (by 22.4% with BackX™ and 11.5% with Laevo™), while males exhibited a significant reduction only when using the BackX™ (by 16.5%).

### 3.2. Energy expenditure

There were both significant main and interaction effects of *Intervention* on energy expenditure (Table C2). Regarding the *Intervention* × *Gender* interaction effect (Fig. 4), *Intervention* was significant for both *Genders* ($p < 0.0091$), while *Gender* was only significant for BackX™ ($p < 0.0001$). Use of either BSE resulted in a significant reduction in energy expenditure for females (by 8.9% with Laevo™ and 13.2% with BackX™), while males experienced a significant reduction only when using the Laevo™ (by 6.4%). Regarding the *Intervention* × *Task Condition* interaction effect (Fig. 5), all simple effects were significant, excepting the effect of *Intervention* in the asymmetric condition ($p = 0.56$). Use of either BSE led to a significant reduction in energy expenditure in both symmetric conditions. Specifically, in the Sym_Ground condition, the

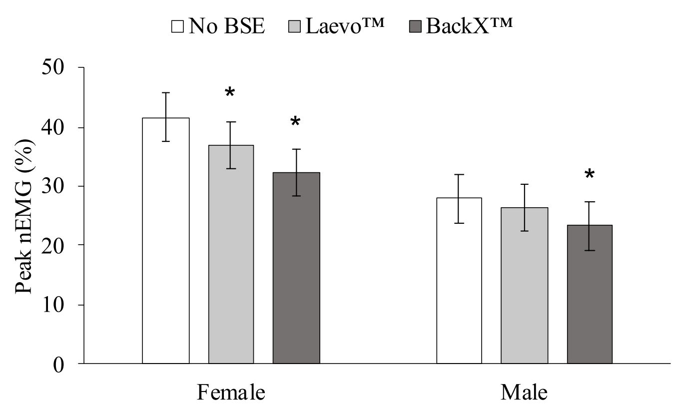


**Fig. 3.** *Intervention* × *Gender* interaction effect on peak normalized activity (nEMG) of the left trunk extensor muscles ($TEM_L$). Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

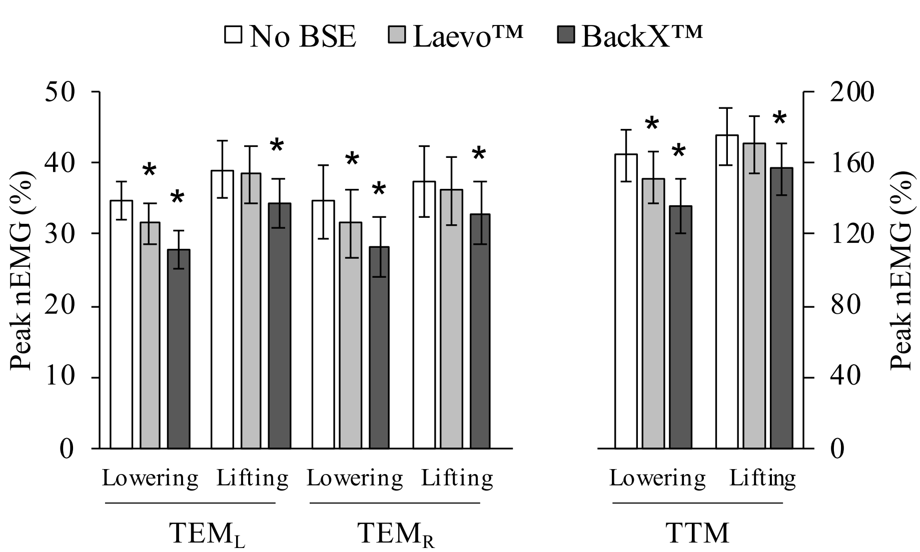


**Fig. 2.** *Intervention* effects on metrics of peak normalized muscle activity (nEMG). Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

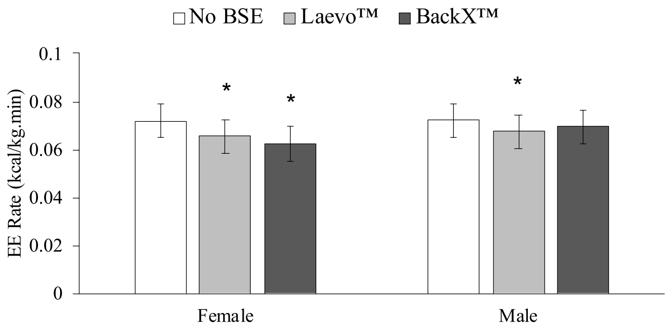


**Fig. 4.** *Intervention* × *Gender* interaction effects on relative energy expenditure rate (EE-rate). Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

reductions were 9.5% with Laevo™ and 13.6% with BackX™; while in the Sym_Knee condition these reductions were 10.2% with Laevo™ and 8.1% with BackX™. In contrast, no significant reductions were observed in the asymmetric condition.

### 3.3. ROM

A summary of ANOVA results for kinematic measures is presented in Table C3. The *Intervention* × *Task Condition* interaction effect was significant for $\text{Trunk}_{FE}$, $\text{Lumbar}_{AR}$, and $\text{Lumbar}_{FE}$. For $\text{Trunk}_{FE}$, the effect of *Task Condition* was significant for all *Interventions* ($p < 0.0001$). In contrast, *Intervention* was not significant for any *Task Condition* ($p > 0.0513$), and differences between *Interventions* within a given *Task Condition* were relatively small (less than ~5°). Similarly, for $\text{Lumbar}_{AR}$ the effect of *Task Condition* was significant for all *Interventions* ($p < 0.0001$), while *Intervention* was only significant in the asymmetric condition ($p = 0.0001$). Regarding $\text{Lumbar}_{FE}$, the effect of *Task Condition* was significant for all *Interventions* ($p < 0.0001$), while *Intervention* was only significant in the Sym_Knee condition ($p = 0.0304$). Further analyses revealed that neither BSE significantly influenced $\text{Lumbar}_{AR}$ or $\text{Lumbar}_{FE}$.

### 3.4. Angular velocity

The main effect of *Intervention* was significant for $\text{Trunk}_{FE}$ while lowering (Table C4). Using the Laevo™ significantly decreased $\text{Trunk}_{FE}$ while lowering, by 7.1% compared to the no BSE condition [Laevo™ = 52.6 (48.9, 56.5) °/s vs. no BSE = 56.6 (52.7, 60.5) °/s]. The *Intervention* × *Task Condition* interaction effect was significant for both $\text{Trunk}_{FE}$ and $\text{Lumbar}_{FE}$ during lifting. Regarding the former, all simple effects were significant, excepting the effect of *Intervention* in the Sym_Knee condition ($p = 0.346$). Using the Laevo™ significantly reduced $\text{Trunk}_{FE}$ when lifting in the Sym_Ground condition compared to no BSE [Laevo™ = 74.3 (68.4, 80.5) °/s vs. no BSE = 84.6 (78.3, 91.2) °/s]. In the Asy_Knee condition, however, neither BSE significantly influence $\text{Trunk}_{FE}$ during lifting. For $\text{Lumbar}_{FE}$ during lifting, all simple effects were significant, excepting the effect of *Intervention* in the Sym_Ground condition ($p = 0.12$). Again, no significant effects of BSE use were found for $\text{Lumbar}_{FE}$ during lifting.

Finally, there was a significant *Intervention* × *Task Condition* × *Gender* interaction effect on $\text{Trunk}_{LB}$ during lowering. Regarding this interaction effect, there were significant effects of *Intervention* × *Task Condition* for both *Genders* ($p < 0.0001$), and the *Gender* × *Task Condition* interaction was significant for all three *Interventions* ($p < 0.0001$), but the *Intervention* × *Gender* interaction was not significant for any *Task Condition* ($p > 0.092$). Post hoc analysis, however, revealed no significant effects of BSE use on $\text{Trunk}_{LB}$ during lowering.

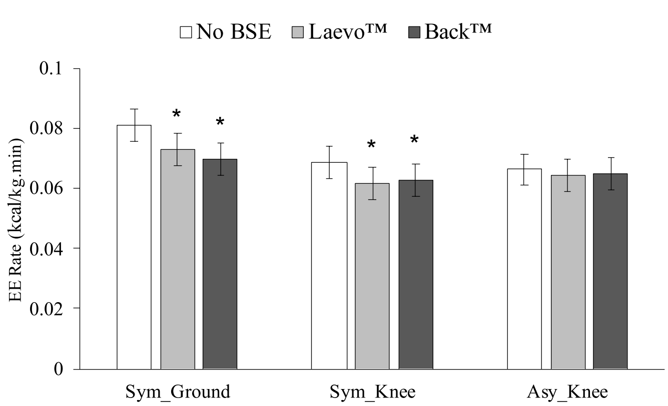


**Fig. 5.** *Intervention* × *Task Condition* interaction effects on relative energy expenditure rate (EE-rate). Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

### 3.5. Subjective ratings

Ratings of perceived discomfort (RPD) at the chest, waist, and thighs were significantly affected by *Intervention* main effects and *Intervention* × *Gender* interaction effects (Table C5 and Fig. 6). Regarding the interaction effect on chest RPD, all simple effects were significant, excepting the effect of *Gender* using the BackX™ ($p = 0.948$). Both genders reported significantly higher RPDs at the chest when using the Laevo vs. BackX™. Simple effects analyses of waist RPDs indicated that *Intervention* was only significant for females ($p < 0.0001$), and *Gender* was only significant when using the BackX™ ($p = 0.036$). Females reported significantly higher RPDs at the waist when using the BackX™. Finally, simple effects analyses for thigh RPDs revealed that *Intervention* was only significant for females ($p = 0.0015$), and *Gender* was not significant for any *Intervention* ($p > 0.303$). Females reported significantly higher RPDs at the thighs when using the BackX™ vs. Laevo™.

There were significant main effects of *Intervention* (Table C5, Fig. 7) on all RPE scores. Using the BackX™ significantly reduced RPE scores in the shoulders, lower back, legs, arms, and abdominal region compared to using no BSE, by 29.8, 40.2, 24.5, 17.6, and 34.9%, respectively. Laevo™ use also resulted in significantly reduced RPEs, by 22.8, 32.7, 24.9, 23.5, and 36.9%, respectively.

### 3.6. Usability ratings

Fig. 8 summarizes overall usability scores reported for both BSEs. Using either BSE was, on average, "moderately" to "very helpful" for both genders. There were no significant main or interaction effects of *Intervention* or *Gender* on overall usability scores ($p > 0.14$; Table C6). A significant main effect of *Intervention* was found regarding perceived fit ($p < 0.003$); participants indicated a better fit using the BackX™ (5.0 (1.1)) than the Laevo™ (3.4 (1.4)) (Fig. 9). There were also no

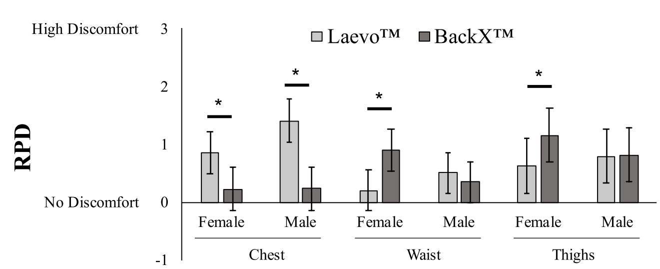


**Fig. 6.** *Intervention* × *Gender* effects on ratings of perceived discomfort (RPD) at the chest, waist, and thighs. Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

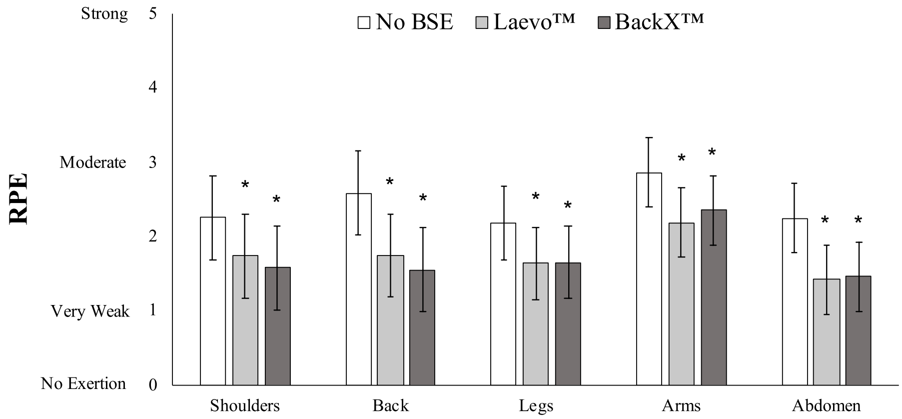


**Fig. 7.** *Intervention* effects on ratings of perceived exertion (RPE) at the shoulders, back, legs, arms, and abdominal region. Note that * denotes significant differences from the control condition (i.e., no BSE), and error bars indicate 95% confidence intervals.

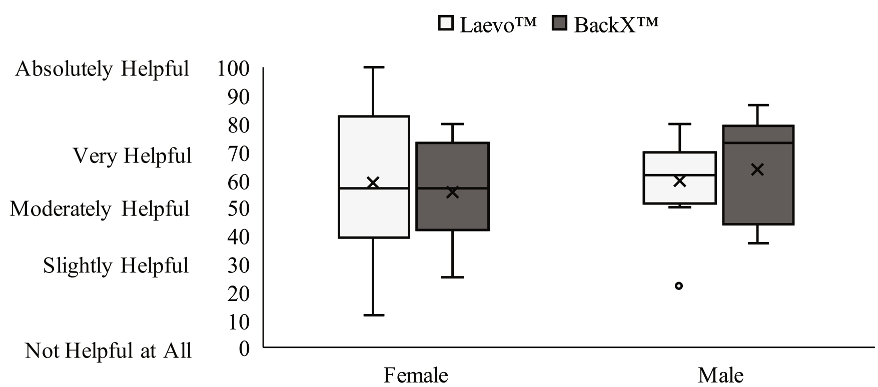


**Fig. 8.** Responses to the question: "Overall, how helpful do you think the device was during the task?", separated by gender and BSE. The symbol " × " indicates mean responses.

significant main or interaction effects of *Intervention* or *Gender* on comfort ($p > 0.42$) or body movement restrictions ($p > 0.44$), with respective overall responses of 3.9 (1.3) and 3.4 (1.3). Finally, the BackX™ was slightly more preferred, with 10 participants (6 males and 4 females) preferred that BSE, and 8 participants (3 males and 5 females) preferring the Laevo™.

## 4. Discussion

### 4.1. Trunk muscle activity

Both BSEs yielded significant reductions in trunk muscle activity, yet the magnitudes of these reductions were dependent both on the specific BSE and the lifting phase. BackX™ use significantly reduced $TEM_L$, $TEM_R$, and TTM, respectively by 20% (7.0% of MVIC), 18.3% (6.3% of MVIC), and 17.3% (28.5% of MVIC) during the lowering phase, and by

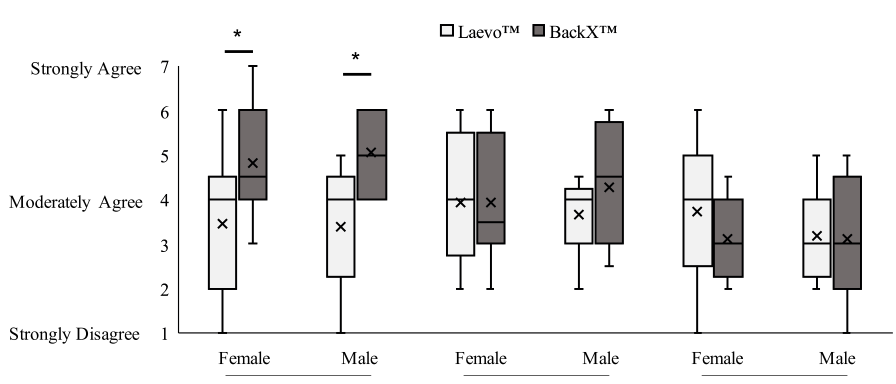


**Fig. 9.** Responses to usability questions regarding overall fit, comfort, and body movement hinderance, separated by gender and BSE. The symbol " × " indicates mean responses, and * denotes significant effects.

9.3% (3.2% of MVIC), 8.7% (3.0% of MVIC), 7.8% (12.8% of MVIC) during the lifting phase. Laevo™ use led to significant reductions only during the lowering phase, with respective reductions of 9.3% (3.2% of MVIC), 8.7% (3.0% of MVIC), 7.8% (12.8% of MVIC). The larger reductions in trunk muscle activity observed with the BackX™ vs Laevo™ might have resulted from participants selecting higher support settings with the former. For example (see Appendix A), most participants (6–8 males and 5–8 females, depending on the task condition) selected the highest level of support when using the BackX™ (i.e., instant mode, high level), but relatively "moderate" support settings when using the Laevo™ (i.e., 5-15° of cam angle). These differences in the choices of support settings might stem from the distinct design features providing supportive torque (i.e., BackX™ pulls the torso backwards while Laevo™ pushes against the chest), differences in the magnitude of assistive torque between the two BSEs, and/or differences in device fit.

In a secondary analysis, we examined peak nEMG of the abdominal muscles, which showed no significant main or interaction effects of *Intervention* on peak activity levels ($p$-values $> 0.11$), and with the magnitudes in the range of 2.7–9.8%, 2.9–10.3%, and 2.8–9.3% for the BackX™, Laevo™, and Control conditions, respectively.

Interestingly, larger reductions in trunk muscle activity were observed when using the BSEs during the lowering vs. lifting phases (Fig. 2). An increased benefit of both BSEs while lowering may have resulted from a hysteresis effect present in the viscoelastic torque generation mechanisms. For example, Koopman et al. (2020) reported that the assistive torque generated by the Laevo™ is considerably higher during the lowering phase compared to lifting. Future BSE designs might thus consider adapting the torque generation mechanisms, such as by minimizing this hysteresis effect or by providing consistent torque profiles during both trunk flexion and extension.

Both BSEs appeared to be more effective for females than males in some aspects (e.g., significant *Intervention* × *Gender* interaction effect on $TEM_L$, Fig. 3), though the associated effect size was rather small ($\eta^2 \sim 0.01$). Specifically, both BSEs tested here reduced $TEM_L$ for females (by 22.4%, or ~9% of MVIC, using BackX™; and by 11.5%, or ~5% of MVIC, using Laevo™), while males experienced significant reductions only when using the BackX™ (by 16.5%, or ~5% of MVIC). We believe the larger reductions experienced by females may be due to their lighter torso mass, considering that preferred support settings were comparable across genders (Appendix A). Further research, however, is needed to determine if such gender-related differences arise primarily from anthropometric differences, or if instead there are inadequacies in BSE design approaches to accommodate both genders (e.g., device fit, torque magnitude).

TEM reductions found here are comparable to results from previous work. Specifically, Koopman et al. (2020) found a significant reduction (by ~10%) in peak activity of the trunk extensor muscles when using the Laevo™ during "far-body" symmetric lifting; however, they found no significant reduction during "near-body" symmetric lifting. Comparable conditions in the current study were Sym_Knee and Sym_Ground, in which $TEM_L$ and $TEM_R$ significantly decreased (by ~9%), but only during the lowering phase. In a recent study, using BackX™ and Laevo™ reduced TEM activity by 24 and 17% during symmetric lifting, respectively, while the respective reductions were 13 and 15% during asymmetric lifting (Alemi et al., 2020). The only comparable condition in the current study was Sym_Ground, in which BackX™ use also yielded a larger reduction in TEM compared to Laevo™ (by 26% vs. 14% during lowering; 11% vs. 2% during lifting). The larger reductions observed by Alemi et al. (2020), however, might be due to the differences in task duration, external load magnitude, or the choice of support settings with each BSE.

Finally, no significant effects of *Intervention* or *Intervention*-related interaction effects were found for peak muscle activity in the shoulder (AD), which suggests that neither BSEs imposed adverse effects on upper extremity muscle groups during the lowering/lifting tasks. This finding is consistent with the results from previous work, wherein only minor changes in shoulder muscle activity were reported during symmetric and asymmetric lifting tasks with the BackX™ and Laevo™ (Alemi et al., 2020). However, it should be emphasized that only a single shoulder muscle was monitored here.

### 4.2. Energy expenditure

We found a significant *Intervention* × *Task Condition* interaction effect, in which using either BSE significantly reduced energy expenditure but only in the two *symmetric* conditions. Specifically, reductions in the Sym_Ground condition were 9.5 and 13.6% with the Laevo™ and BackX™, respectively; respective reductions in the Sym_Knee condition were 10.2 and 8.1%. Contrarily, no significant reductions in energy expenditure were observed in the *asymmetric* condition. The inability of either BSE to reduce energy expenditure in the asymmetric condition might stem from the torque generation mechanisms in these exoskeletons, which appear to be inefficient beyond moderately symmetric conditions. Earlier work also reported no significant effects of Laevo™ and BackX™ use in reducing the energy expenditure during standing and asymmetric lifting tasks (Alemi et al., 2020).

Females here experienced a greater reduction in energy expenditure when using either BSE. Wearing the BackX™ and Laevo™ respectively resulted in 13.2 and 8.9% reductions in energy expenditure among females, while males experienced a significant reduction only when using the Laevo™ (by 6.4%). This gender difference might be due to the lower torso weight among females, again given that preferred support settings were comparable across genders (Appendix A). Such gender-related differences could also arise from a difference in the adequacy of support settings to provide an "optimum" level of resistive torque, such as based on core strength. Similar to the suggestion above regarding muscle activity, future work seems needed to differentiate whether gender-related differences in the effects of BSE use on energy expenditure are secondary to anthropometric differences or reflect design limitations to accommodate both genders.

Energy expenditure reductions found here with BSE use are in agreement with recent work (Alemi et al., 2020) that found a significant reduction during 5-min of symmetric lifting of a 6.8-kg box from the ground (12.6% with BackX™ and 8.9% with Laevo™), while reductions in the asymmetric lifting were not significant. Baltrusch et al. (2019) further reported a non-significant ~8% reduction and a significant ~17% reduction for the Low-cam and High-cam settings, respectively, when using the Laevo™ during 5-min of symmetric lifting of a 10-kg box from knee or ankle heights. A recent study of the VT-Lowe's exoskeleton showed a significantly reduced metabolic cost, by up to 7.9% during 12-min of symmetric lifting of a box weighing 20% of body weight (Alemi, 2019). An earlier study, however, found no significant effect of a personal lift-assistive device on oxygen consumption during 15-min of symmetric lifting of a box requiring 10% of maximum back strength (Whitfield et al., 2014). This discrepancy might have resulted from differences in task duration, BSE design features, and/or lifting techniques employed. Future work is suggested to establish a standardized methodology for investigating the dependence of energy expenditure on specific BSE design approaches (e.g., torque-angle relationship) during diverse lifting tasks.

### 4.3. Kinematic measures

Neither BSE substantially influenced triaxial trunk or lumbar ROMs. These results are in agreement with earlier work (Baltrusch et al., 2019; Koopman et al., 2020), in that minor changes in $Lumbar_{FE}$ and $Trunk_{FE}$ ROM ($\leq 6°$) were reported when using the Laevo™ during symmetric lifting from ankle or knee height. Similarly, no postural changes were reported when using a personal lift-assistive device (Abdoli-e et al., 2006; Abdoli-e & Stevenson, 2008), a biomechanically-assistive garment (Lamers et al., 2018), or a bending non-demand return device (Ulrey and Fathallah, 2013) during symmetric and/or asymmetric lifting tasks. Our results, along with this earlier evidence, suggests that no (or only minor) changes in postures occur when using a BSE. However, it is unclear if this is a beneficial outcome: increased trunk motion (i.e., flexion) during lifting tasks could serve to enhance the support provided by a BSE, but would also likely change the loads imposed on the spine.

In contrast to ROMs, we found a significant reduction in $Trunk_{FE}$ velocity (by ~7%) when using the Laevo™ during the lowering phase [Laevo™ = 52.6 (48.9, 56.5) °/s vs. no BSE = 56.6 (52.7, 60.5) °/s]. Wearing the Laevo™ also reduced $Trunk_{FE}$ velocity during the lifting phase in the Sym_Ground condition, by ~12% [Laevo™ = 74.3 (68.4, 80.5) vs. no BSE = 84.6 (78.3, 91.2) °/s]. While the magnitudes of these reductions are rather small, we believe these changes might stem from potentially inadequate assistive torque provided by the Laevo™. As shown above, when using the Laevo™ participants increased their trunk muscle activity (in comparison to BackX™ use), perhaps to compensate for inadequate assistive torque generated by this device. As a result, they might have attenuated their lifting speed to mitigate mechanical demands on the spine. These outcomes are consistent with earlier evidence, in which up to an 18% reduction in peak $Trunk_{FE}$ velocity was found during symmetric lifting with the Laevo™ (Koopman et al., 2020). The larger reduction in $Trunk_{FE}$ velocity reported by Koopman et al. (2020) vs. here, though, might be due to differences in the simulated lifting conditions or external load magnitude, or the fact that their study controlled the support settings (at low and high cam angles).

### 4.4. Perceived discomfort and exertion

Participants overall reported low-to-medium levels of discomfort at the chest, waist, and thighs (Fig. 7). Both genders, though, reported significantly higher discomfort at the chest when using the Laevo™. Additional verbal feedback from the participants revealed that the relatively higher chest discomfort experienced when using the Laevo™ was likely due to its chest plate, which can pivot during movements causing the plate to rub against the chest during trunk movements, especially when twisting. Females also experienced higher waist and thigh discomfort when using the BackX™, which we believe resulted from the waist belt and leg pads of BackX™ not sufficiently accommodating them (vs. males). Specifically, females may have experienced more pressure from the waist belt and thigh pads, resulting in a higher discomfort, because of differences in hip width.

Perceived exertion at the shoulders, lower back, legs, arms, and abdominal region all significantly decreased when using either BSE (Fig. 6). RPE reductions at the lower back were anticipated, since both BSEs are designed to offset external flexor moments on the torso by providing a counterbalance torque. Our observations regarding the lower back agree with earlier evidence of reduced levels of perceived exertion in this region when using BackX™ or Laevo™ (Alemi et al., 2020), or a personal lift-assistive device (Lotz et al., 2009), in manual lifting tasks, and are also consistent with the reductions in trunk muscle activity discussed earlier. Reductions in perceived exertion found here at other body regions suggest further that the external load transferred from the torso did not adversely affect other body regions, a conclusion supported by results regarding shoulder muscle activity (which indicated no adverse effect of BSE use on the anterior deltoid muscle).

### 4.5. Usability ratings and user feedback

Participants perceived using either BSE to be moderately to very helpful (Fig. 8), and these ratings were comparable across genders. Ratings of fit showed that the BackX™ was superior for both genders (Fig. 9). Participants moderately agreed with the question regarding overall comfort of the BSEs to wear at work, and the results were again comparable across genders. While responses regarding body movement hinderance when wearing the BSEs were also comparable across both genders and BSEs (Fig. 9), females expressed concerns regarding movement hinderance when using the Laevo™ (mainly due to shifting and moving of the chest and thigh pads, and the fit of the waist pad and buttock belts). Males also commented on the contact between the torso rods and their ribcage while twisting. Finally, there was no clear indication of a preferred BSE, with slightly more participants preferring the BackX™ (10 participants out of 18) over the Laevo™ (8 participants), which is generally consistent with the other usability outcomes observed.

### 4.6. Limitations

A few limitations of the present study need to be noted. First, the sample only included young healthy adults (20–35 yrs), so caution should be taken in generalizing the findings for an older population. Second, participants were familiarized with each BSE and practiced the lifting tasks only during an initial training session. Whether this training was sufficient for participants to benefit fully from the BSEs remains unknown. Third, we focused here on relatively short-term effects of different BSEs (i.e., 4 min of repetitive lowering/lifting), and it is unclear if the BSE effects reported here can be generalized for more prolonged and/or frequent use of a BSE. Fourth, the current lifting tasks were simulations, performed in a controlled laboratory environment, and thus the relevance of our results to actual work settings, especially with suboptimal working conditions (uneven ground surfaces, restricted working space, etc.), warrants further investigation.

## 5. Conclusions

Occupational tasks involving repetitive lifting/lowering can be challenging to eliminate or modify in practice, and alternative interventions such as assistive devices are promising. We evaluated the effects of two commercially-available back-support exoskeletons on peak muscle activity, joint kinematics, energy expenditure, perceived discomfort and exertion (at shoulder, lower back, and leg), and usability, during symmetric and asymmetric lifting tasks. Using both BSEs reduced peak trunk extensor muscle activity (by ~9–20%, or 3–7% of maximum) and reduced energy expenditure (by ~8–14%). No substantial changes in trunk or lumbar kinematics were observed when using either BSE, which suggests that neither BSEs substantially influenced lifting methods. Use of both BSEs generally had positive impacts on subjective ratings. Our results further suggest that the beneficial effects of both BSEs are more pronounced in symmetric vs. asymmetric lifting and lowering tasks, and that within these tasks there are differences between BSE designs. Future work is recommended to better characterize this task specificity and to determine the generalizability of BSE effects on objective and subjective outcomes among a wider range of task conditions and users.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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