Ergonomics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/terg20

Age and gender differences in the perception and use of soft vs. rigid exoskeletons for manual material handling

Rahul Narasimhan Raghuraman, Dechristian França Barbieri, Jessica Aviles & Divya Srinivasan

To cite this article: Rahul Narasimhan Raghuraman, Dechristian França Barbieri, Jessica Aviles & Divya Srinivasan (13 Apr 2024): Age and gender differences in the perception and use of soft vs. rigid exoskeletons for manual material handling, Ergonomics, DOI: 10.1080/00140139.2024.2338268

To link to this article: https://doi.org/10.1080/00140139.2024.2338268

ERGONOMICS
https://doi.org/10.1080/00140139.2024.2338268

RESEARCH ARTICLE

Age and gender differences in the perception and use of soft vs. rigid exoskeletons for manual material handling

Rahul Narasimhan Raghuraman, Dechristian França Barbieri, Jessica Aviles and Divya Srinivasan

Department of Industrial Engineering, Clemson University, Clemson, SC, USA

ABSTRACT

We investigated age and gender differences in the perception and use of soft (Apex) vs. rigid (Paexo Back) passive back-support exoskeletons (BSE) for repetitive lifting and lowering. A gender-balanced sample of 20 young (18–30 years) and 16 old (45–60 years) individuals were recruited. In the first session, participants' self-reported maximum acceptable load (MAL) was assessed using a psychophysical approach. Changes in muscle activity and kinematics due to BSE use in repetitive lifting/lowering tasks were also assessed. Overall, both BSEs increased MAL (by ~7%), and reduced trunk extensor muscle activity across all groups (by ~7–18%), compared to the control condition. Both BSEs promoted more squatting postures, increased quadriceps muscle activity (by ~34%) and abdominal muscle activity during asymmetric tasks (by 5–20%). Some age and gender differences were significant, particularly for the trunk kinematics when using the Apex. Future work should include more diverse user groups in studying willingness to adopt BSEs and characterising their consequent effects on the body.

Practitioner summary: Manual material handling is difficult to eliminate in several industries. There are now viable rigid and soft exosuit systems that can offer varying levels of support. We found both kinds of exoskeletons to be equally effective in reducing trunk extensor muscle activity, among young and old males and females.

ARTICLE HISTORY
Received 7 September 2023
Accepted 27 March 2024

KEYWORDS
EMG; posture; psychophysics; biomechanics; repetitive lifting

1. Introduction

Work-related musculoskeletal disorders (WMSDs) continue to be highly prevalent in manual material handling (MMH) tasks, with back injuries alone accounting for 39% of all WMSDs, accentuated by cumulative trauma from repetitive lifting and holding non-neutral postures (da Costa and Vieira 2009; U.S. BUREAU 2018). The National Safety Council recently reported an estimated \$164 billion in expenditure due to such work-related injuries (NSC 2020). Exoskeletons are a wearable technology of increasing interest in the occupational domain, as they are designed to support users while performing work tasks and reduce physical workload by providing external forces to body segments (de Looze et al. 2016; Nussbaum et al. 2019; Theurel and Desbrosses 2019).

Exoskeletons are generally classified into active or passive types based on their force-generation mechanisms (Crea et al. 2021). Passive exoskeletons can have rigid or soft structures, varying in design and in body contact area for support. An example of a rigid passive exoskeleton to support the back is the Paexo Back (Ottobock) which was recently tested in a study by Schmalz et al. (2022) and demonstrated a reduction in trunk extensor muscle activity during a repetitive lifting and lowering task. Another study by Alemi et al. (2020) compared two rigid, passive back-support exoskeletons on muscle activity during symmetric and asymmetric repetitive lifting. The results showed up to 30% reduction in peak trunk extensor muscle activity when using the BackX (SuitX™) and Laevo (V2.5) devices, and that these reductions were more pronounced in symmetric tasks. Within the few available commercial models of textile-based soft passive exosuits, the HeroWear Apex (HeroWear, Nashville, USA) is a contemporary device that has been shown to produce a ~15% reduction in erector spinae muscle activity during lifting and lowering tasks (Lamers et al.

CONTACT Divya Srinivasan sriniv5@clemson.edu Department of Industrial Engineering, Clemson University, Clemson, SC, USA
Supplemental data for this article is available online at https://doi.org/10.1080/00140139.2024.2338268.

2018, 2020; Yandell et al. 2022). A laboratory study performed by Goršič et al. (2022) also evaluated a soft passive-support exoskeleton, the Auxivo (LiftSuit 1.1), and showed up to ~10% reduction in trunk muscle activity, during lifting and lowering of a 30-lb box.

However, little is known about the general comparative effects of rigid vs. soft passive back-support exoskeletons. The only study, to our knowledge, that has reported comparisons between rigid and soft passive devices is a recent study (Schwartz et al. 2021) that compared the Laevo® and Corfor® devices among young adults performing a repetitive lifting/lowering task in the sagittal plane at a single load level and reported comparable effects of both devices. Nevertheless, comparative effects of rigid vs. soft designs in terms of their effectiveness and user acceptance, across a range of different tasks and user-profiles, are still lacking.

Furthermore, while most prior studies have reported objective metrics such as metabolic energy expenditure, muscle activity, and kinematic measures to demonstrate device effectiveness, understanding users' perceived benefit from the device is somewhat limited. For instance, a very recent study has shown that users may not perceive metabolic benefits provided by exoskeletons unless there is on average, at least a 23% increase in metabolic rate (Medrano et al. 2022). However, this study was conducted for assisting locomotion and the concept of 'when' a user perceives benefits from an exoskeleton device is unexplored in the context of MMH. An increasing number of studies have demonstrated that worker acceptance and perceived benefits are major driving factors when it comes to exoskeleton adoption in practice (Kim et al. 2019; Schwerha et al. 2021; Upasani et al. 2019). Hence, understanding which factors may determine a user's acceptance of exoskeletons is a necessary next step, to resolving key barriers to the practical implementation of exoskeletons. In this context, a recent study by Elprama et al. (2020) assessed the attitudes of industrial workers regarding exoskeleton use at their workplace and demonstrated that 'effort expectancy' (how easy it seems to use the exoskeleton) and 'social expectancy' (what people think about who uses the device) were the most important factors in predicting workers' intention to adopt the exoskeleton. This study also showed that the results were influenced by age, as the construct of performance expectancy (job performance) was more important for the younger group's intention to adopt exoskeletons and perception of exoskeleton support was another important variable that impacted a user's intention to use an exoskeleton (Elprama et al. 2020).

A user's perceived support and performance expectancy from an exoskeleton could be evaluated through a psychophysical approach (Ciriello et al. 1993; Karwowski et al. 1999; Snook 1999). In general, a psychophysical approach involves designing experiments and using quantitative methods to understand the relationship between physical stimuli (e.g. load demands) and the psychological responses they elicit (e.g. perceived effort) (Chaffin and Page 1994; Ciriello et al. 1993; Elfeituri and Taboun 2002; Potvin 2014; Snook 1999). Psychophysics has played a specific and prominent role in the development of comprehensive ergonomics guidelines for MMH (Snook 1999). Furthermore, it has been shown that among industrial workers, low back pain was reported more frequently among those who perceived their work to be harder (Snook 1999). The only known application of a psychophysics methodology to evaluate exoskeleton use is the study by Alabdulkarim and Nussbaum (2019), where three arm-support exoskeletons were compared in terms of the maximum acceptable frequency of work in a simulated overhead drilling task. Psychophysics, in conjunction with biomechanical approaches, to study the perceived and objective differences in physical demands when using back-support exoskeletons could provide new evidence relevant to the industry adoption of exoskeleton devices for MMH.

Although exoskeletons are intended to be effective, comfortable, and usable across diverse groups of users (e.g., of different sizes, strengths, gender, and ages), most laboratory studies have recruited only young (college-age) participants (Theurel and Desbrosses, 2019). Some significant gender differences in the reduction of trunk-extensor muscle activity associated with exoskeleton use for repetitive lifting has been reported by some studies (Madinei et al. 2020a), while others have reported no significant gender differences (Schwartz et al. 2021). However, to the best of our knowledge, there have been no systematic investigations of differences in exoskeleton effectiveness across age, which might be important considering that the participation rates of older age groups in the workforce have been steadily increasing in the last two decades, and this trend is further projected to increase (Dubina et al. 2021). Recent systematic reviews and position papers have also begun to raise wider ethical concerns on the limited demographics represented in current exoskeleton studies (Pote et al. 2023; Søraa and Fosch-Villaronga 2020; Theurel and Desbrosses 2019) this research with limited participant representation forms the current evidence basis informing exoskeleton technology design, including critical design features such as sizing, assistance mechanisms, and human-exoskeleton interface, which could broadly impact exoskeleton usefulness and adoptability. Thus, to be equitable in accessibility and usefulness across a broad range of users, it is important to expand the study of exoskeleton effectiveness and use across different age and gender groups (Alemi et al. 2020; Madinei et al. 2020a, 2020b; Nussbaum et al. 2019), as well as understand age and gender differences in willingness to adopt exoskeletons.

The goal of this study was to evaluate both the self-rated maximum acceptable load and physiological benefits of exoskeleton use in terms of muscle activity and kinematics changes during repetitive lifting/lowering tasks for different age and gender groups (young group of 18–30-year-old males and females vs. old group of 45–60-year-old males and females). The specific goals of this study were:

- Session 1—Investigate age and gender differences of self-rated maximum acceptable load and BSE adoption/effectiveness through usability evaluation. We expected all participants to show an increase in maximum acceptable load (MAL) when using the BSEs, although the magnitude of differences may vary with device type and age. We expected the older group to have a greater awareness of exoskeleton benefits and be more accepting of adopting the technology, since we expected that age-related decline in strength and/or endurance may make them more appreciative of assistance from an external device. Additionally, considering that a soft textile-based exoskeleton is lighter and easier to don (Elprama et al. 2020), we expected participants to prefer the soft device.
- Session 2—Quantify the physiological benefits of BSE use by measuring muscle activity and kinematics changes during repetitive lifting/lowering tasks. Lifting tasks were varied in load level and included symmetric and asymmetric lifting/lowering conditions. Based on prior work, we anticipated the biomechanical benefits (reduction in trunk extensor muscle activity) would be greater for the rigid device that has a structural frame for postural support, compared to the soft device that offers no postural support from the exoskeleton body.

2. Methods

2.1. Study population and ethics

A gender-balanced sample of thirty-six adults, with 20 young (10 M and 10 F; 18–30 years) and 16 old (8 M and 8 F; 45–60 years) individuals with no recent (12 months) history of musculoskeletal injuries/disorders and no prior experience using back support exoskeletons were recruited for this study using convenience sampling from the university and the local community in Clemson, SC. These age groups were chosen to be representative of working-age adults (defined as 15–64 years by OECD 2023), with maximum possible separation between the two groups. Relevant participant demographic characteristics are reported in Table 1. This research was approved by the Clemson University Institutional Review Board (#IRB2021-0843). Written informed consent was obtained from all participants prior to data collection in accordance with the Declaration of Helsinki.

2.2 Exoskeletons compared

For the aims of this study, we were primarily interested in comparing rigid vs. soft devices that were significantly different in weight, form, assistance mechanism and other design features such as the way they attach to the body. So, we chose two very different types of passive BSEs, both of which are commercially available and actively being explored for industrial use-cases: (1) A soft exosuit called Apex from HeroWear, LLC, Nashville, TN, USA and (2) a rigid exoskeleton called Paexo Back from Ottobock SE & Co. KGaA, Duderstadt, Germany. The Apex BSE weighs 1.6 kg, it assists in lifting using dual elastic bands, that stretch to absorb energy when bending and releases it when lifting. The elastic bands are variable in length and stiffness, the former is chosen according to the participant's anthropometry and the latter is chosen according to the level of resistance provided (Light, Strong, or Extra Strong) (HeroWear 2021). On the other hand, the Paexo Back BSE weighs 4 kg, it offloads trunk extension moment for lifting using its energy storage mechanism that absorbs force when bending and releases it again when lifting. Paexo Back allows for different size adjustments at trunk, hip, back, and thighs (Ottobock 2020). Figure 1 shows the two BSEs used in this study.

Table 1. Age and anthropometric data of the participants ($n = 36$) of participants.

	Young adults ($n = 20$)	Old adults ($n = 16$)
	Mean (SD)	Mean (SD)
Age (years)	25.1 (6.1)	51.9 (7.6)
Body mass (kg)	70.0 (19.8)	77.1 (18.9)
Stature (m)	1.70 (0.06)	1.72 (0.09)
BMI (kg/m^2)	24.1 (6.1)	25.9 (5.2)

Figure 1. Paexo Back (left) and Herowear Apex (right) passive back-support exoskeletons with parts marked and labelled.

2.3. Experimental design and procedures

In this study, user-perception of BSE usefulness was measured using a psychophysical approach to obtain maximum acceptable workload (session 1). Additionally, objective biomechanical effects of BSEs (e.g., changes in kinematics and muscle activity of the trunk and legs) were obtained during the performance of standardised tasks (session 2). A repeated measures design was used for the two sessions, conducted on two different days at least 3 days apart. In both sessions, three experimental conditions: Control (No BSE), Apex, and Paexo Back were included, and the order of exposure to the experimental conditions was counterbalanced, and randomly assigned across participants.

2.3.1. Session 1: Psychophysical approach

Session 1 totally lasted for ~3 h. This session began with exoskeleton fitting and familiarisation. Both exoskeleton devices were fitted according to manufacturer recommendations based on participant anthropometry. Following this, a brief familiarisation period of ~10 min was provided for each device. For the Apex device, during the familiarisation period, participants were asked to perform lifting/lowering of a box (weighing 10 kg) with the three different elastic stiffness levels for 2 min each, and they selected the elastic band they preferred to use during the remainder of the study. For the Paexo Back device, assistance was set at 'Early Support mode' as per manufacturer recommendations for repetitive bending/lifting tasks.

Next, participants completed multiple trials of symmetric lifting and lowering a box in front of them for durations of 1 min each, at a pace of 10 bpm (i.e., 5 lifts and lowers per minute), until the participant reported having reached their maximum acceptable load (MAL). The protocol for this session is shown in Figure 2. A wooden box (dimensions: 40 H × 25 W × 23 L cm, with 4 cm cut-outs for handles) was placed on an adjustable table (set at participant waist height) at ~30 cm horizontally in front of the participant, who then lifted/lowered the box with varying levels of loads from the table to a pallet placed at their mid-shank level. A minute-long break was provided between successive lifting trials. Participants completed two rounds of lift/lowers. Each round started with either a 6.3 kg (minimum) or 20 kg (maximum), and load levels were continuously increased (or decreased) in standardised increments of 2.7 kg at the end of every 1-min trial. Participants were not aware of the actual load magnitudes. MAL was defined as the maximum load which the participant would feel comfortable lifting if they had to work for a full 8-h working shift without experiencing any injury or soreness. Participants rated usefulness and ease of use on a Likert scale of 0 (extremely unlikely) to 8 (extremely likely), if wearing an exoskeleton made them feel safer, and if using an exoskeleton made them seem weaker on a Likert scale of 0 (strongly disagree) to 10 (strongly agree) after each experimental condition and each BSE adapted from Alabdulkarim and Nussbaum 2019.

2.3.2. Session 2: Biomechanical outcomes during standardised lifting

In this session (see Figure 3) lasting ~4 h, participants performed repetitive symmetric and asymmetric lifting/lowering of a standard high load (7.3 kg) and a low load (3.6 kg) at 10 bpm for 3 min each with control

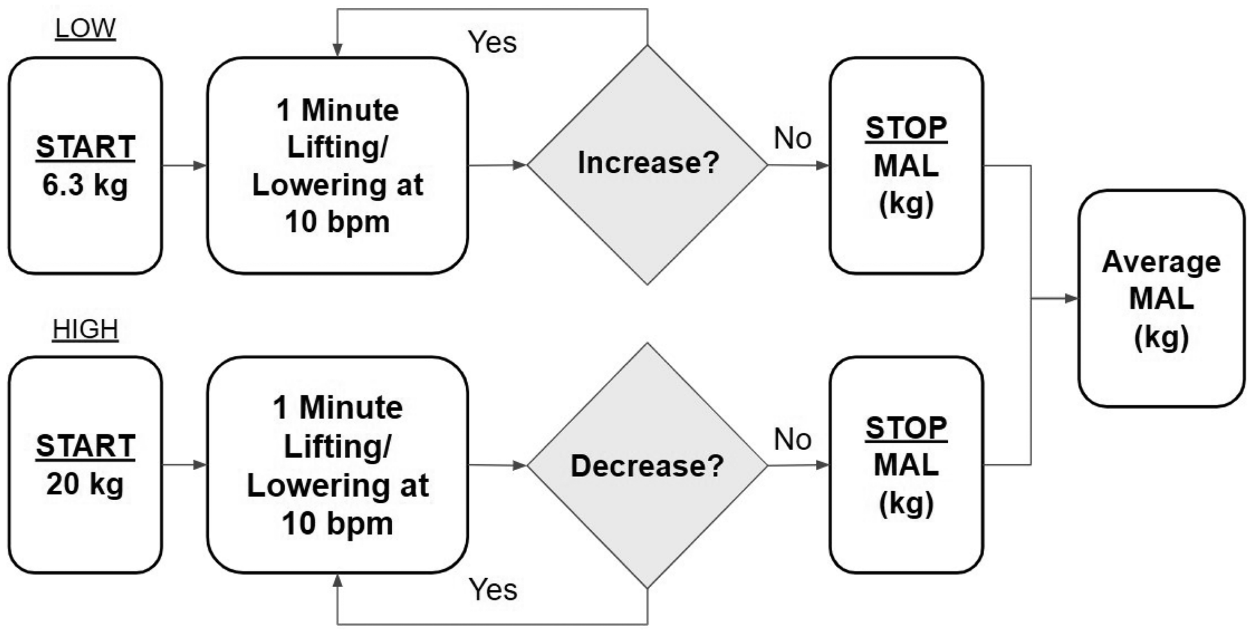

Figure 2. Psychophysical protocol in Session 1 to determine the MAL in control and each BSE condition.

and both the BSEs. The symmetric lifting/lowering setup was similar to session 1. For asymmetric lifting/lowering, participants were asked to twist 45° to the side of their dominant arm without moving their feet (to isolate trunk/pelvis twisting action). Participants were instrumented with measurement systems for recording body kinematics and muscle activities, as described below. After completing each trial shown in Figure 3, participants were asked to rate their perceived level of discomfort (RPD) at their shoulder, low back and thigh using 10-point Likert scales (Kuijt-Evers et al. 2007) and rate their perceived level of exertion (Borg 1982).

2.3.2.1. Instrumentation and data processing. Segmental body kinematics were recorded using a wearable Inertial Measurement Unit system with 17 units (Xsens Technologies, B.V., Netherlands, MTw Awinda) at 60 Hz, and the data were low pass filtered at 5 Hz using a 4th order bidirectional Butterworth filter. The standard ZXY rotation sequence recommended by ISB was used to analyse kinematic data (Wu et al. 2002). Each 3-min repetitive lifting/lowering task from session 2 was split into 15 lifting and 15 lowering segments. The peak (95th percentile) angles for flexion/extension and axial rotation of the trunk (i.e., thorax w.r.t. vertical) and knee (thigh to tibia) and angular velocity were computed for each lifting and lowering segment (15 lifting peaks and 15 lowering peaks for each 3-min condition), and averages across trials are reported.

Muscle activity was recorded using surface electromyography (EMG) using a telemetered surface EMG system (TeleMyo Desktop DTS, Noraxon, AZ, USA), at 2000 Hz. After appropriate skin preparation, pairs of pre-gelled, bipolar, Ag/AgCl electrodes with a 2.5 cm inter-electrode spacing were placed over a total of six accessible muscle groups. Four of the muscle groups included those crossing the lower lumbar, thoracic, and abdominal regions: bilateral iliocostalis lumborum (ILL), thoracic erector spinae (TES), external oblique (EO), rectus abdominis (RA). The remaining included the dominant vastus medialis (VM) and biceps femoris (BF). The BF and VM muscles were specifically chosen as major muscles that are active during squatting actions: BF activates to extend the thigh/flex the knee when going from an upright to a squatting position (while lowering loads to the ground), while VM activates to extend the knee from a squatting position to bring the body upright (while lifting loads up from the ground). Figure 4 shows the placement locations for the EMG electrodes and IMU sensors, and Table 2 lists the references for electrode placement for each muscle.

At the start of the session, participants completed three trials of maximum voluntary contractions (MVC) for each muscle group. Procedures for the MVC tests are reported in terms of the references adopted, in Table 2. The raw surface EMG signals from the trials were band pass filtered at 20–450 Hz range with an 8th order bidirectional Butterworth filter (Boettcher et al. 2008). RMS of the filtered EMG data was computed using overlapping 100 ms moving windows, normalised to the corresponding MVCs, and reported as nEMG. Trunk extensor muscle activity was computed as an

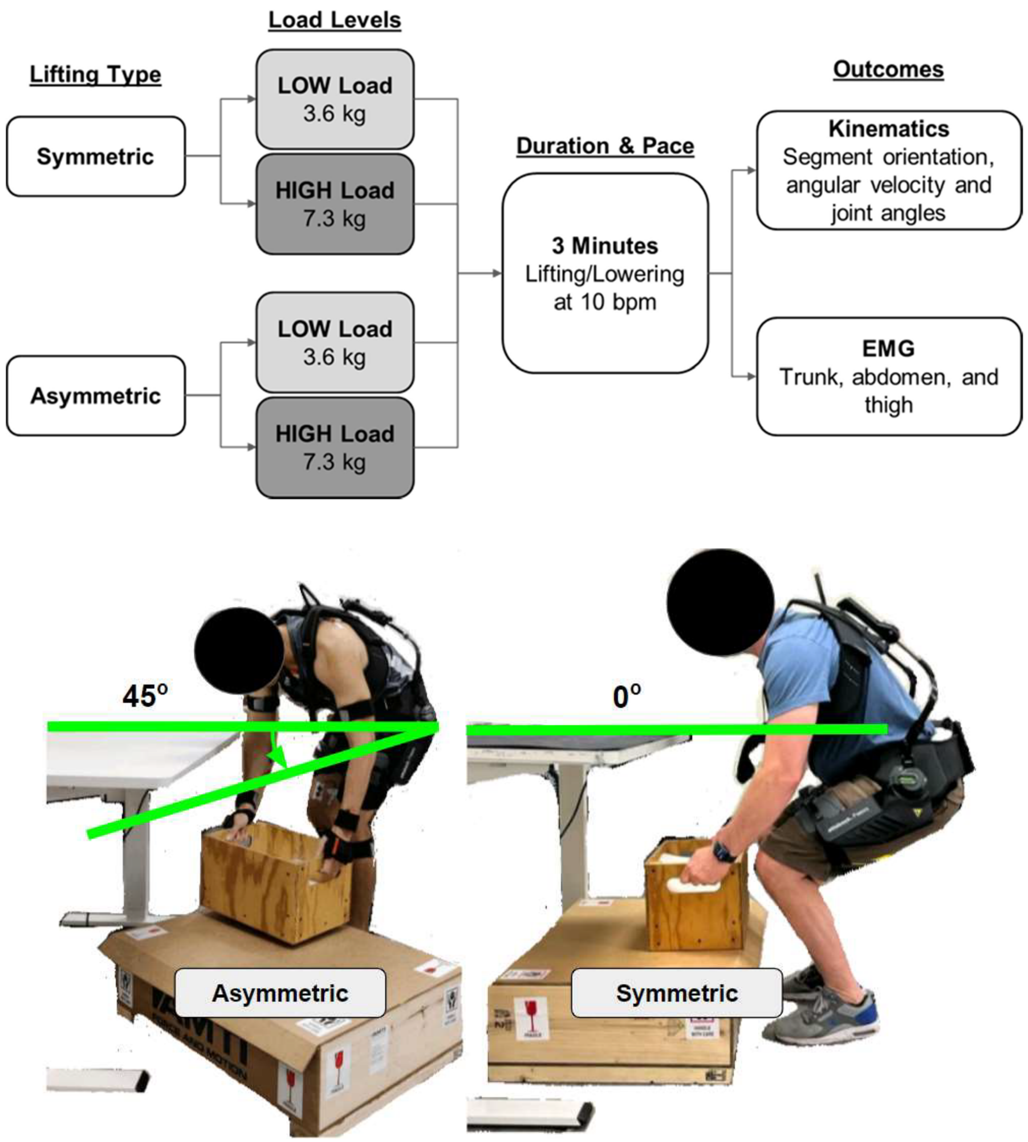

Figure 3. Top panel: session 2 protocol to determine biomechanical outcomes during standardised lifting in control and each exoskeleton conditions. Bottom panel: task setup for asymmetric and symmetric lifting/lowering tasks.

average of TES and ILL [TrunkExt = (ILL + TES)/2] and separately estimated for dominant and non-dominant sides (Madinei et al., 2020b). Trunk Flexor muscle activity was computed as an average of RA and EO [TrunkFlex = (RA + EO)/2], separately for the dominant and non-dominant sides. Peak (95th percentile) nEMG of TrunkExt, TrunkFlex, VM, and BF were calculated for each lifting and lowering segment (15 lifting peaks and 15 lowering peaks for each 3-min condition) and averages across trials are reported.

2.4. Statistical analyses

During EMG data processing and analysis, every single trial was visually inspected for data quality, and ~11% of the trials (i.e., ~100 of >850 trials) were discarded due to poor quality of the EMG data, before computing the outcome measures for statistical analysis. Separate three-way repeated measures ANOVA were used to test the effects of exoskeleton condition (three levels), age group (two levels) and gender (two levels) on MAL and perceived usefulness and usability from session 1, and peak body kinematics and muscle activity collected during session 2. Significant effects were followed by *post hoc* pairwise comparisons (Tukey's HSD) where relevant. Descriptive data were reported on subjective perceptions of exertion, and discomfort. All statistical analyses were performed using JMP Pro 14 (SAS, Cary, NC), with statistical significance concluded when $p < .05$.

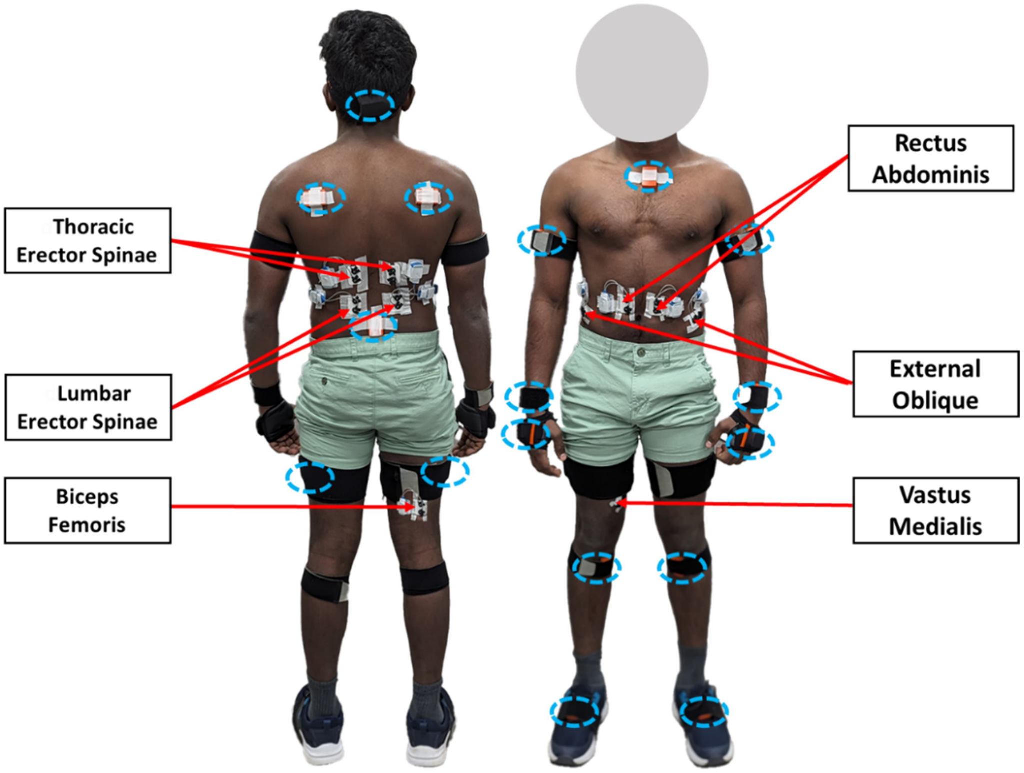

Figure 4. Participants equipped with EMG electrodes (as per references in Table 2) and 17 IMU sensors (dashed blue locations) based on manufacturer reference.

Table 2. Procedures followed for EMG electrode placements and MVC tests.

Muscles	Abbreviations	Electrode placement	MVC test
Thoracic erector spinae	TES	(Criswell 2011)	(Jackson et al. 2017)
Iliocostalis lumborum	ILL	(SENIAM 1999)	(Jackson et al. 2017)
Rectus abdominis	RA	(Dankaerts et al. 2004)	(Dankaerts et al. 2004)
External oblique	EO	(Dankaerts et al. 2004)	(Dankaerts et al. 2004)
Vastus medialis	VM	(SENIAM 1999)	(Criswell 2011)
Biceps femoris	BF	(SENIAM 1999)	(Llurda-Almuzara et al. 2021)

3. Results

3.1. Session 1

3.1.1. Maximum acceptable load (MAL)

The average (mean) MAL was 11.9 (SD 2.5) kg in the control condition, 12.7 (SD 2.9) kg with the Apex device, and 12.5 (SD 2.5) kg in the Paexo Back condition. There was a significant main effect of BSE ($p = .01$) on MAL: MAL increased significantly with the Apex BSE (6.9%) and with the Paexo Back BSE (5.9%), compared to the control (no BSE) condition. No gender or age group interactions with BSEs were statistically significant. These results are illustrated in Figure 5.

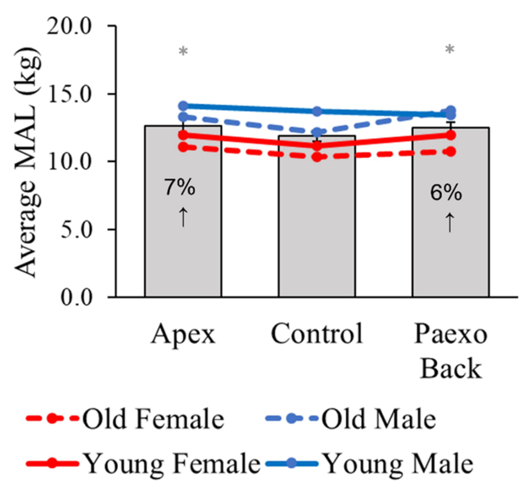

Figure 5. Average-MAL (in kg) for repetitive lifting with different BSE conditions compared to control (no exoskeleton condition). Bars indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control.

3.1.2. Perceptions of exoskeleton usefulness and usability

The mean ratings for 'Safety' (i.e., if wearing an exoskeleton made them feel safer) and 'Social perception' (i.e., if using an exoskeleton made them seem weaker) are shown in the left panel of Figure 6, while perceived 'Usefulness' and 'Ease of Use' are shown in the

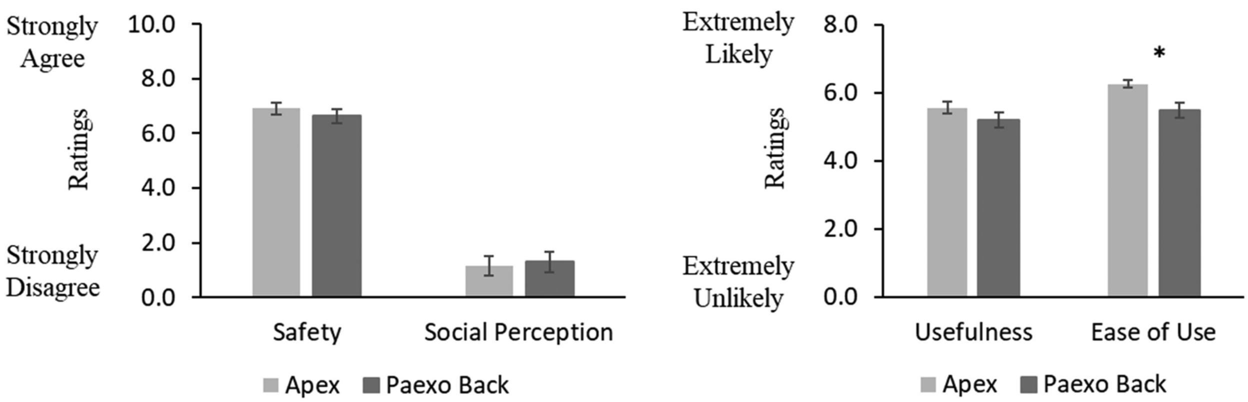

Figure 6. Left panel: ratings for safety and social perception (0: strongly disagree to 10: strongly agree); right panel: usefulness and ease of use (0: extremely unlikely to 8: extremely likely) with Apex and Paexo Back. *Asterisk* denotes statistically significant differences between the BSEs.

right panel of the same figure. No significant differences were found except for 'Ease of Use' in which Apex was rated as being significantly easier to use than Paexo Back (as shown in the right panel of Figure 6).

3.2. Session 2

3.2.1. Kinematics

A summary of ANOVA results (*p*-values and partial eta-squared effect sizes) for trunk and knee kinematics are shown in Appendix A1.

3.2.1.1. Trunk kinematics (95th percentile). There was a main effect of BSE for peak trunk flexion/extension angle and peak trunk flexion/extension velocity across all symmetric and asymmetric high and low-load conditions during lifting and lowering (Figure 7). These changes ranged from 5 to 10% reduction in trunk flexion angles, and 10 to 20% reduction in angular velocity, across the different conditions. There was also a main effect of BSE for peak trunk rotation velocity for most asymmetric conditions. Specifically, there were significant changes in trunk rotation angular velocity in the asymmetric conditions (~5% reductions with BSE-use) while there were minimal changes in trunk rotation angles (<2%) across all other conditions).

BSE × age × gender interaction effect was significant for peak trunk flexion/extension angle in several symmetric and asymmetric conditions (Figures 7 and 8). Most of these interaction effects were more pronounced for the Apex device compared to the control condition. For example, while young males showed greater reductions in trunk angle and angular velocity in the Apex condition compared to control during the symmetric task conditions (compared to other age/gender groups), old females showed greater reductions in trunk angle and angular velocity compared to the other groups in the asymmetric tasks, also in the Apex condition. These main and interaction effects along with overall means and percentage changes for peak trunk flexion angle and peak trunk flexion velocity are shown in Figure 7, and for peak trunk rotation angle and peak trunk rotation velocity are shown in Figure 8.

3.2.1.2. Knee flexion angle (95th percentile). There was a main effect of BSE for knee flexion angle across all symmetric and asymmetric tasks in low and high load conditions. On average, using Apex and Paexo Back BSEs increased peak knee flexion angle by ~10% across all task conditions (Figure 9). No interaction effects of age or gender with BSE were significant.

3.2.2. Muscle activity

3.2.2.1. Peak trunk muscle activity (95th percentile). The main effect of BSE was significant for peak TrunkExt (dominant and non-dominant) nEMG (%MVC) across all symmetric and asymmetric conditions (*p* values for the Dominant TrunkExt muscles are reported in Appendix A2, and graphical results shown in top panel of Figure 10). Overall, the reduction in peak TrunkExt EMG was greater during the lowering tasks than the lifting tasks (8–20% range of reduction in lowering vs. 3–12% during lifting). Secondly, the average reduction in nEMG of the trunk extensor muscles for both BSEs were similar across both symmetric and asymmetric lifting/lowering tasks. Finally, post-hoc tests indicated that as compared to the control condition, the Paexo back produced a significantly greater reduction in TrunkExt EMG than the Apex device across most task conditions.

The TrunkFlex muscles were not very active during the symmetric task conditions (peak of ~5% MVC). Within that, only the Apex BSE led to significant reductions in TrunkFlex EMG in the symmetric tasks. For the asymmetric task conditions, results from only the non-dominant side are emphasised in this section

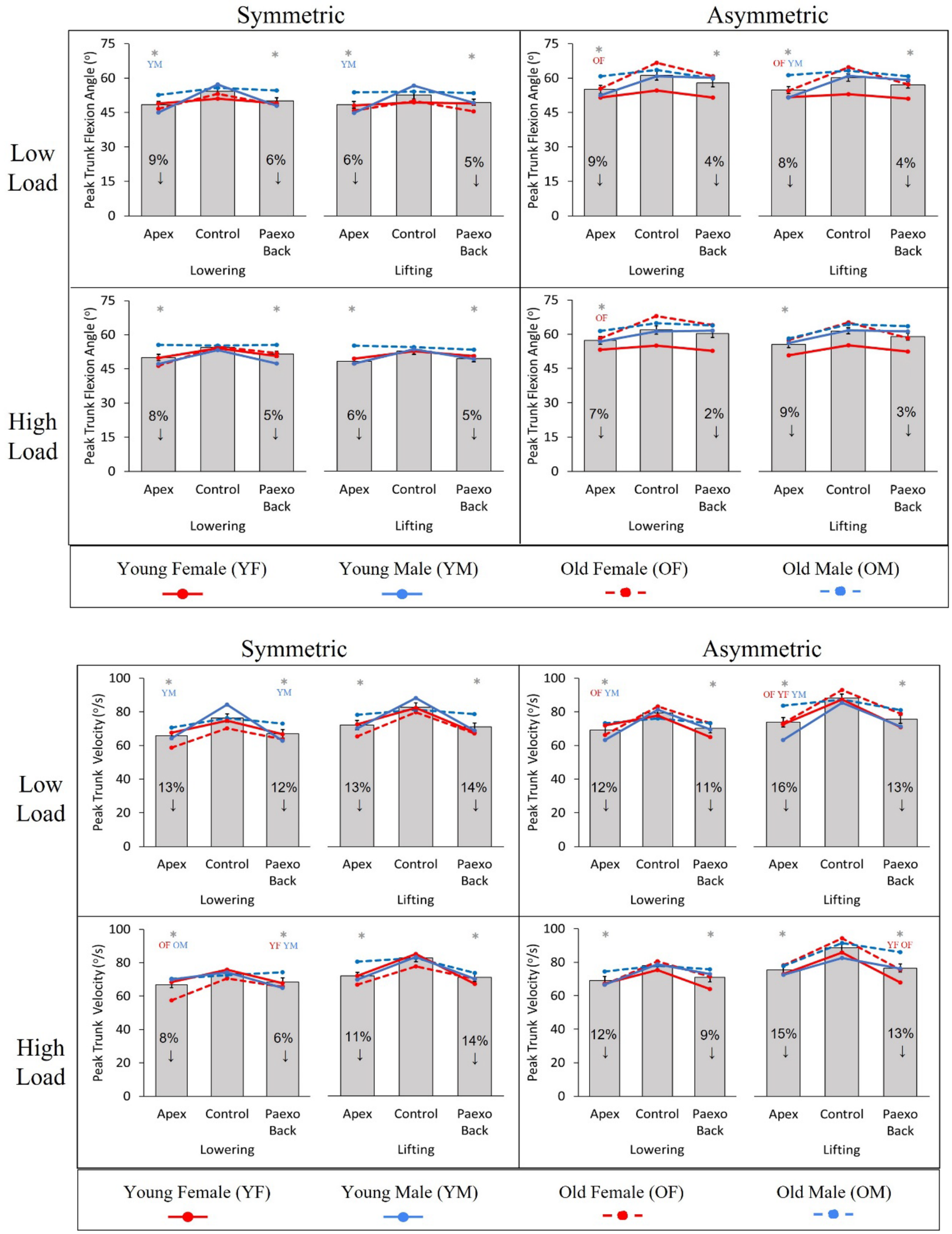

Figure 7. Top panel: peak trunk flexion angle (°) and bottom panel: peak trunk flexion velocity (°/s) for repetitive lifting/lowering with different BSE conditions compared to control (no exoskeleton condition). *Bars* indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control (i.e., main effect of BSE), and coloured text denoting YF/YM/OF/OM indicate significant age and/or gender interaction effects with BSE.

because the asymmetric task was performed contralaterally (i.e., towards the dominant side), thereby potentially affecting the activity of the external obliques and the rectus abdominus muscles on the non-dominant side. During the asymmetric task conditions, peak muscle activity in the control condition

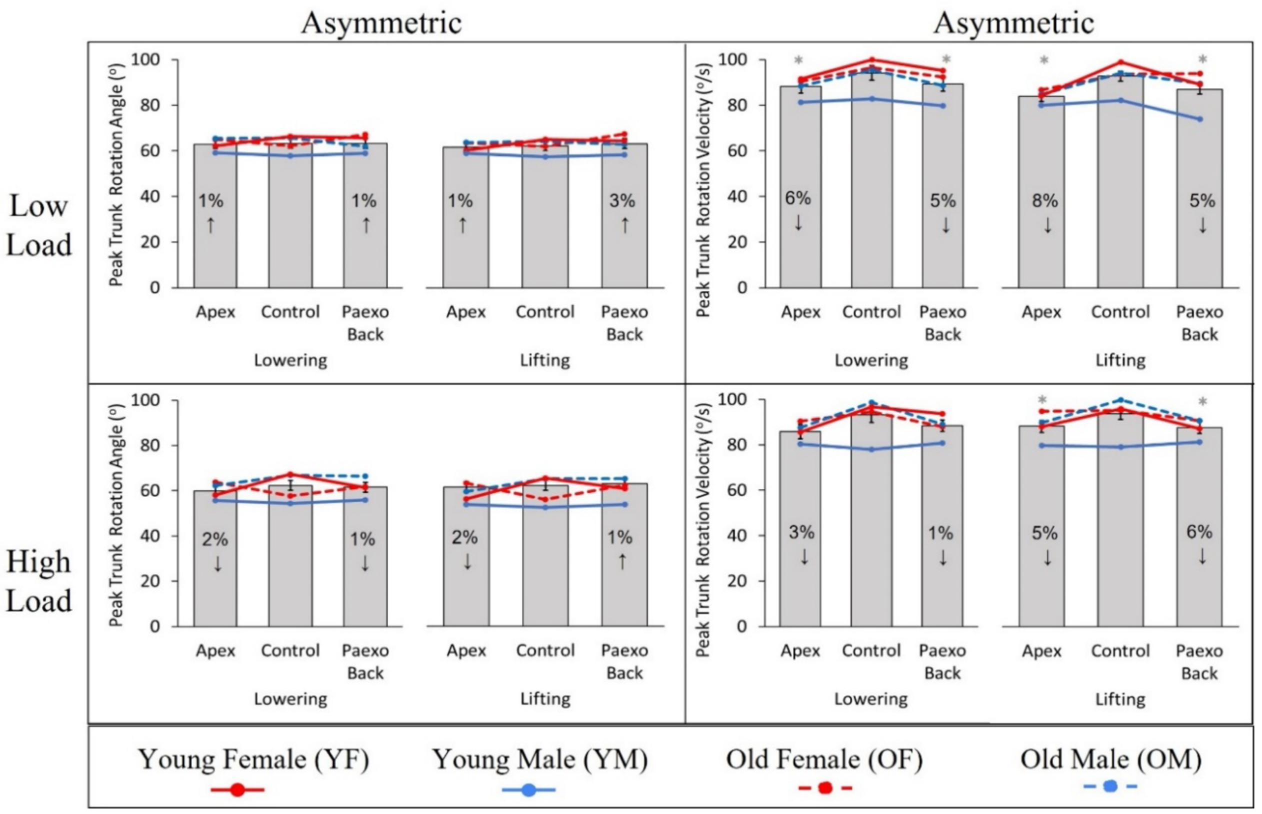

Figure 8. Peak trunk rotation angle (°) and trunk rotation velocity (°/s) for repetitive lifting/lowering with different BSE conditions compared to control (no exoskeleton condition). *Bars* indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control (i.e., main effect of BSE), and coloured text denoting YF/YM/OF/OM indicate significant age and/or gender interaction effects with BSE.

was ~10% MVC, and there was a significant main effect of gender: women showed ~30–40% higher activity than men in TrunkFlex during the asymmetric tasks. Additionally, there was a main effect of BSE on peak TrunkFlex (non-dominant) nEMG for most asymmetric task conditions. Both BSEs predominantly caused an increase in TrunkFlex EMG, and in the range of 5–23%, depending on the task.

3.2.2.2. Peak upper leg muscle activity. Both leg muscles instrumented in the study showed substantial activation in all asks at baseline (control condition), with the peak biceps femoris (BF) muscle activity being ~20–30% MVC, and the peak vastus medialis (VM) muscle activity being 30–50% MVC The main effect of BSE was significant for the BF in most tasks, and on average, both BSEs led to reductions in peak BF muscle activity by ~8–12% across the different task conditions. However, for the vastus medialis (VM), both BSEs caused an increase in peak VM EMG across all tasks, in the range of 2-34%, with most of these changes being statistically significant (Figure 11). There were a few significant interactions of BSE × gender for the leg muscles across the various task conditions.

3.2.3. Rating of perceived exertion and discomfort

Mean Ratings of Perceived Discomfort (RPD) for the low back, shoulder and thigh were not significant for BSE type and values ranged from 0.6 to 0.8. Mean ratings of perceived exertion were not significant for BSE type and values ranged from 8.9 to 10.4.

4. Discussion

The overall goals of this study were to investigate age and gender differences in the perception, use, and effects of passive back-support exoskeletons (BSEs) during repetitive lifting/lowering tasks. Two types of BSEs were tested—a soft and rigid exoskeleton. In summary, both BSEs improved the participants' perceived 'Maximum Acceptable Load' (MAL). Both BSEs were generally perceived as being safe, useful, and easy to use, and were not associated with any negative social perceptions. There were no significant age or gender interactions with either BSE in these subjective measures. Objective measures from the standardised task demonstrated that both BSEs elicited lower trunk flexion, lower trunk flexion velocity and in

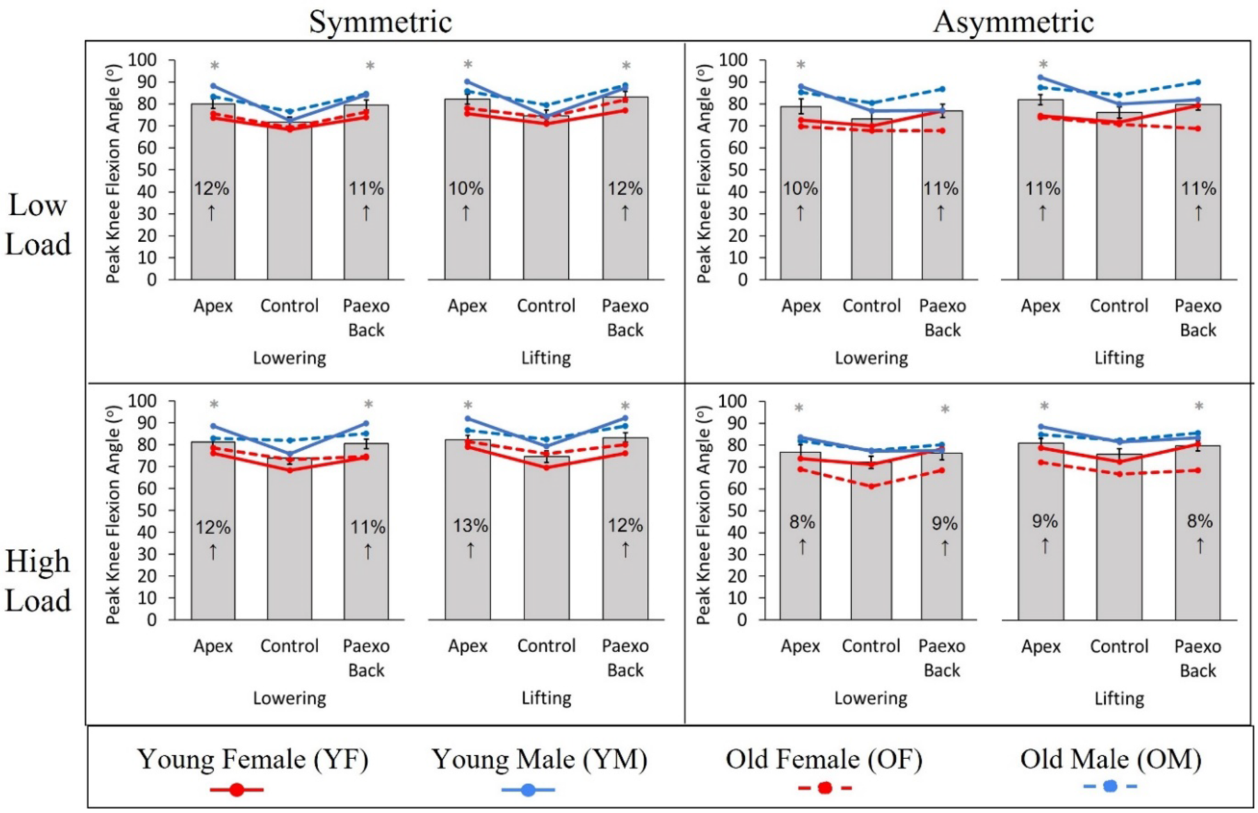

Figure 9. Peak knee flexion angle for repetitive lifting/lowering with different BSE conditions compared to control (no exoskeleton condition). *Bars* indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control (i.e., main effect of BSE).

general, more squatting—thereby increasing peak knee flexion angles compared to the control condition. These kinematic changes were also accompanied by corresponding changes in muscle activity: trunk extensor and hip extensor (hamstrings) muscle activities were reduced, while the vastus medialis (quadriceps) was more active when using the BSEs. Furthermore, there was some evidence of differences in BSE use with age and gender, primarily in the trunk kinematics.

4.1. Maximum acceptable load and usability

When compared with the control (average MAL of 11.9 kg), there was a slight (6–7%) increase in MAL with the Apex and Paexo Back. It was surprising that there were no significant age or gender interactions in MAL, because user preferences of exoskeleton support level were different across the groups. For the Apex exoskeleton, there were three levels of support: Light, Strong, and Extra Strong. In general, the young adults and older males typically chose the 'Strong' setting, while most older females chose the 'Light' setting. For the Paexo Back, since we had fixed the support at 'Early Support Mode' as recommended by the manufacturers for the tasks studied here, there were no differences in the support provided by the Paexo Back across the different user groups.

There is limited prior work on using psychophysics approaches to quantify exoskeleton benefits. The only study, to our knowledge (Alabdulkarim and Nussbaum 2019), evaluated the maximum acceptable frequency (MAF) of work in a simulated overhead drilling task across three different occupational exoskeleton conditions. Their results showed that MAF was significantly influenced by exoskeleton type, with an arm support exoskeleton leading to a higher MAF than other conditions. Although this previous study also reported gender x exoskeleton interactions in MAF, we did not detect any significant age- or gender-interactions in our work.

Since acceptance and adoption of exoskeletons has been a challenge in industrial environments (Crea et al. 2021; Elprama et al. 2020), we aimed to use a psychophysics approach and measure MAL, to understand whether users could perceive tangible benefits associated with exoskeleton use. Such perceived performance benefits were expected to be reflected by the changes in self-rated performance (load), as

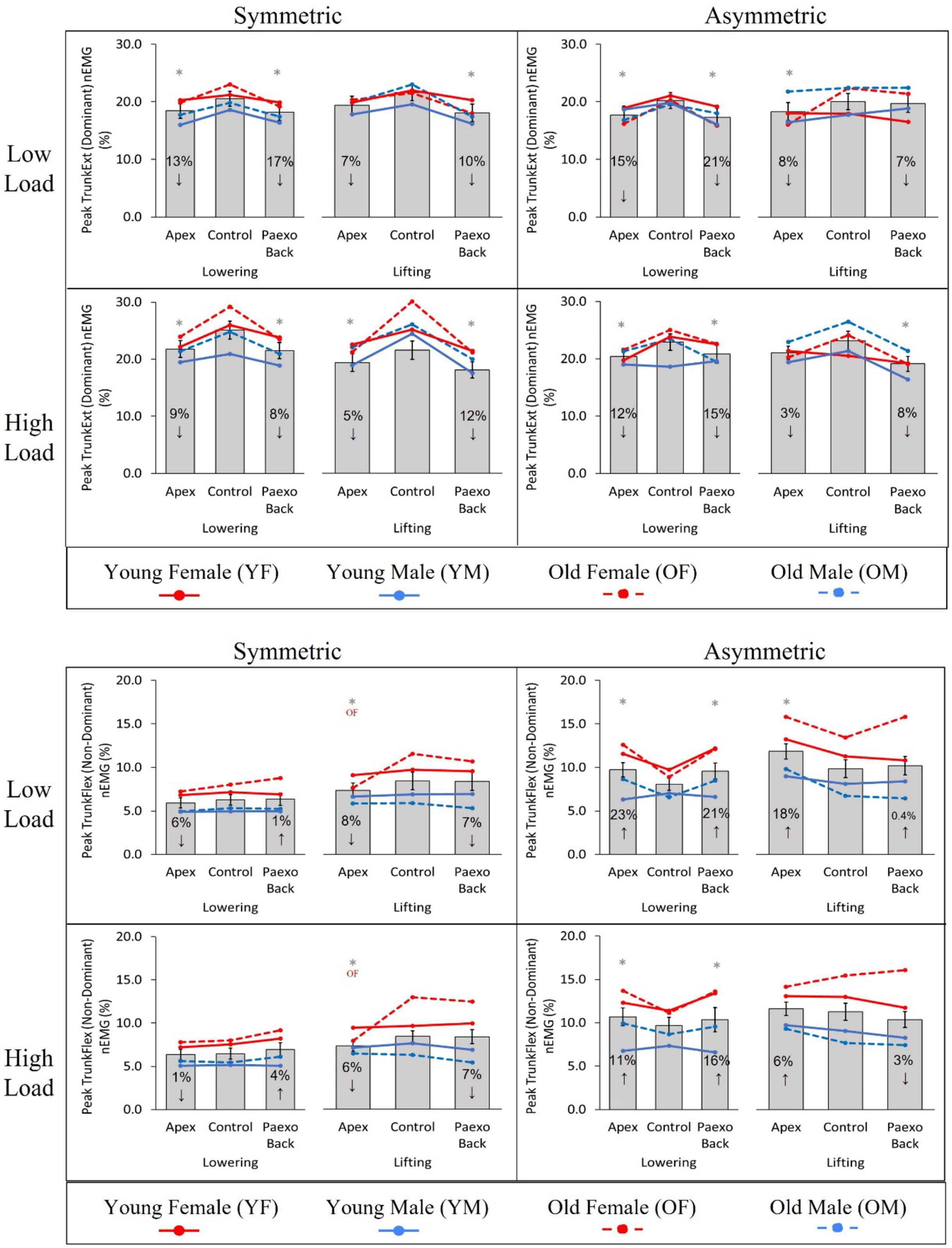

Figure 10. Top panel: peak TrunkExt (dominant) nEMG (%), bottom panel: peak TrunkFlex (non-dominant) nEMG (%) for repetitive lifting/lowering with different BSE conditions compared to control (no exoskeleton condition). *Bars* indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control, and coloured YF/YM/OF/OM indicate age and/or gender effects.

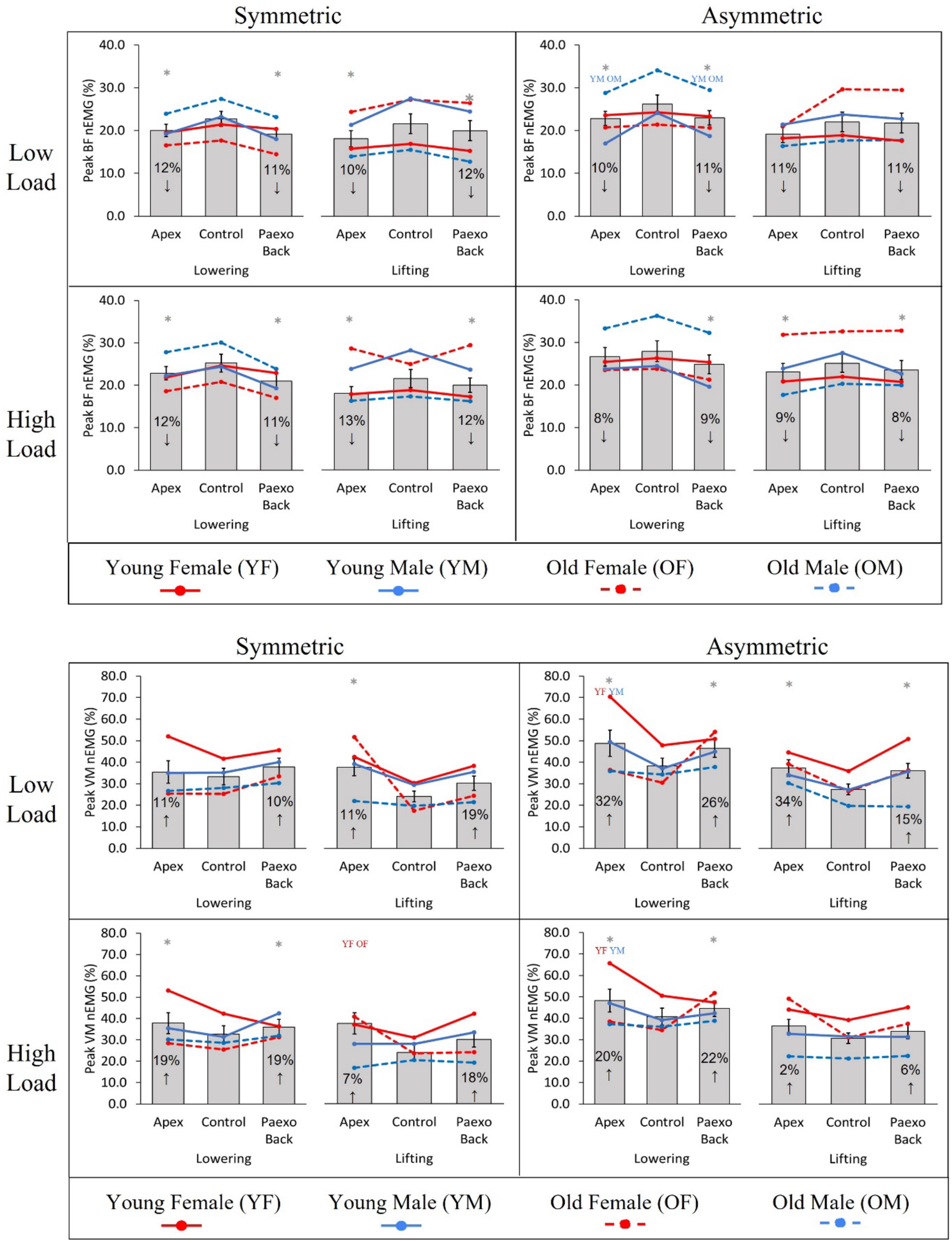

Figure 11. Top panel: peak BF nEMG (%), bottom panel: peak VM nEMG (%) for repetitive lifting/lowering with different BSE conditions compared to control (no exoskeleton condition). Bars indicate overall means and overlayed coloured lines indicate different groups; *Asterisk* denotes statistically significant differences of each BSE condition from the control, and coloured YF/YM/OF/OM indicate age and/or gender effects.

compared to a no-exoskeleton control condition. However, BSE use was associated with only a modest 6–7% increase in perceived MAL. While this increased MAL does suggest positive benefits of BSEs, it is unknown whether this small increase in MAL will be perceived as *sufficient* by users to promote long-term user adoption of exoskeletons in real life. A recent study (Medrano et al. 2022) showed that a metabolic benefit of at least 22.7% was required from an ankle exoskeleton assisting gait, for participants to reliably perceive the difference and hence realise the beneficial effects of the device. Although the exoskeleton device, assisted joint, and tasks of this study were different from ours, Medrano et al. (2022) study was the first to report 'just noticeable difference' of relevant physiological outcomes such as metabolic rate changes when using exoskeletons. Similar studies in the occupational realm may help provide quantitative thresholds (minimum detectable differences) that can be perceived by users, to help guide user adoption of exoskeleton devices.

Based on usability ratings, participants reported that BSEs made them feel safer, without negatively impacting social perception. They also reported moderate to high usefulness of both BSEs, and that both BSEs were easy to use, especially the soft type (Apex). Our results on usability and ease-of-use are quite similar to other studies on BSEs, such as the study by Madinei et al. (2020a), and that of Goršič et al. (2021). Our study did not find any significant age- or gender-interactions in these subjective measures of usability, safety, ease-of-use and social perceptions associated with wearing the device.

4.2. Kinematics

Both BSEs decreased the peak trunk flexion angles across symmetric and asymmetric (low and high loads) conditions by 5–10% from baseline (i.e., by 5°–8°). Prior studies (e.g., Goršič et al. (2021) and Schmalz et al. (2022) have found similar ranges of 5–10% reduction in trunk ROM when using the Apex and Paexo Back BSEs, although these differences were not statistically significant for most tasks. Similar results have also been reported for other BSE types. For example, using the Flx exoskeleton (StrongArm Technologies™) presented a 14.2° reduction in peak trunk flexion (Picchiotti et al. 2019), and the SPEXOR exoskeleton was associated with a 7.3° reduction in peak trunk flexion in a study by Koopman et al. (2020). We also observed a reduction in peak trunk velocity with both the BSEs during symmetric and asymmetric conditions (~10–20% change from baseline). Similar reduction in trunk velocity was also reported by Koopman et al. (2020), where using SPEXOR reduced trunk angular velocity by ~33°/s. BSE × gender × age interactions were present in trunk kinematics in several task conditions, and in general, differences between age- and gender-groups were more pronounced (and statistically significant) for the Apex device than the Paexo back. Young males and old females were more significantly influenced (showed greater reductions in peak trunk flexion angle and velocity) when using the Apex in symmetric and asymmetric tasks, respectively.

Participants seemed to have compensated for the reduced trunk flexion with greater knee flexion (~10%) during lowering/lifting movements in symmetrical and asymmetrical conditions while using the BSEs. Thus, the participants squatted more to achieve the same tasks when wearing both BSEs. Although neither BSE is designed to alter trunk kinematics, similar outcomes were also reported by Luger et al. (2023), where using Laevo V2.56 increased knee flexion angle by ~12° during lifting. It is not clear as to whether participants intentionally used more squat-like postures (which would be a positive benefit of BSE-use) or perceived some restriction/resistance to flexing their trunk and squatted more as a work-around for perceived joint restrictions. Whatever may be the reason, reduction in peak trunk flexion angles during lifting/lowering tasks can reduce the compression forces in the lower back (Koopman et al. 2020; Lamers et al. 2018; Schmalz et al. 2022). However, it is important to understand if secondary joints (e.g., knees) get overloaded as a result, due to such compensatory postural strategies.

4.3. Muscle activity

Both BSEs had a significant main effect in reducing the strain in the back muscles. On average, the Apex reduced trunk extensor muscle activity by 10.7% during lowering and by 5.6% during lifting tasks in the symmetric task condition, and by 13.6 and 5.6% in lowering and lifting tasks in the asymmetric condition, when compared to the control condition. Use of the Paexo Back resulted in 12.6 and 10.8% reduction in trunk extensor muscle activity in lowering and lifting tasks in the symmetric task condition, and 17.9 and 7.7% reduction in lowering and lifting tasks in the asymmetric condition, compared to the control condition. Goršič et al. (2021) evaluated the Apex and documented a general reduction in the erector spinae muscle activity by around 15% during lifting and lowering tasks, with a wide range of 5–30% depending on task type (symmetric/asymmetric), lifting vs. lowering, and load-level. The study by Schmalz et al. (2022) evaluated the Paexo Back in a symmetric repetitive lifting and lowering task, and observed a similar reduction in trunk extensor muscle activity in the range of 12–18%. Hence, the magnitude of reduction in trunk extensor muscle activity from the Paexo back in our study are in accordance with earlier studies.

However, our results on the Apex device showed smaller reductions than those reported in prior work. We believe that this was primarily because of the diversity of the user group included in our study, and our participants' preferences on how to use the Apex device, as compared to Goršič et al. (2021): the authors reported that 75% of their users were young men (mean age of 25 years) and that they were given a choice between 'strong' and 'very strong' support levels, and that 65% of their participants preferred the 'very strong' support level; while in our study, 45% of participants were old adults (equal number of men and women, with mean age of 52 years), all participants were given a chance to choose any of the available support settings, and most adults in the old female group preferred to use the device on the 'Light' support setting. This was despite having the chance to perform a psychophysical protocol using each exoskeleton device, which lasted for ~45–60 min per device, to perform repeated lifting/lowering tasks during session 1. This may indicate that older adults may prefer lower levels of support from back-support exoskeletons: whether this is specific to elastic band-based support or generally transcends other mechanisms of back support remains to be understood.

Participants performed more squatting (as evident from more erect trunk and increased knee flexion) to accomplish the lifting/lowering tasks. This was accompanied by a statistically significant decrease of ~8–12% in the biceps femoris (BF) muscle activity, and a significant increase in the vastus medialis (VM) muscle activity (average of 18%, but ranging up to 34%). Given that the primary function of the BF muscle is to extend the thigh/flex the knee when going from an upright to a squatting position (while lowering loads to the ground), and that the BSEs provide external assistance to support hip extension, it seems reasonable that there was a significant reduction in BF activity when using the exoskeletons. Similar results of decreased BF muscle activity owing to the supportive hip extensor moment applied by BSEs were reported by Bosch et al. (2016) and Schmalz et al. (2022). However, the VM is part of the quadriceps muscle group, and activates to extend the knee from a squatting position to bring the body upright (while lifting loads up from the ground). The reason for the increase in VM activity is not completely clear. One explanation is that the greater extent of squatting performed by our participants when using BSEs necessitated significant knee extension moment to be produced, to bring the body back up from the ground, resulting in increased VM activity. Another explanation is that the VM shares synergistic action with the other parts of the quadriceps muscle group, and some muscles such as the rectus femoris are bi-articular and are also involved in hip flexion. The external torque produced by BSEs typically resists hip flexion, and this may have partially contributed to the increase in VM muscle activity. The impact of these altered muscle activation patterns of loading (or potential overloading) of the knee joint remains to be understood, especially when BSEs are used by middle to old, aged working adults for prolonged durations.

During asymmetric tasks, when twisting the trunk towards the dominant side, there was a substantial main effect of gender on abdominal muscle activity on the contra-lateral (non-dominant) side, with ~30% higher trunk flexor EMG among females as compared to males. Prior studies that have considered gender differences in spinal loading and kinematic compensation strategies have reported higher activity among females in the external obliques and rectus abdominis muscles (e.g., Marras, Davis, and Jorgensen 2002; Granata and Orishimo 2001). These authors have cited several factors to explain the observed gender differences such as (1) women were reported as recruiting additional secondary muscles to support lifting activities due to lower strength in the primary erector spinae muscle groups, (2) women exhibited different patterns of muscle co-activation (that involved greater utilisation of abdominal muscle groups), and (3) women showed a greater reliance on the pelvis. However, using the BSEs increased the muscle activity of abdominal muscles by ~5–20% for both males and females in this study, with no gender × BSE interaction effects. This indicates that all participants had to overcome BSE-generated resistance to perform complex trunk motions, that included trunk flexion and/or rotation. Such results have not been reported in the prior literature about the Apex device until now (to the best of our knowledge), and we are not aware of any studies of asymmetric lifting tasks performed with the Paexo Back. Baltrusch et al. (2019) has, however, reported similar increase in abdominal muscle activity when using the Laevo V2.56.

4.4. Limitations

There were several limitations in the present study, mainly related to restrictions associated with controlled laboratory studies and convenience samples. First, only healthy young and old adults (free of musculoskeletal disorders) that could fit into the two BSEs (as per manufacturer specifications on anthropometry) were included in this study. Also, our participants were not representative of real population of workers with manual material handling experience. Hence, caution is advised when generalising these results to other user-groups. Second, the tasks in the study were only simulations of lifting/lowering tasks in a controlled laboratory environment and the relevance of our findings to actual work settings will need further investigation. For example, in the asymmetric task condition, participants were forced to exhibit complex trunk motion by restricting the movements of their feet, while in actual practice, they may move their feet to reduce trunk loading. Finally, our participants had only short-term exposure to each BSE, and the effects of prolonged/frequent exposure and any resultant adaptations in kinematics/muscle activity patterns cannot be predicted from this study.

5. Conclusion

Manual material handling tasks like repetitive lifting/lowering are ever present in multiple industries and might often be difficult to eliminate or modify. In this context, the state of the art among passive exoskeletons is evolving, and there are now viable rigid and soft exosuit systems that can offer varying levels of support. Overall, both the Apex and Paexo Back exoskeletons were rated as being usable and safe, and both were similarly effective in increasing perceived maximum acceptable workload and reducing activity of the primary trunk extensor muscle groups. Additionally, both BSEs promoted more squatting postures and increased quadriceps muscle activity. BSE use also increased abdominal muscle activity on the contralateral side during asymmetric tasks, compared to the control condition. Although there were several statistically significant BSE x age x gender interactions, and particularly for the trunk kinematics when using the Apex device, the general patterns and trends of most results were similar across all the groups in our study. The older adults preferred less support from the Apex device, and this led to somewhat smaller benefits from the device when compared to earlier reports in the literature. Future work should include diverse user-groups to further explore individual differences in support-level preferences and consequent device benefits, and also investigate how users adapt to exoskeleton use over prolonged periods.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by NSF Grant Nos. #1839946 and #2128926. The sponsors did not influence the data collection, analysis, interpretation of results, or the decision to publish.

References

Alabdulkarim, S., and M. A. Nussbaum. 2019. "Influences of Different Exoskeleton Designs and Tool Mass on Physical Demands and Performance in a Simulated Overhead Drilling Task." *Applied Ergonomics* 74: 55–66. doi:10.1016/j.apergo.2018.08.004.

Alemi, M. M., S. Madinei, S. Kim, D. Srinivasan, and M. A. Nussbaum. 2020. "Effects of Two Passive Back-Support Exoskeletons on Muscle Activity, Energy Expenditure, and Subjective Assessments during Repetitive Lifting." *Human Factors* 62 (3): 458–474. doi:10.1177/0018720819897669.

Baltrusch, S. J., J. H. van Dieën, S. M. Bruijn, A. S. Koopman, C. A. M. van Bennekom, and H. Houdijk. 2019. "The Effect of a Passive Trunk Exoskeleton on Metabolic Costs during Lifting and Walking." *Ergonomics* 62 (7): 903–916. doi:10.1080/00140139.2019.1602288.

Boettcher, C. E., K. A. Ginn, and I. Cathers. 2008. "Standard Maximum Isometric Voluntary Contraction Tests for Normalizing Shoulder Muscle EMG." *Journal of Orthopaedic Research* 26 (12): 1591–1597. doi:10.1002/jor.20675.

Borg, G. A. 1982. "Psychophysical Bases of Perceived Exertion". *Medicine and Science in Sports and Exercise* 14 (5): 377–81. doi:10.1249/00005768-198205000-00012.

Bosch, T., J. van Eck, K. Knitel, and M. de Looze. 2016. "The Effects of a Passive Exoskeleton on Muscle Activity, Discomfort and Endurance Time in Forward Bending Work." *Applied Ergonomics* 54: 212–217. doi:10.1016/j.apergo.2015.12.003.

Chaffin, D. B., and G. B. Page. 1994. "Postural Effects on Biomechanical and Psychophysical Weight-Lifting Limits." *Ergonomics* 37 (4): 663–676. doi:10.1080/00140139408963681.

Ciriello, V. M., S. H. Snook, and G. J. Hughes. 1993. "Further Studies of Psychophysically Determined Maximum Acceptable Weights and Forces." *Human Factors* 35 (1): 175–186. doi:10.1177/001872089303500110.

Crea, S., P. Beckerle, M. De Looze, K. De Pauw, L. Grazi, T. Kermavnar, J. Masood, L. W. O'Sullivan, I. Pacifico, C. Rodriguez-Guerrero, N. Vitiello, D. Ristić-Durrant, and J. Veneman. 2021. "Occupational Exoskeletons: A Roadmap toward Large-Scale Adoption. Methodology and Challenges of Bringing Exoskeletons to Workplaces." *Wearable Technologies* 2: e11. doi:10.1017/wtc.2021.11.

Criswell, E. 2011. *Cram's Introduction to Surface Electromyography*. 2nd ed. Sudbury, MA: Jones and Bartlett Publishers. https://

books.google.com/books?id=RgfX5jXrmzMC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false.

da Costa, B. R., and E. R. Vieira. 2009. "Risk Factors for Work-Related Musculoskeletal Disorders: A Systematic Review of Recent Longitudinal Studies." *American Journal of Industrial Medicine* 53 (3): 285–323. doi:10.1002/ajim.20750.

Dankaerts, W., P. B. O'Sullivan, A. F. Burnett, L. M. Straker, and L. A. Danneels. 2004. "Reliability of EMG Measurements for Trunk Muscles during Maximal and Sub-Maximal Voluntary Isometric Contractions in Healthy Controls and CLBP Patients." *Journal of Electromyography and Kinesiology* 14 (3): 333–342. doi:10.1016/j.jelekin.2003.07.001.

de Looze, M. P., T. Bosch, F. Krause, K. S. Stadler, and L. W. O'Sullivan. 2016. "Exoskeletons for Industrial Application and Their Potential Effects on Physical Work Load." *Ergonomics* 59 (5): 671–681. doi:10.1080/00140139.2015.1081988.

Dubina, K. S., L. Ice, J. L. Kim, and M. J. Rieley. 2021. "Projections Overview and Highlights, 2020–30." *Monthly Labor Review*, 1–38.

Elfeituri, F. E., and S. M. Taboun. 2002. "An Evaluation of the Niosh Lifting Equation: A Psychophysical and Biomechanical Investigation." *International Journal of Occupational Safety and Ergonomics: JOSE* 8 (2): 243–258. doi:10.1080/10803548.2002.11076527.

Elprama, S. A., J. T. A. Vannieuwenhuyze, S. De Bock, B. Vanderborght, K. De Pauw, R. Meeusen, and A. Jacobs. 2020. "Social Processes: What Determines Industrial Workers' Intention to Use Exoskeletons?" *Human Factors* 62 (3): 337–350. doi:10.1177/0018720819889534.

Goršič, M., Y. Song, B. Dai, and D. Novak. 2021. "Evaluation of the HeroWear Apex Back-Assist Exosuit during Multiple Brief Tasks." *Journal of Biomechanics* 126: 110620. doi:10.1016/j.jbiomech.2021.110620.

Goršič, M., Y. Song, B. Dai, and V. D. Novak. 2022. "Short-Term Effects of the Auxivo LiftSuit during Lifting and Static Leaning." *Applied Ergonomics* 102: 103765. doi:10.1016/j.apergo.2022.103765.

Granata, K. P., and K. F. Orishimo. 2001. "Response of Trunk Muscle Coactivation to Changes in Spinal Stability." *Journal of Biomechanics* 34 (9): 1117–1123. doi:10.1016/S0021-9290(01)00081-1.

HeroWear 2021. HeroWear® ApexTM Exosuit User Manual. https://herowearexo.com/wp-content/uploads/HeroWear-Apex-User-Manual-v2.1-EN.pdf

Jackson, J. A., S. E. Mathiassen, J. P. Callaghan, and P. G. Dempsey. 2017. "Precision Based Guidelines for Sub-Maximal Normalisation Task Selection for Trunk Extensor EMG." *Journal of Electromyography and Kinesiology* 37: 41–51. doi:10.1016/j.jelekin.2017.07.001.

Karwowski, W., W. Lee, B. Jamaldin, P. Gaddie, R L. Jang, and K K. Alqesaimi. 1999. "Beyond Psychophysics: The Need for a Cognitive Engineering Approach to Setting Limits in Manual Lifting Tasks." *Ergonomics* 42 (1): 40–60. doi:10.1080/001401399185793.

Kim, S., A. Moore, D. Srinivasan, A. Akanmu, A. Barr, C. Harris-Adamson, D. M. Rempel, and M. A. Nussbaum. 2019. "Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 185–191. doi:10.1080/24725838.2018.1561557.

Koopman, A. S., M. Näf, S. J. Baltrusch, I. Kingma, C. Rodriguez-Guerrero, J. Babič, M. P. de Looze, and J. H. van Dieën. 2020. "Biomechanical Evaluation of a New Passive Back Support Exoskeleton." *Journal of Biomechanics* 105: 109795. doi:10.1016/j.jbiomech.2020.109795.

Kuijt-Evers, L. F. M., T. Bosch, M. A. Huysmans, M. P. de Looze, and P. Vink. 2007. "Association between Objective and Subjective Measurements of Comfort and Discomfort in Hand Tools." *Applied Ergonomics* 38 (5): 643–654. doi:10.1016/J.APERGO.2006.05.004.

Lamers, E. P., J. C. Soltys, K. L. Scherpereel, A. J. Yang, and K. E. Zelik. 2020. "Low-Profile Elastic Exosuit Reduces Back Muscle Fatigue." *Scientific Reports* 10 (1): 15958. doi:10.1038/s41598-020-72531-4.

Lamers, E. P., A. J. Yang, and K. E. Zelik. 2018. "Feasibility of a Biomechanically-Assistive Garment to Reduce Low Back Loading during Leaning and Lifting." *IEEE Transactions on Biomedical Engineering* 65 (8): 1674–1680. doi:10.1109/TBME.2017.2761455.

Llurda-Almuzara, L., N. Labata-Lezaun, C. López-de-Celis, R. Aiguadé-Aiguadé, S. Romaní-Sánchez, J. Rodríguez-Sanz, C. Fernández-de-las-Peñas, and A. Pérez-Bellmunt. 2021. "Biceps Femoris Activation during Hamstring Strength Exercises: A Systematic Review." *International Journal of Environmental Research and Public Health* 18 (16): 8733. doi:10.3390/ijerph18168733.

Luger, T., M. Bär, R. Seibt, M. A. Rieger, and B. Steinhilber. 2023. "Using a Back Exoskeleton during Industrial and Functional Tasks—Effects on Muscle Activity, Posture, Performance, Usability, and Wearer Discomfort in a Laboratory Trial." *Human Factors* 65 (1): 5–21. doi:10.1177/00187208211007267.

Madinei, S., M. M. Alemi, S. Kim, D. Srinivasan, and M. A. Nussbaum. 2020a. "Biomechanical Assessment of Two Back-Support Exoskeletons in Symmetric and Asymmetric Repetitive Lifting with Moderate Postural Demands." *Applied Ergonomics* 88: 103156. doi:10.1016/j.apergo.2020.103156.

Madinei, S., M. M. Alemi, S. Kim, D. Srinivasan, and M. A. Nussbaum. 2020b. "Biomechanical Evaluation of Passive Back-Support Exoskeletons in a Precision Manual Assembly Task: "Expected" Effects on Trunk Muscle Activity, Perceived Exertion, and Task Performance." *Human Factors* 62 (3): 441–457. doi:10.1177/0018720819890966.

Marras, W. S., K. G. Davis, and M. Jorgensen. 2002. "Spine Loading as a Function of Gender." *Spine* 27 (22): 2514–2520. doi:10.1097/00007632-200211150-00017.

Medrano, R. L., G. C. Thomas, and E. J. Rouse. 2022. "Can Humans Perceive the Metabolic Benefit Provided by Augmentative Exoskeletons?" *Journal of NeuroEngineering and Rehabilitation* 19 (1): 26. doi:10.1186/s12984-022-01002-w.

NSC. 2020. *Work Injury Costs*. National Safety Council (NSC). https://injuryfacts.nsc.org/work/costs/work-injury-costs/

Nussbaum, M. A., B. D. Lowe, M. de Looze, C. Harris-Adamson, and M. Smets. 2019. "An Introduction to the Special Issue on Occupational Exoskeletons." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 153–162. doi:10.1080/24725838.2019.1709695.

OECD 2023. *Working Age Population*. Organisation for Economic Co-Operation and Development (OECD). https://data.oecd.org/pop/working-age-population.htm#indicator-chart

Ottobock 2020. *20ES100 = 1 Paexo Back (User Manual)*. https://ottobockexoskeletons.com/

Picchiotti, M. T., E. B. Weston, G. G. Knapik, J. S. Dufour, and W. S. Marras. 2019. "Impact of Two Postural Assist Exoskeletons on Biomechanical Loading of the Lumbar Spine." *Applied Ergonomics* 75: 1–7. doi:10.1016/j.apergo.2018.09.006.

Pote, T. R., N. V. Asbeck, and A. T. Asbeck. 2023. "The Ethics of Mandatory Exoskeleton Use in Commercial and Industrial Settings." *IEEE Transactions on Technology and Society* 4 (4): 302–313. doi:10.1109/TTS.2023.3264807.

Potvin, J. R. 2014. "Comparing the Revised NIOSH Lifting Equation to the Psychophysical, Biomechanical and Physiological Criteria Used in Its Development." *International Journal of Industrial Ergonomics* 44 (2): 246–252. doi:10.1016/j.ergon.2013.07.003.

Schmalz, T., A. Colienne, E. Bywater, L. Fritzsche, C. Gärtner, M. Bellmann, S. Reimer, and M. Ernst. 2022. "A Passive Back-Support Exoskeleton for Manual Materials Handling: Reduction of Low Back Loading and Metabolic Effort during Repetitive Lifting." *IISE Transactions on Occupational Ergonomics and Human Factors* 10 (1): 7–20. doi:10.1080/24725838.2021.2005720.

Schwartz, M., J. Theurel, and K. Desbrosses. 2021. "Effectiveness of Soft versus Rigid Back-Support Exoskeletons during a Lifting Task." *International Journal of Environmental Research and Public Health* 18 (15): 8062. doi:10.3390/ijerph18158062.

Schwerha, D. J., N. McNamara, M. A. Nussbaum, and S. Kim. 2021. "Adoption Potential of Occupational Exoskeletons in Diverse Enterprises Engaged in Manufacturing Tasks." *International Journal of Industrial Ergonomics* 82: 103103. doi:10.1016/j.ergon.2021.103103.

SENIAM. 1999. *European Recommendations for Surface Electromyography: Sensor Locations*.

Snook, S. 1999. "Future Directions of Psychophysical Studies." *Scandinavian Journal of Work, Environment & Health*. 25 (4): 13–18.

Søraa, R. A., and E. Fosch-Villaronga. 2020. "Exoskeletons for All: The Interplay between Exoskeletons, Inclusion, Gender, and Intersectionality." *Paladyn, Journal of Behavioral Robotics* 11 (1): 217–227. doi:10.1515/pjbr-2020-0036.

Theurel, J., and K. Desbrosses. 2019. "Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 264–280. doi:10.1080/24725838.2019.1638331.

U.S. Bureau. 2018. *Back Injuries Prominent in Work-Related Musculoskeletal Disorder Cases in 2016*. U.S. BUREAU OF LABOR STATISTICS. https://www.bls.gov/opub/ted/2018/back-injuries-prominent-in-work-related-musculoskeletal-disorder-cases-in-2016.htm

Upasani, S., R. Franco, K. Niewolny, and D. Srinivasan. 2019. "The Potential for Exoskeletons to Improve Health and Safety in Agriculture—Perspectives from Service Providers." *IISE Transactions on Occupational Ergonomics and Human Factors* 7 (3-4): 222–229. doi:10.1080/24725838.2019.1575930.

Wu, G., S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D. D. D'Lima, L. Cristofolini, H. Witte, O. Schmid, I. Stokes, and Standardization and Terminology Committee of the International Society of Biomechanics 2002. "ISB Recommendation on Definitions of Joint Coordinate System of Various Joints for the Reporting of Human Joint Motion—Part I: Ankle, Hip, and Spine." *Journal of Biomechanics* 35 (4): 543–548. doi:10.1016/S0021-9290(01)00222-6.

Yandell, M. B., A. E. Wolfe, M. C. Marino, M. P. Harris, and K. E. Zelik. 2022. "Effect of a Back-Assist Exosuit on Logistics Worker Perceptions, Acceptance, and Muscle Activity." *Biosystems and Biorobotics* 27: 7–11. doi:10.1007/978-3-030-69547-7_2.