

Full title:

Passive arm-support and back-support exoskeletons have distinct phase-dependent effects on physical demands during cart pushing and pulling: An exploratory study

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ABSTRACT

Arm-support exoskeletons (ASEs) and back-support exoskeletons (BSEs) can be effective in reducing physical demands during various occupational tasks, yet evidence of their effects in pushing and pulling tasks remains limited. We examined the effects of using a passive ASE and a BSE on task completion time, trunk and shoulder kinematics, and muscle activity in the back and shoulder while pushing and pulling a moderately–loaded (100 kg) cart. Forty volunteers (24 M and 16 F) completed the study. Using the BSE substantially reduced thoracic and lumbar erector spinae muscle activity for males, especially during the initial and ending phases of pushing (by up to ~31.4%) and pulling (by up to ~25.4%) compared to the *No Device* (ND) condition. In contrast, using the ASE showed no significant benefits, with females experiencing an increase in anterior deltoid muscle activity (by up to ~46.3%) compared to ND. Findings from this study help to understand the effects of BSEs and ASEs in pushing and pulling tasks and support the development of more versatile exoskeletons.

Keywords: Kinematics; Muscle activity; Biomechanics; Versatility

1. Introduction

Occupational exoskeletons (EXOs), wearable devices designed to assist/support specific body joints, are an emerging alternative intervention to prevent or reduce the risk of work-related musculoskeletal disorders (WMSDs). Existing evidence suggests that EXO use can lower physical demands and potentially reduce WMSD risk (e.g., De Bock et al., 2022; Kermavnar et al., 2021; van Sluijs et al., 2023), although the extent of such benefits varies depending on the specific task demands and EXO designs (e.g., Schwartz et al., 2021; Park et al., 2022; Luger et al., 2023; Reimeir et al., 2023). Consequently, much research has emphasized the importance of matching EXOs to specific tasks for effective workplace implementation.

Most commercially-available EXOs are designed for the shoulders or the lower back, likely due to the high prevalence of WMSDs in these areas. In line with this, existing research has focused on examining EXO effects for shoulder- or back-intensive jobs, such as those involving lifting or overhead tasks. However, real-world jobs often require workers to transition between different tasks, some of which may not be strictly shoulder- or back-intensive. Passive EXOs are designed to generate assistance via elastic elements that produce torques based on joint angles—storing energy during one phase of movement and releasing it during another. Yet it is unclear how much of this elastic assistance is engaged in working situations with more diverse task demands, which involve complex, multi-joint dynamics that may not align with the optimal activation range of these devices. For example, a worker wearing an arm-support EXO (ASE) for overhead work may also need to push/pull a cart or operate a tool at waist level—tasks that require arm exertion but are not predominantly or exclusively shoulder-intensive. Similarly, a worker wearing a back-support EXO (BSE) for lifting may also engage in load carriage or pushing/pulling a cart. While these additional tasks still engage the body region supported by an EXO (e.g., the shoulders or back), these tasks do not align directly with the EXO's primary intended use cases. Such tasks, referred to as *secondary* tasks hereafter, involve movements for which EXO assistance may not be fully optimized. Although EXOs seem likely to have some influence on physical demands in secondary tasks, these influences remain largely unknown. A better understanding of how EXOs function beyond their *primary* applications could improve task-specific selection strategies.

Empirical evidence on EXO use in secondary tasks is rather sparse. Theurel et al. (2018) examined ASE use during typical back-intensive tasks such as lifting, lowering, and load carriage. While ASE use reduced anterior deltoid activity compared to a baseline (i.e., no ASE), it also increased shoulder antagonist muscle activity, postural strains, and cardiovascular demands. Additionally, erector spinae activity increased during load carriage, although this effect was not statistically significant. Similarly, Reimeir et al. (2023) demonstrated that BSE effectiveness varied between tasks, with some designs reducing muscle activity in lifting and lowering but also increasing trunk inclination during carrying. Poliero et al. (2020) explored whether an active BSE designed for symmetric lifting could also be beneficial for carrying tasks. They found that though the EXO provided some assistance, it lacked versatility, particularly in adapting to leg movements, limiting its effectiveness beyond primary applications. Field studies corroborate these concerns. Hensel and Keil, (2019) reported that in automotive assembly, BSE use was distracting during workers performing tasks not targeted specifically by the device. Similarly, Spada et al. (2019) indicated that ASEs had limited effectiveness in supporting all required arm movements for certain automotive assembly tasks.

Although pushing and pulling are not typically the primary focus of EXO design, these are common tasks in manual material handling environments such as warehousing and distribution centers (Argubi-Wollesen et al., 2017; Garg et al., 2014), wherein they contribute to an increased risk of back and shoulder WMSDs (Hoozemans et al., 2002; Nimbarte et al., 2013). Passive ASEs and BSEs may potentially help reduce muscle activity by providing supportive torques around the shoulders or the back, along with structural support for postural maintenance. However, the effectiveness of these EXOs during pushing and pulling remains uncertain, particularly since these tasks involve working postures and force applications quite distinct from overhead work and lifting. Recently, Bennett et al. (2022) investigated the effects of using a soft BSE (or exosuit) during cart pushing (n=4) in a construction setting but found no significant change on pelvis kinematics (i.e., sagittal pelvic tilt). However, their study did not consider the impact of exosuit use on physical exertion, leaving the overall effect of exosuit use on pushing tasks unclear. Tröster et al. (2020) explored an active ASE for patient transfer tasks involving pushing, pulling, and lifting. Their musculoskeletal modeling approach suggested that while passive ASEs may be less effective for pushing and pulling, active ASEs could be more beneficial, though empirical validation remains lacking. Considering that pushing and pulling can accompany primary tasks such as lifting and overhead work, while imposing distinct work demands (De Looze et al., 2000; Garg et al., 2014; Lee et al., 1991; Schibye et al., 2001), there is a current need to assess how different EXO designs affect physical demands during such secondary tasks to support effective workplace implementation.

We thus assessed the effects of two different passive EXOs (an ASE and a BSE) during cart pushing and pulling tasks. Given the lack of prior research, our study was exploratory in nature, limiting our ability to formulate explicit hypotheses. However, we expected that using an ASE or BSE would reduce physical demand compared to no EXO use. Given that pushing and pulling tasks typically involve three motion phases: initial, sustained, and ending (e.g., Snook and Ciriello, 1991; Bennett et al., 2008; Hoozemans et al., 2004; Lee et al., 2011), we further expected that the effects of ASE and BSE use would differ between these phases. Additionally, since females generally have lower maximum acceptable pushing and pulling forces than males (Garg et al., 2014; Van Der Beek et al., 2000), we considered potential biological sex differences in ASE and BSE effectiveness. Findings from our study could provide a better understanding of the potential benefits and limitations of using EXOs for the secondary tasks of pushing and pulling, to inform evidence-based workplace implementation strategies.

2. Methods

2.1. Participants

A convenience sample of 40 (24 M and 16 F) participants was recruited from the university and local community. Each participant was assigned randomly to either an ASE or a BSE group; summary statistics for demographic and anthropometric information are provided in Table 1. Before collecting any data, informed consent was obtained from all participants following procedures approved by the Virginia Tech Institutional Review Board (IRB). All participants self-reported having no musculoskeletal injuries or disorders currently or in the last 12 months.

Table 1. Summary [means (SD)] of participant demographic and anthropometric information. Note that two-sided, independent samples *t*-tests revealed no significant differences between groups ($p > 0.170$).

Group	Sex	Age (yrs.)	Stature (m)	Shoulder Height (m)	Hip Height (m)	Body Mass (kg)	BMI (kg/m^2)
ASE	M (n = 13)	22.6 (6.7)	1.81 (0.09)	1.55 (0.08)	0.92 (0.06)	80.4 (13.9)	24.6 (3.0)
	F (n = 7)	22.5 (3.2)	1.69 (0.05)	1.46 (0.06)	0.87 (0.04)	70.0 (7.8)	24.6 (3.1)
BSE	M (n = 11)	22.4 (3.4)	1.81 (0.04)	1.57 (0.04)	0.94 (0.04)	87.1 (20.5)	26.5 (5.5)
	F (n = 9)	23.8 (2.8)	1.66 (0.06)	1.43 (0.06)	0.85 (0.05)	72.1 (7.2)	26.3 (2.0)

2.2. Exoskeletons

Commercially available passive EXOs were used since these remain predominant in field applications. The specific ASE and BSE were the Ekso Bionics EVO™ (www.eksobionics.com) and SuitX™ backX™ Model S (www.suitx.com), respectively. The EVO™ supports the shoulders through a linkage structure with gas springs acting at both shoulders, and which is attached via a hip belt, upper arm straps, and arm cuffs. The backX™ assists the lower back during forward bending, with gas springs at the hip joints generating supportive extension torque. It is worn using a waist belt and thigh pads connected to the chest via rigid structures. At the time of the study, we selected the EVO™ because it had been reported to reduce physical demands during overhead tasks (Jorgensen et al., 2022), while backX™ had been shown to reduce physical demands during lifting (Alemi et al., 2020; Schwartz et al., 2021) and static tasks requiring trunk bending (Madinei et al., 2020).

2.3. Experimental tasks, design, and procedures

Participants were asked to perform trials that consisted of both pushing and pulling a cart. Each trial involved pushing the cart 5 meters in one direction, then pulling it back to the starting point. They were asked to perform these pushing and pulling tasks at a "purposeful" working speed, imagining they are actual workers in a workplace, while keeping the cart moving as straight as possible. Before each trial, the cart was positioned with the casters aligned parallel to the direction of movement to ensure consistent starting conditions. However, we did not constrain whether they remained in a leading or trailing orientation throughout the trial. Cart dimensions were 0.52 m in width, 1.0 m in length, and had a total height of 0.86 m, consisting of a base height of 0.67 m and a fixed handle height of 0.19 m above the base. The cart was loaded with 100 kg of mass (Figure 1). The cart handle was fixed at a height of 0.19 m. The cart load was selected to align with prior studies on hand forces and workloads during pushing and pulling tasks in manual handling and aviation contexts, which used loads ranging from 30 kg to 181 kg (Al-Eisawi et al., 1999; Botti et al., 2020; Boyer et al., 2013; Glitsch et al., 2007). While the 100 kg load may not represent high-risk tasks, it was chosen to reflect the demands of pushing/pulling tasks likely common in various work environments. Note that the cart dimensions and handle height were intended to represent a common, non-adjustable industrial cart. While the handle height of 0.86 m is lower than some recommended ranges for optimal force reduction (e.g., Garg et al., 2014; Snook and Ciriello, 1991), it is consistent with prior studies that investigated pushing and pulling tasks in realistic work settings (Al-Eisawi et al., 1999; Lee et al., 1991).

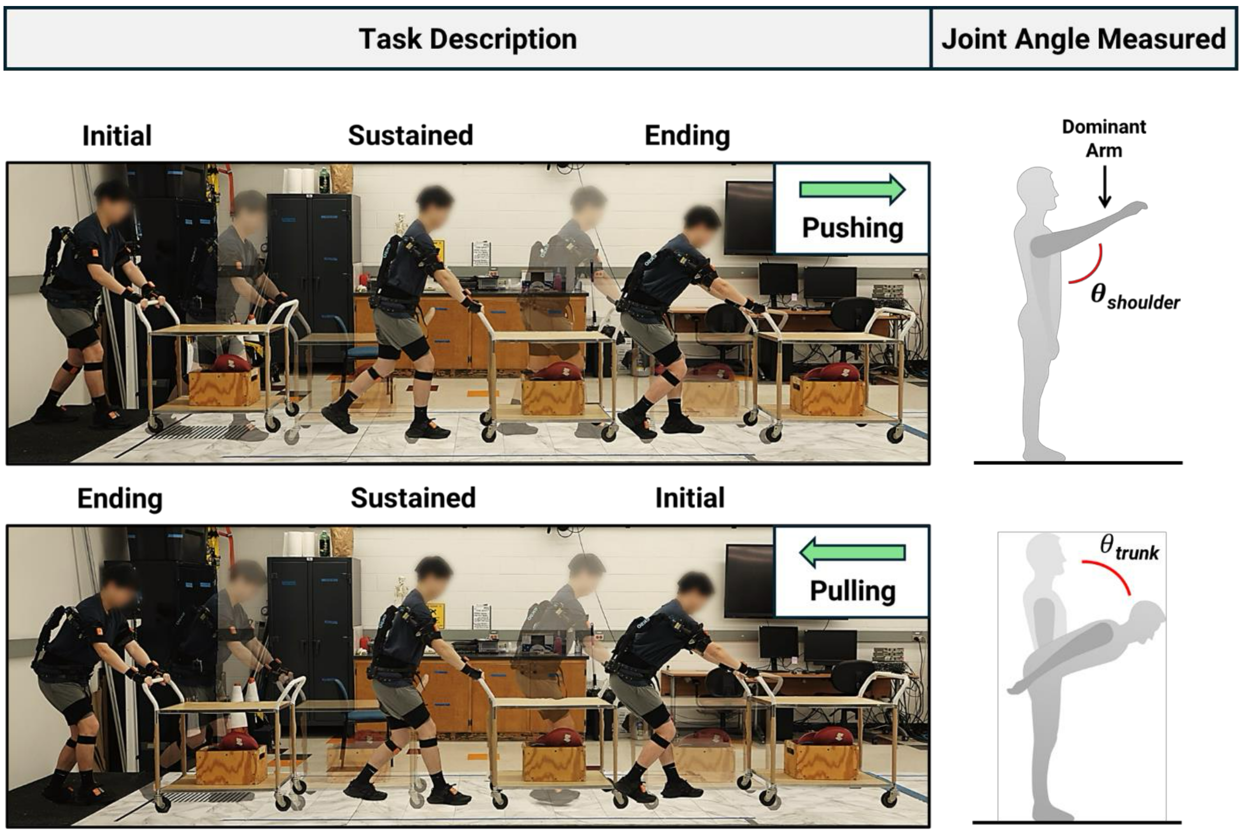

Figure 1. Task Description: Illustration of a participant performing cart pushing (top) and pulling (bottom) along a 5 m track at a "purposeful" working speed. **Joint Angles Measured**: Depiction of trunk flexion (top) and shoulder flexion (bottom) monitored during the tasks.

Participants completed one familiarization session followed by two experimental sessions in a laboratory environment, with each session conducted on separate visits and separated by at least one day. During the familiarization session, participants were fitted with their assigned EXO according to the manufacturer's recommendations and practiced the tasks while exploring the

EXO assistance settings to find their preferred level of support, which remained constant throughout data collection (see Appendix for the selected settings). In each experimental session, participants completed a set of tasks, including cart pushing and pulling. Note that the work reported here was part of a larger project, in which participants completed several different tasks using a single EXO type. Accordingly, to minimize potential learning and adaptation effects from switching between two different EXO types, a between-subjects design was chosen. This approach ensured that differences observed could be more confidently attributed to EXOs rather than individual variability. Each experimental session included 10 trials of pushing and pulling tasks while wearing the EXO, with a minimum of 1-minute rest between trials. The first experimental session was treated as additional training to allow for further adaptation to the EXO. For data analysis, we only used the 10 trials from the second experimental session, assuming participants had sufficiently adapted to the EXO by that time. An additional trial without the EXO was performed only in the second session to serve as a *No Device* (ND) or control condition. This approach was taken to ensure that any differences observed between the EXO and ND conditions could be attributed to the EXO itself, rather than to improvements in task performance due to practice.

2.4. Data Collection

Muscle activity was monitored using a telemetered surface electromyography (EMG) system (Ultium^{TM} Noraxon, AZ, USA). After appropriate skin preparation (shaving and cleaning with alcohol), pairs of pre-gelled, bipolar, Ag/AgCl electrodes were placed with a 2.5 cm inter-electrode spacing over five muscle groups following earlier recommendations (Criswell, 2010). Specific muscle groups monitored were the anterior deltoid (AD) on the dominant shoulder and bilaterally over two low back extensors – thoracic erector spinae (TES) and lumbar erector spinae (LES). These muscle groups were selected since they coincide with body regions targeted by the EXO support (shoulder and back), and they were accessible while wearing the EXOs used in our study. Additionally, these muscles are commonly used to assess physical demands during push/pull cart tasks like in laboratory settings (Lin et al., 2010), nursing environments (Kao et al., 2015), and manual material handling scenarios (Chen et al., 2015).

Maximum voluntary isometric contractions (MVICs) were performed for each muscle group, based on the procedures from earlier studies for back muscles (da Silva et al., 2009) and the AD (Boettcher et al., 2008). Each MVIC trial was repeated three times with non-threatening verbal encouragement, and at least 30 seconds of rest were provided between trials. Following MVICs, participants were given a minimum of five minutes of rest before proceeding with the experimental tasks. Raw EMG signals were sampled at 1.5 kHz during both MVIC and task trials, and then processed using band-pass filtering (20-450 Hz, 4^{th}-order Butterworth, bidirectional), rectification, and low-pass filtering (3 Hz, 4^{th}-order Butterworth, bidirectional) to create linear envelopes. EMG signals were normalized (NEMG) using peak values obtained from corresponding MVIC trials.

Whole-body kinematics were recorded at 60 Hz using a wearable inertial motion capture system (MVN Awinda, Xsens Technologies B.V., Netherlands). Triaxial orientation data for the thorax (using T8 vertebra as a proxy) and the upper arm on the dominant side were obtained from the Xsens MVN software system. Task completion time (CT) was measured using a stopwatch, starting when the cart was initially moved and stopping when it returned to the starting point.

2.5. Data Processing and Outcome Measures

Data from only the second experimental session were analyzed to minimize potential effects of learning or initial unfamiliarity with the EXO and tasks. Each trial was first segmented into distinct pushing and pulling tasks, using hand segment velocity in the sagittal plane to detect the transition time from pushing to pulling (see Figure 2). The segmented tasks were further segmented into three motion phases: initial, sustained, and ending phases, based on the descriptions provided by previous studies (e.g., Snook and Ciriello, 1991; Bennett et al., 2008; Hoozemans et al., 2004; Lee et al., 2011). These studies have generally used hand forces or cart kinematics to identify these phases. Following the approach by Hoozemans et al. (2004), we used hand horizontal velocity data to define the motion phases (Figure 2).

Specific outcome measures were obtained for each phase of pushing and pulling. Kinematic outcomes included mean flexion (MF) of the trunk and shoulder in the sagittal plane. Trunk flexion angle was measured globally as the angle between the thorax and the gravitational axis. Shoulder flexion was computed as the relative rotation between the upper arm and thorax segments using Cardan angles with a rotation sequence of flexion-extension, abduction-adduction, and internal-external rotation (Figure 1). Muscle activity was quantified using median (50^{th}) and peak (95^{th}) NEMG values for the AD, TES, and LES. Since the experimental task was predominantly sagittal and symmetric, mean values were obtained for muscle groups monitored bilaterally as follows: $\mathrm{TES} = \left(\frac{\mathrm{TES_L}+\mathrm{TES_R}}{2}\right)$ and $\mathrm{LES} = \left(\frac{\mathrm{LES_L}+\mathrm{LES_R}}{2}\right)$. A single outcome measure was obtained for CT, from the original (unsegmented) trial of combined pushing and pulling tasks. For each trial, difference scores for joint kinematics, and peak and median muscle activity served as the dependent variables, while original values were used for CT. A *difference score* (ΔX) for each outcome measure was defined as $\Delta X_i = X_i - X_{ND}$, where X_i is the measurement in trial *i* using the EXO, and X_{ND} is the corresponding measurement obtained without the EXO. This approach was chosen to account for individual variability in baseline measurements, given that there was only one control trial without EXO use and multiple trials with EXO use. By using the difference score, we aimed to effectively isolate the effect of EXO use on each outcome measure.

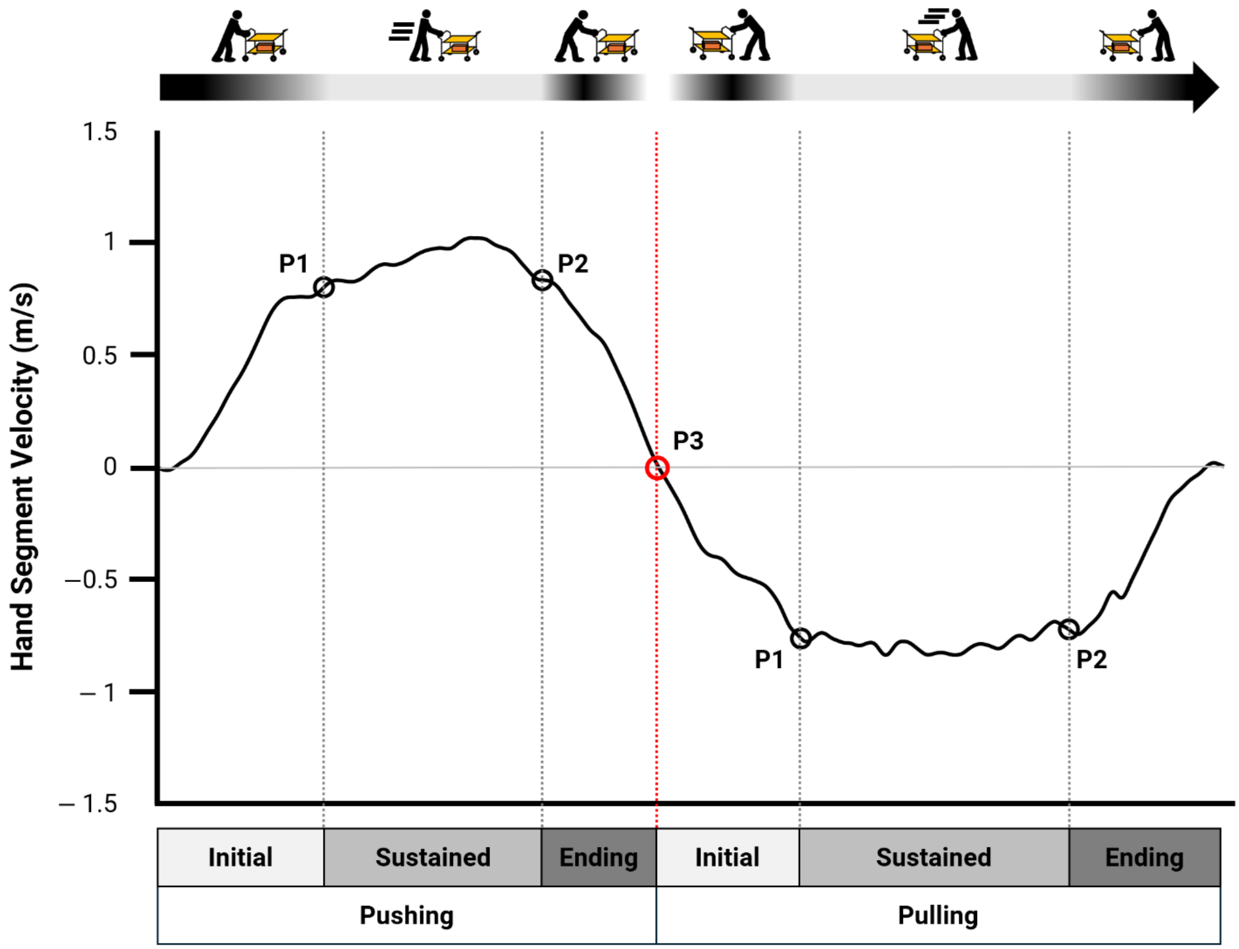

Figure 2. Sample segment velocity profile (m/s) in the sagittal plane, recorded by an IMU sensor placed on the dorsal side of the dominant hand during a single trial of pushing and pulling tasks. The transition from pushing to pulling was identified at the zero-crossing point (P3) denoted with red dotted line, where segment velocity changes from positive to negative. Each task was segmented into three phases based on the dominant hand's velocity relative to its maximum velocity. The initial phase was defined from the start of the movement until hand velocity reaches 80% of its maximum value (P1); sustained phase was defined from P1 until hand velocity drops below 80% of its maximum value (P2); and ending phase was defined from P2 to the end of the pushing or pulling movement.

2.6. Statistical Analyses

We conducted our analyses in two steps. First, a mixed-factor analysis of variance (ANOVA) was used to assess the effects of EXO type (*Type*, a between-subjects factor) on CT; CT was measured after completing both pushing and pulling trials, so motion phase was not included. Second, ANOVAs were also used to examine the effects of *Type* and motion phase (*Phase*, a within-subjects factor) on ΔMF and ΔNEMG. Separate models were used for each outcome measure and for pushing and pulling. Biological sex (*Sex*) was included as a blocking variable. Simple effects testing was performed to examine significant interaction effects involving *Type*, *Phase*, and *Sex*. Planned comparisons were also completed, using *t*-tests within each *Sex* to compare the effects of ASE versus BSE within individual motion phases. We further determined if EXO effects were significant, using one sample *t*-tests to assess if mean difference scores were ≠ 0. All statistical analyses were performed in R software (R Core Team, 2024): ANOVAs were performed using the *lme4* package (v1.1-35.2; Bates et al., 2015), and planned comparisons were conducted using the *emmeans* package (v1.10.1; Lenth, 2024). Parametric model assumptions were supported for all ANOVAs. Statistical significance was concluded when $p < 0.05$. Note that p values were not adjusted for multiple pairwise tests, since specific, planned comparisons were made. Effect sizes are reported using partial eta squared (η_p^2).

3. Results

A summary of ANOVA results and those from *post hoc* testing is provided in the Appendix (Tables A1 to A8). Recall that difference scores (Δ) were used to determine the effects of ASE and BSE use during the pushing and pulling tasks. Detailed results are provided subsequently for task completion time, joint kinematics, and muscle activity.

3.1. Task Completion Time (CT)

CT was significantly affected by which EXO was used by the participants (*Type*). Using either an ASE or BSE significantly increased pushing and pulling CT, compared to the ND condition, though this increase was relatively small (roughly 1 second, or ~5.4% of mean CT).

3.2. Joint Kinematics

Shoulder and trunk ΔMF during the pushing task was significantly influenced by the *Phase* main effect, the *Type* × *Phase* interaction, and the *Phase* × *Sex* interaction effects (Figure 3 and Table A1 in the Appendix). Wearing an ASE resulted in significant increases in shoulder MF for both males and females during the initial phase, with males experiencing increases of up to 13.6° (44.4%) and females up to 10.3° (34.8%) compared to the ND condition (Figure 3). Across phases, males exhibited similar shoulder MF between ASE and BSE, with differences of less than 2.1°. In contrast, females exhibited greater increases in shoulder MF with ASE compared to BSE use during the initial and sustained phases by up to 7.5°. Neither EXO type significantly altered trunk MF compared to the ND condition for males and females (Tables A5 and A6 in the Appendix), with a mean change of approximately 1.9° (7.1%) across phases (Tables A9 and A10 in the Appendix for ND values). Furthermore, effects of using ASE and BSE did not significantly differ on trunk MF for both males and females (Table A3 in the Appendix).

There were no significant main and interaction effects of *Type*, *Phase*, and *Sex* for shoulder ΔMF for both males and females. For males, using BSE led to significant increases in shoulder MF for males across motion phases (Table A8), with increases of up to 6.4° (17.2%), compared to ND condition. In contrast, using the ASE consistently increased shoulder MF for females during the initial and ending phases by 7.4° (16.8%) and 8.7° (39.7%), respectively.

Trunk ΔMF during the pulling task was significantly influenced by the *Phase* main effect, the *Type* × *Phase* interaction, and the *Phase* × *Sex* interaction effects (Figure 3 and Table A2 in the Appendix). Trunk MF was generally higher with EXO use for both males and females compared to the ND condition. Among males, trunk MF was significantly greater during the initial phase when using the BSE, with an increase of 7.2° (54.3%). This effect persisted during the sustained phase with the BSE, where trunk MF increased by 6.2° (44.0%). While trunk MF was also generally higher for females with BSE, increasing by up to 4.8° (33.5%) across phases, no statistical significance was found.

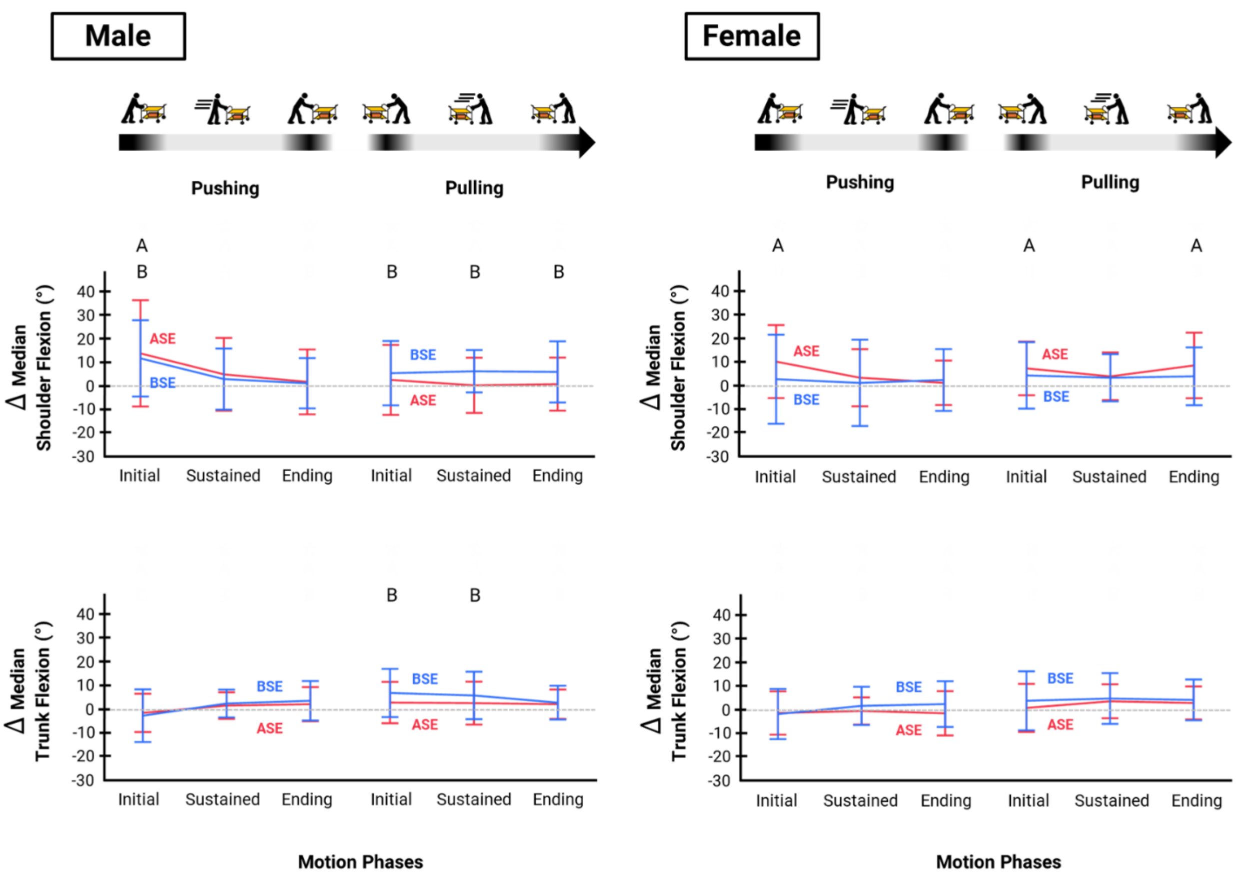

Figure 3. Median shoulder (Top) and trunk flexion (Bottom) in the sagittal plane. Solid lines represent the mean values of difference scores [(Δ; EXO – ND (No Device)] for the ASE (red) and BSE (blue) groups. Dashed grey lines represent the baseline (no change from the ND condition). Error bars represent standard deviations. The symbol * denotes a significant paired difference between the ASE and BSE groups within a specific motion phase. Letters ‘A’ and ‘B’ indicate significant paired differences of the ASE and BSE from the ND condition, respectively.

3.3. Muscle activity

At the shoulder, the *Type* × *Phase* × *Sex* interaction significantly affected median and peak AD difference scores (ΔAD) during pushing, and peak ΔAD during pulling. Generally, no significant reductions were found in AD muscle activity with the ASE (vs. ND condition) for either males or females (Figures 4 and 5). For females, using the ASE during the initial phase of pushing significantly increased median AD activity by 5.6% of max NEMG (a 41.2% relative increase) and peak AD activity by 11.7% of max NEMG (46.3%) compared to ND. Males, on the other hand showed minimal effects when using the ASE, with changes in AD muscle activity remained less than 1.0% of max NEMG across phases of pushing and pulling compared to the ND condition. Using the BSE generally did not significantly affect AD muscle activity for either males or females during pushing or pulling, except in two cases: females exhibited a significant reduction in median AD activity (3.8% of max NEMG, or a 41.4% decrease vs. ND) during the sustained phase of pushing, and males showed a significant reduction in peak AD activity (3.2% of max NEMG, or a 33.3% decrease vs. ND) during the ending phase of pulling.

At the back, significant *Type* × *Phase* × *Sex* interactions were found for both median and peak ΔLES during pushing and for peak ΔLES as well as median and peak ΔTES during pulling tasks (Figures 3 and 4; Tables A1 and A2 in the Appendix). During the initial and ending phases, the effects of ASE and BSE use on TES and LES differed by sex, with significant device-specific differences (ΔTES and ΔLES) ranging from 2.8 to 5.8% of max NEMG among males, whereas no significant differences were observed among females. Overall, back muscle activity (TES and LES) decreased among males when using the BSE. These reductions reached up to 5.1% of max NEMG (24.7% reduction vs. ND condition) during pushing and 5.9% of max NEMG (29.4% reduction vs. ND) during pulling. Specifically, significant reductions in median and peak LES occurred during the initial and ending phases of pushing and initial phase of pulling (Figures 4 and 5). In pushing, median TES decreased during the initial phase and peak TES during the ending phase, while in pulling, both median and peak TES were significantly reduced during the ending phase. Using the ASE provided some benefits among males during pushing, with median and peak LES reducing by up to 2.7% of max NEMG (18.2%) across phases. However, using ASE did not offer clear benefits during pulling in terms of reducing back muscle activity.

In contrast, females exhibited comparable or increased back muscle activity when using both EXOs compared to ND (Tables A5 to A8 in the Appendix). Using the BSE did not result in any significant reductions in back muscle activity among females throughout pushing and pulling tasks. Moreover, ASE use generally led to increased back muscle activity in females. Specifically, during the ending phase, peak TES activity increased significantly by 5.9% of max NEMG (27.9%) in pushing and by 4.5% of max NEMG (26.0%) in pulling (Figure 5).

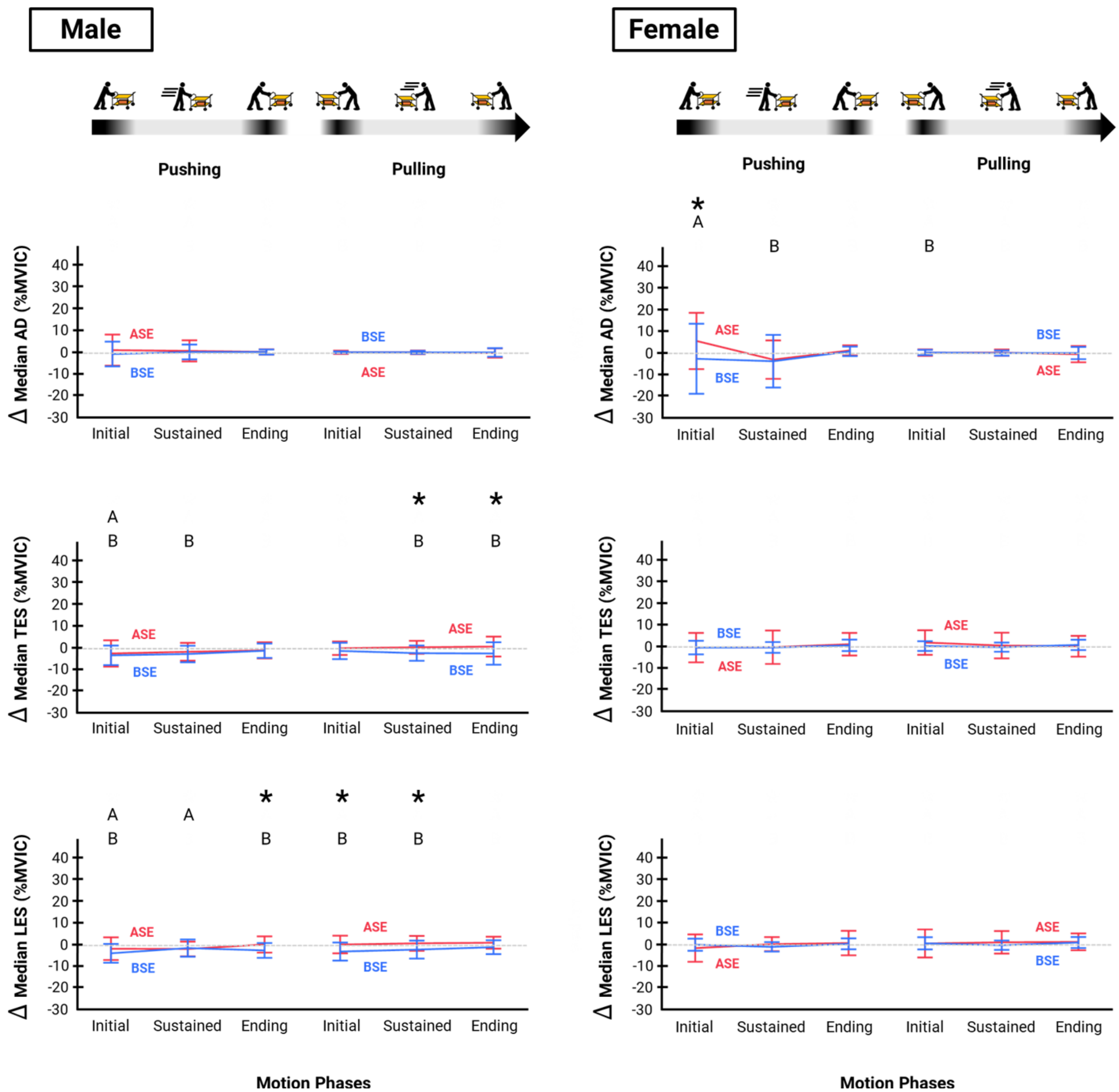

Figure 4. Median muscle activity of the anterior deltoid (AD), thoracic erector spinae (TES), and lumbar erector spinae (LES). Solid lines represent the mean value of difference scores [(Δ; EXO – ND (No Device)] for the ASE (red) and BSE (blue) groups. Dashed grey lines represent the baseline (no change from the ND condition). Error bars represent standard deviations. The symbol * denotes a significant paired difference between the ASE and BSE groups within a specific motion phase. Letters 'A' and 'B' indicate significant paired differences of the ASE and BSE from the ND condition, respectively.

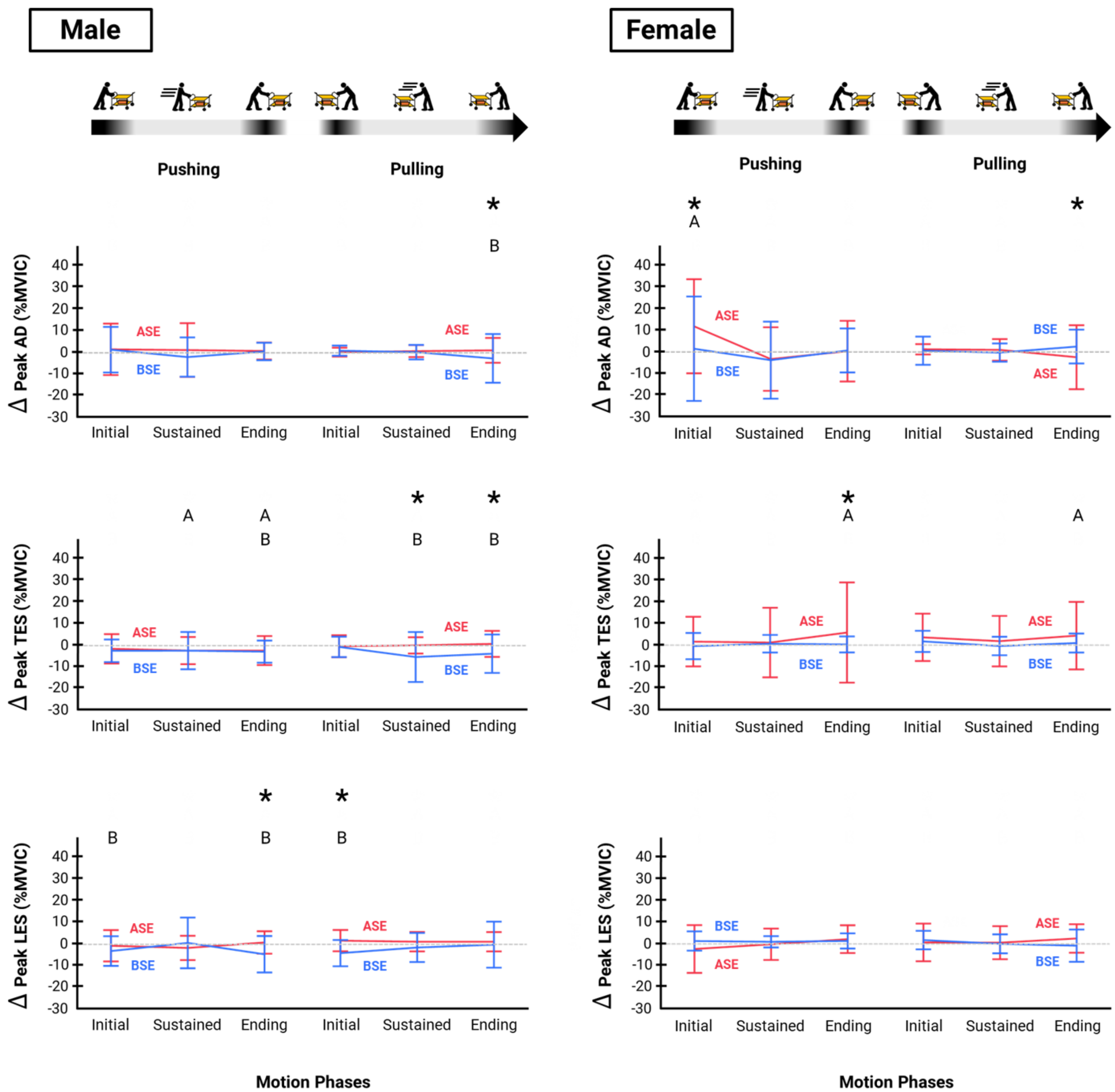

Figure 5. Peak muscle activity of the anterior deltoid (AD), thoracic erector spinae (TES), and lumbar erector spinae (LES). Solid lines represent the mean values of difference scores [(Δ; EXO – ND (No Device)] for the ASE (red) and BSE (blue) groups. Dashed grey lines represent the baseline (no change from the ND condition). Error bars represent standard deviations. The symbol * denotes a significant paired difference between the ASE and BSE groups within a specific motion phase. Letters 'A' and 'B' indicate significant paired differences of the ASE and BSE from the ND condition, respectively.

4. Discussion

We assessed the effects of two different passive EXO types—a passive ASE (EVO™) and a BSE (backX™ Model S)—during cart pushing and pulling as example secondary tasks. Our results suggest mixed effects of ASE and BSE use, with changes in joint kinematics and muscle activity varying by push and pull phases and sexes. Specifically, BSE use reduced back muscle activity during pushing and pulling particularly for males during the initial and ending phases (Tables A6 and A8 in the Appendix). In contrast, ASE use had minimal effect on shoulder muscle activity, showing limited effectiveness for both males and females (Tables A5 and A7 in the Appendix).

4.1. Phase-dependent effects of EXO use

The initial and ending phases of pushing and pulling generally require greater physical effort than the sustained phase (De Looze et al., 2000; Hoozemans et al., 2004; Schibye et al., 2001; Van Der Beek et al., 2000), which is not surprising given the large changes in cart inertia. Since passive EXOs generate assistive torques in response to body joint angular deviations (e.g., Madinei et al., 2022; Watterworth et al., 2023), the differences we observed between ASE and BSE use during these phases may arise from both phase-specific postural requirements and posture changes specific to each EXO type. Our results (Figures 4 and 5) suggest that during the physically demanding phases, trunk flexion (relative to the thigh) was likely sufficient for the BSE to generate enough assistive (extension) torque to reduce back muscle activity. However, shoulder flexion with ASE use did not appear to generate sufficient external torque to meaningfully reduce AD muscle activity, likely because ASEs are designed for overhead work, during which larger flexion angles generate more assistive torque. During the sustained phase, the limited trunk and shoulder flexions likely resulted in minimal assistive torques from either EXO, which is consistent with the negligible differences observed in both AD and back muscle activity with EXO use compared to ND (Figures 4 and 5).

Further analyses showed that both males and females used shoulder and trunk flexion that ranged from approximately 29° to ~53° and ~18° to ~38°, respectively, across phases and tasks. In comparison, Watterworth et al. (2023) reported that the EVO™ provides peak support torque between 90° and 105° of shoulder flexion, while the backX™ Model S provides support within a trunk flexion range of approximately 10° to 120°, with assistance increasing as the flexion approaches 120° (Madinei et al., 2022). These comparisons indicate that neither sex in our study approached the optimal joint flexion ranges for maximizing the assistive benefits of the ASE or BSE. Consequently, the presence of phase-specific variations in muscle activity may not solely be due to differences in posture, but instead may be due to the limited support provided by the devices under the conditions we tested.

4.2. Sex-dependent differences in EXO effectiveness

EXO effectiveness varied between sexes, particularly during the demanding task phases (initial and ending). For example, when using an ASE, females had significantly increased AD activity during the initial pushing phase and increased TES activity during the ending phases of both pushing and pulling. Males, in contrast, had AD and TES muscle activities comparable to the ND condition. Analyses using the ND values showed that during the initial phase of pushing with an ASE males used 4.5° more shoulder flexion than females (44.3° vs. 39.8°). Likewise, trunk flexion with BSE use was slightly (5°) higher among males during both the initial and ending phases. Although these slight increases in shoulder and trunk flexion among males may have resulted in marginally more ASE and BSE support, it seems unlikely that this alone explains the lower AD and back muscle activity we found for males.

Due to differences in stature, males and females likely adopted different working postures when using a fixed cart handle height of 0.86 m. In our study, females were on average 13.7 cm shorter than males. Lower handle heights can enhance pushing and pulling strength and delay fatigue (Al-Eisawi et al., 1999; Chaffin et al., 1983) but may also increase lower back stress from increased forward leaning (Hoozemans et al., 2004). Conversely, higher handles have been associated with less lumbar flexion and more efficient use of body weight, thereby reducing spinal loading and shoulder stress (Hoozemans et al., 2004; Lett and McGill, 2006). Among males using the ASE during the initial phase of pushing, slightly greater shoulder flexion and a higher trunk flexion angle (38.5°) were observed compared to females (32.6°), suggesting that males may have leaned forward more. While this posture might have helped align their shoulders to the handle level, it could have also increased lower back stress. Interestingly, despite this forward lean, males exhibited a mean reduction of approximately 33% (4% of max NEMG) in back muscle activity compared to females. In contrast, for females the shorter stature likely reduced the need for forward lean. Yet, they showed an increase of roughly 68% (15% of max NEMG) peak AD activity compared to males using an ASE. These findings suggest that the 100 kg cart load could simply be more physically demanding for females, and the increased AD and back muscle activations of females likely reflect a greater overall physical effort rather than differences in working posture or insufficient ASE support.

Interestingly, the selected support settings were rather comparable between the sexes for both the ASE and BSE. For instance, 77.0% of males and 85.7% females selected high support levels (≥ Level 3), and 54.6% of males and 44.5% of females chose either instant high or standard high settings (Figure A1 in the Appendix). However, despite these similar support settings and comparable magnitudes of joint flexion, only males showed a notable reduction in back muscle activity (while females showed increased AD muscle activity during some phases). This discrepancy suggests that factors beyond trunk flexion and support settings may have contributed to the observed sex differences in EXO effectiveness, such as anthropometric characteristics, device types, and maximum pushing/pulling forces.

Notably, females were on average 15.4 kg lighter than males (Table 1), and because the cart weight was not normalized to participant body mass, the task may have been more physically demanding for lighter individuals. Although the EXOs we used were relatively light (~6.8 kg for the EVO™ and ~3.6 kg for the backX™), wearing these devices may have affected postural balance compared to the ND condition. Park et al. (2021) indicated that wearing a BSE elevates the center of mass from the greater trochanter to the waist. Following similar reasoning, wearing an ASE may result in an even more elevated center of mass. According to the simplified inverted pendulum model of upright human posture (Winter, 2009), postural sway increases as the center of mass is elevated vertically. Hence, wearing an ASE could lead to an increased postural challenge during pushing and pulling. Females also generally have lower absolute strength than males (Garg et al., 2014; Van Der Beek et al., 2000). The increased AD activity observed among females with ASE use may therefore result from the additional physical burden imposed by device mass and increased postural sway, leading to greater relative effort. Further research, though, is needed to confirm both the existence and magnitudes of these effects.

4.3. Practical Implications

Our findings suggest that considering *both* primary and secondary tasks may be important when selecting an EXO for workplace use. While EXOs are primarily designed for specific tasks, we found that a BSE could offer some benefits for certain secondary tasks, like pushing and pulling, by reducing back muscle (up to 31.4% during pushing and 25.4% during pulling). In contrast, ASE use did not provide meaningful reduction in shoulder and back muscle activity and, for females, resulted in either comparable or increased shoulder muscle activity. These findings extend prior research by demonstrating that EXOs can influence physical demands even in tasks they were not explicitly designed for. This highlights the need for future research to assess how EXO effectiveness translates across different task types and worker populations, particularly in multi-task environments where workers transition between primary and secondary tasks.

Beyond muscle activity, our results indicate that neither EXO substantially affected efficiency during pushing and pulling, since both the ASE and BSE resulted in only a slight increase in task completion time (~1 second, or ~5.4%). Theurel et al. (2018) reported similar increases (~1 second, or ~5.0%) when walking with an ASE (EXHAUSS Stronger®), but found that ASE use during a stacking task increased work duration more substantially (~10.7 seconds, or ~30.0%). These findings suggest that while ASEs may hinder performance in certain dynamic shoulder-intensive tasks such as stacking, their influence on secondary tasks like pushing and pulling may be minimal. However, participants in our study were instructed to perform the tasks at a purposeful working speed without explicit emphasis on speed, meaning further research is needed to evaluate EXO effects under circumstances wherein efficiency is a more substantial concern.

In summary, our results suggest that BSEs could help reduce back muscle activity among males during the dynamic phases (i.e., initial and ending phases) of pushing and pulling tasks, although these changes were modest (less than 6–10% MVIC). However, both ASEs and BSEs may offer limited benefits during less dynamic tasks (i.e., sustained phase). There are also concerns about slip, trip, and fall risks when wearing EXOs. Recently, Park et al. (2024) reported that wearing the backX™ could impair balance recovery by altering kinetics during reactive stepping, while Dooley et al. (2024) suggested that wearing an ASE (i.e., Ottobock Shoulder and EVO^{TM}) and a BSE (i.e., Laevo FLEX) could increase the risk of slip and trip-induced falls. Therefore, careful assessment of push/pull task conditions and movement phases is important when selecting and implementing EXOs to better understand their effects and trade-offs in workplace settings.

4.4. Limitations

Some limitations of the current study should be noted. First, relatively homogeneous participants (i.e., novice university students) were recruited for the study. To be able to generalize our findings, broader samples should be considered in the future, with more balanced representation of sexes, different ages, work experiences, and anthropometric characteristics. Second, only one task condition was examined for each EXO type, including a single cart with fixed handle height, load mass, and travel distance. Effects of EXOs may be dependent on these aspects of task conditions and others (e.g., surface slope and frictional characteristics). For instance, our study tasks were performed under ideal conditions, with low rolling friction, a flat and obstacle-free surface, and a well-functioning cart. As conditions deteriorate (e.g., the presence of ramps/curbs, increased cart weight), physical demands are likely to increase, potentially altering the effects of EXO use. Given that the cart load here was 100 kg, the current results may not be directly applicable to tasks involving heavier (or lighter) loads or to tasks performed under suboptimal working conditions (e.g., slippery or sloped surfaces). Further research is needed to examine EXO performance under non-ideal conditions to determine the broader impacts of BSEs and ASEs for pushing and pulling tasks. Third, kinetics and hand forces were not measured, and additional muscle groups were not monitored (e.g., biceps brachii and triceps brachii). Including these measurements in future studies could provide more comprehensive assessments of the effects of EXOs during pushing and pulling tasks. Fourth, a between-subject design was used, and the ND condition was tested using only a single trial per participant. Although we provided initial familiarization trials and applied a difference-score approach to account for baseline variability, some confounding effects may remain that could affect comparisons across EXO groups. Finally, only a single type of ASE and BSE were used here, and future work is needed to determine if similar effects are found with different designs, especially those using soft components (i.e., exosuits) and active support mechanisms.

5. Conclusions

We characterized the effects of ASE and BSE use on physical demands during secondary tasks, specifically cart pushing and pulling tasks. Increased shoulder muscle activity observed during the initial push phase suggests that ASEs may be suboptimal for females during such activities. On the contrary, BSE use effectively reduced back muscle activity, especially among males during the dynamic phases (i.e., initial and ending phases) of pushing and pulling tasks. However, both EXOs provided limited benefits during the sustained phase, highlighting the importance of considering task-phase specificity in EXO selection. While ASE and BSE use resulted in a statistically significant but small (~1 second) increase in task completion time, this change appears to have minimal practical importance for efficiency. More broadly, our findings emphasize the need for a comprehensive approach when integrating EXOs into workplaces. While EXOs are primarily designed for specific tasks, their influence on secondary tasks suggests that task transitions, movement dynamics, and individual differences (e.g., sex, strength, and anthropometry) should also be considered. Further research should explore the effects of EXOs across a wider range of secondary tasks and investigate design improvements to enhance EXO adaptability and effectiveness in multi-task work environments.

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