Evaluating back-support exoskeletons in simulated construction-relevant tasks: Effects on task completion time and aspects of usability

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Abstract

Back-support exoskeletons (BSEs) are a promising intervention in reducing physical demands during diverse occupational tasks. However, limited information is available about the effectiveness of different BSE designs during construction work and if those effects are consistent between novices and experienced workers. In our study, we aimed to identify the benefits and potential unintended consequences of BSEs during construction work, considering worker experience levels. Forty participants (20 novices and 20 experienced, balanced in both groups by biological sex) completed lab-based simulations of several construction-relevant tasks. These tasks were performed under a control condition (no BSE) and with three BSEs, each of which was tested in two support settings (on and off). Task performance was measured using completion time, and perceptions of diverse aspects of usability were obtained. Generally, BSE use increased task completion time, perceived discomfort, and perceived interference of BSEs during simulated tasks, while its effects on perceived physical effort were mixed. Rigid BSEs particularly increased perceived movement restrictions, while exosuits did not. In a few cases, the effects of BSEs on completion time and BSE usability differed between novice and experienced groups. Nonetheless, we suggest that future work could generalize results from novice participants to experienced participants. Overall, our results suggested that the effects of BSEs on completion time and perceptions of usability were distinct and task-specific, with no single BSE design emerging as being clearly superior across the simulated tasks.

Keywords: Work-related musculoskeletal disorders, Construction, Assistive devices, Exoskeleton, Obstacle course

1.0 Introduction

Construction workers continue to experience high rates of work-related musculoskeletal disorders (WMSDs). In 2020, the rate in the U.S. was 6% higher than the rate of 25.4 per 10,000 full-time workers for all private industries combined (U.S. Bureau of Labor Statistics, 2021). These high rates has been attributed to the physically demanding nature of construction work, involving heavy lifting, substantial physical exertions, and non-neutral postures (Goldsheyder et al., 2002; Goldsheyder et al., 2004; Merlino et al., 2003). Back disorders are particularly prevalent, accounting for around 30% of all cases (U.S. Bureau of Labor Statistics, 2021). In addition, WMSDs impose a substantial financial burden; in 2023, for example, the U.S. construction industry paid $2.09 billion in compensation for direct costs associated with overexertion injuries (Liberty Mutual Insurance, 2023). Despite various interventions aimed at reducing worker exposures to WMSD risk factors (Harden et al., 1999; Silverstein & Clark, 2004; van de Wijdeven et al., 2023), the continued prevalence of WMSDs suggests a need for additional and innovative intervention approaches.

Back-support exoskeletons (BSEs), designed to reduce physical demands on the back, are a promising alternative intervention to reduce exposure to WMSD risks during physical activities. A growing number of studies have examined the benefits and limitations of BSE use across various tasks. These tasks include repetitive lifting and carrying (Antwi-Afari et al., 2021; Schmalz et al., 2022), static holding (Bosch et al., 2016; Koopman et al., 2019), trunk bending (Giustetto et al., 2021; Koopman et al., 2020a; Koopman et al., 2020b; Poliero et al., 2022), and assembly tasks (Bosch et al., 2016; Madinei et al., 2020). Reported benefits include reductions of up to 33% in back muscle activity (Antwi-Afari et al., 2021; Giustetto et al., 2021); up to 80% in perceived physical exertion at the lower back (Madinei et al., 2020); 30 – 50% in local lower back discomfort (Antwi-Afari et al., 2021; Giustetto et al., 2021); and 14% in perceived effort (Giustetto et al., 2021). However, task-specific limitations have also been reported. For example, Luger et al. (2021) observed a 9% increase in erector spinae muscle activity during repetitive lifting with a BSE, and Madinei et al. (2021) found that BSE use could alter neuromuscular control strategies in the trunk during repetitive lifting. Additionally, Baltrusch et al. (2018) found that BSE use increased perceived difficulty when used for some functional tasks. Such findings suggest a need for further research to evaluate BSE effectiveness across diverse, construction-relevant tasks.

Recently, some studies have assessed the efficacy of BSEs in reducing physical demands in construction-specific tasks (Bennett et al., 2023; Gonsalves et al., 2023; Song et al., 2024; Yan et al., 2023). Two example applications highlight the potential of BSEs in reducing physical demands or improving task performance in such contexts. First, Song et al. (2024) showed that BSE use can reduce erector spinae muscle activation (by 5 – 25%) during simulated tasks that involved manual handling of lumber. Second, Bennett et al. (2023), in a small-scale field study (*n* = 4), found that BSE use can reduce task completion time when pushing and emptying a construction gondola on a platform (though by a small magnitude, of ~6%). Although limited in scale and task variety, these results support the potential of BSE use to control WMSD risks and improve performance in construction settings.

However, current evidence regarding BSEs in construction has three important limitations. First, there is a limited understanding of BSE effects during a range of construction-relevant tasks. While BSEs have been examined for manual material handling tasks, especially lifting, under different conditions (Alemi et al., 2019; Baltrusch et al., 2020; Iranzo et al., 2022; Lanotte et al., 2018; Simon et al., 2021), construction work often involves non-repetitive tasks performed in complex and/or dynamically changing environments (Forde & Buchholz, 2004; Kramer et al., 2009). Second, comparative studies on different BSE designs remain scarce, and those reported included only a narrow set of tasks relevant to construction. For instance, Yan et al. (2023) investigated the effects of two BSEs on task completion time and body kinematics, yet they focused exclusively on roofing tasks. Third, the influence of work experience on BSE perceptions and effectiveness remains unclear. For example, Song et al. (2024) reported that novice and experienced construction workers had similar trunk kinematics during dynamic tasks, but that novices exhibited larger trunk rotation during static tasks. Additionally, experienced workers often adopt task-specific work strategies, while novices often use more consistent strategies across tasks (Lee & Nussbaum, 2012; Plamondon et al., 2014; Plamondon et al., 2010).

Our objective in the current study was to investigate the effects of three commercially available BSE designs—two rigid BSEs and one soft BSE (or exosuit)—during diverse simulated construction-relevant tasks. We were interested in understanding both the benefits and potential drawbacks of BSE use. The latter can include discomfort at the low back and increases in perceived physical demand, effort, and balance (Kranenborg et al., 2023), and such adverse effects could be especially concerning during complex construction activities. We were also interested in whether BSE effects differed between novices and experienced workers. We included a broad range of outcome measures, such as task completion time and subjective assessments regarding several aspects of usability. Based on previous findings, we expected that the effects of BSE use would depend on the specific tasks and BSE designs as well as participant experience level.

2.0 Methods

2.1 Participants

A convenience sample of 40 participants (20 novices and 20 experienced) completed the study. The sample was sex-balanced within the novice and experienced groups, and participants were recruited from the university and local community (see Table 1 for a summary of participant characteristics). Inclusion criteria included self-reporting no current or recent (past 12 months) musculoskeletal disorders or injuries. Additionally, the novice group was required to have no construction experience, while the experienced group must have had at least one year of construction experience. Five participants self-reported being left-handed. The research reported herein complied with the tenets of the Declaration of Helsinki and the study protocol was approved by the Institutional Review Board at Virginia Tech. Written informed consent was obtained from all participants prior to any data collection.

Table 1: Summary [mean (SD)] of anthropometric and demographic characteristics of participants in each experience group.

Group	Total	Male				Female			
		n	Age (Yrs)	Body Mass (kg)	Stature (cm)	*n*	Age (Yrs)	Body Mass (kg)	Stature (cm)
Novice	20	10	24.5 (5.7)	78.8 (14.9)	176.5 (6.9)	10	22.3 (1.8)	56.4 (6.9)	164.8 (5.2)
Experienced	20	10	33.2 (12.0)	73.6 (13.7)	176.2 (7.6)	10	24 (5.1)	64.3 (9.7)	164.4 (4.9)

2.2 Back-support Exoskeletons (BSEs)

Three BSEs were included: suitX backX^{TM} model S (BX); Paexo Back version 1 (PB; Ottobock^{TM}); and HeroWear Apex version 1 (HW). These BSEs were selected for two reasons. First, to represent diverse design characteristics (see Table A1 in the Appendix). Second, existing studies have demonstrated the effectiveness of these BSEs (either current or older versions) in reducing perceived physical exertion and discomfort during several manual work tasks (Alemi et al., 2020; Goršič et al., 2021; Schmalz et al., 2022).

2.3 Task Simulations

Donning and doffing, as well as construction-relevant manual tasks, were simulated to evaluate BSE usability. For the former, the time required to don and doff each BSE was measured to assess a key aspect of usability, reflecting the practical needs of users who may need to alternate between wearing and not wearing a BSE during some jobs. Several construction-relevant manual tasks were simulated in a laboratory environment, representing a range of tasks that workers might perform at a construction site while wearing a BSE (see Figure 1). These tasks were selected as construction-relevant from among those examined by Baltrusch et al. (2018), and with consideration of the feasibility and cost of lab-based simulation. We then broadly categorized the tasks into two types: *stationary* vs. more *ambulatory*. The former required participants to mainly work in one place, while the latter involved movement from one place to another. The following tasks were simulated (see Appendix A for more detailed descriptions of each task).

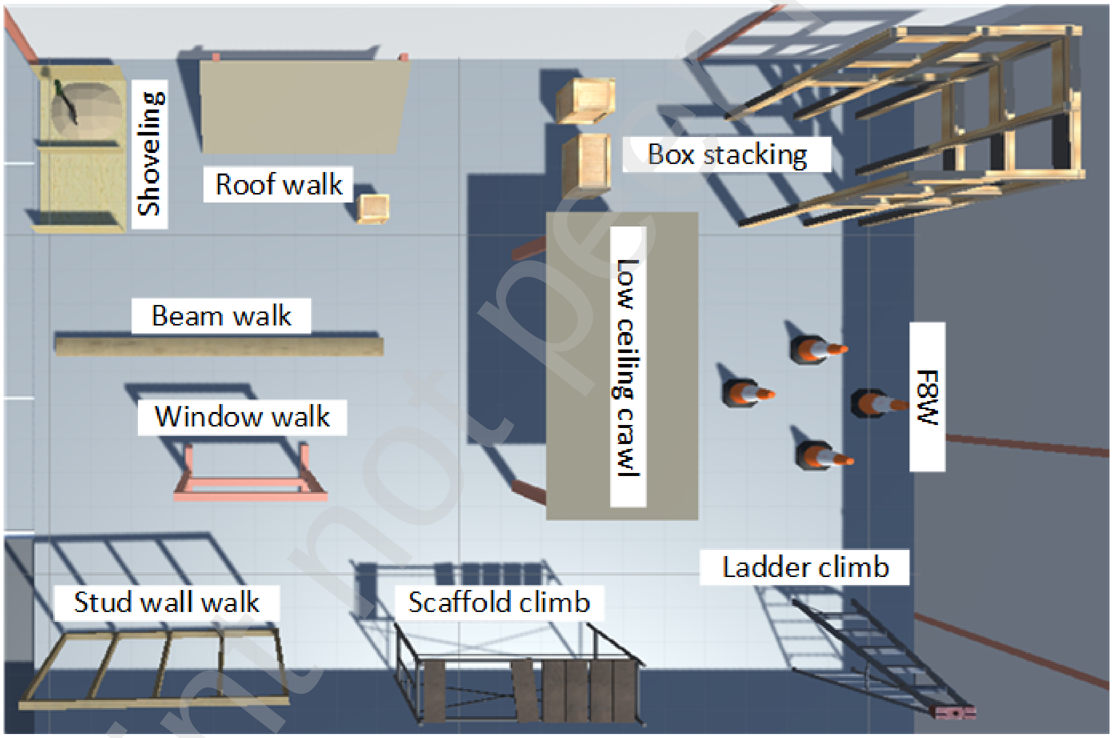

Figure 1: 3D Layout illustrating several of the simulated construction-relevant tasks. F8W = Figure Eight Walking.

Stationary Tasks:

- *Squatting:* Squat down three times and hold the squat position briefly.
- *3-point kneeling:* Kneel with one hand on the floor while using the other hand to perform a precision manual task.

- *Bolting (Assembly):* Performed bolting tasks in a confined space with two different ceiling heights, screwing and unscrewing bolts in one corner of the space at their comfortable working speed.
- *Shoveling:* Transfer sand from a filled area to an unfilled area.

Ambulatory Tasks:

- *Stair climbing:* Ascend and descend a straight flight of stairs
- *Ladder climbing:* Climb up and down a step ladder
- *Material stocking:* Stack five boxes into a mock confined space with two different ceiling heights.
- *Stud wall walking:* Walk through and back a stud wall.
- *Scaffold climbing:* Climb to the top deck of a mobile scaffold through a narrow opening, walk across the deck, and then descend using an access ladder.
- *Low ceiling crawling:* Traverse a low ceiling space.
- *Window opening crossing:* Pass through a window opening situated above the ground.
- *Figure 8 walking:* Walk in a figure-eight shape, involving both straight and curved paths.
- *Roof walking:* Walk up, sideways, and down on a simulated roof set at two different slopes.
- *Beam walking:* Walk back and forth on a narrow wooden beam.

2.4 Experimental Design and Procedures

A randomized incomplete block design with a block size of three was employed for novices, wherein each participant completed three of four levels of *Intervention*—a control or No Device (ND) condition, and the three BSEs noted earlier. Specifically, participants completed the activities and tasks in the ND condition, along with two of the three BSEs. This design was informed by pilot testing, which indicated that completing all four *Intervention* levels in a session led to excessively long durations and moderate physical fatigue for some participants. We also found that pilot sessions with experienced participants progressed relatively faster than novice participants, likely because they were accustomed to the tasks, requiring less explanation. Thus, experienced participants were given the option to complete all four *Intervention* levels if they did not experience more than minor fatigue (i.e., using a complete block design). For each condition involving a BSE, two levels of *Support Setting* were included: "On" (with torque generation mechanism engaged) vs. "Off" (without engagement).

All participants completed a single experimental session (~3.5hrs), which consisted of training and experimental phases. In the training phase, we verbally introduced the simulated tasks and fitted the participants with each of the BSEs following manufacturer recommendations. They were then asked to practice each task with each BSE, exploring different BSE support levels before selecting their preferred level for each device. Participants were informed that their chosen BSE support level would remain consistent during the experimental phase, and practice continued until participants indicated feeling comfortable and competent. Finally, we demonstrated how to don and doff each BSE according to the manufacturer's instructions, and we asked participants to practice donning and doffing until they again reported feeling comfortable and competent.

In the experimental phase, participants completed a trial of each simulated task at a given *Intervention* level. For *Intervention* levels involving a BSE, participants were first asked to don and doff the BSEs three times before performing any of the other tasks. Each task with a BSE was then completed twice, once with the support engaged and once disengaged. The presentation order of *Intervention* levels was counterbalanced using Latin Squares, and within each *Intervention* level the presentation order of *Support Setting* was alternated across participants. Participants alternated between completing all stationary tasks first or all of the ambulatory tasks. For tasks involving multiple levels of height (Bolting/Assembly) or slope (Roof walking), *Height* and *Slope* levels were alternated. A minimum of three minutes of rest was given between *Intervention* conditions. Participants were instructed to perform the tasks using their preferred work strategies and at a pace they would adopt at a construction site. Note that participants were informed that they could opt out of any tasks if they felt uncomfortable or unsure about their ability to perform the task safely. For example, some participants chose not to perform scaffold climbing, roof walking, or material stocking due to concerns over the elevation or the restricted space.

2.5 Instrumentation, Data Collection, and Data Processing

Task completion time was measured using a digital stopwatch (except 3-point kneeling), as a measure of task performance. After each task using a BSE, participants were asked to rate perceived ease of donning and doffing the BSE, and aspects of BSE usability using visual analog scales (VASs; Appendix D). VASs were used, instead of numerical scales, to allow for finer distinctions in participant opinions, by reducing the variation of individual interpretations (Kersten et al., 2012). Usability ratings included six aspects: physical effort required to complete the task (Q1), perceived discomfort (Q2), movement restrictions (Q3), sense of safety (Q4), interference of the BSE when performing the task (Q5), and sense of imbalance (Q6). For the ND condition, participants were asked to respond to all usability questions except Q5. In all cases, ratings ranged from 0 to 10, with 0 representing the most positive perception (e.g., not difficult at all, no discomfort at all, no effort) and 10 representing the most negative perception (e.g., extremely difficult, extreme discomfort, extreme effort).

2.6 Statistical Analyses

Separate two-way, repeated measures analyses of variance (ANOVAs) were used to assess the effects of *Intervention* and *Experience Level* on donning and doffing duration, as well as on perceived ease of donning and doffing. For the stationary and ambulatory tasks, difference scores (Δ = BSE – ND) were calculated for each outcome measure. Using difference scores allowed clearer comparisons of the relative effects of the BSE condition versus the ND condition. For most simulated tasks (excluding Bolting, Material Stocking, and Roof Walking), separate three-way, repeated measures ANOVAs were used to assess the effects of *Intervention, Experience Level*, and *Support Setting*. For Bolting and Material Stocking, separate four-way repeated measures ANOVAs were used to include *Height* as an additional factor. Similarly, for Roof Walking, separate four-way repeated measures ANOVAs were used, including *Slope* as an additional factor.

Biological sex (Sex) and the presentation order of experimental conditions (*BSE order, Support Setting, Height*, and *Slope*) were included as blocking effects for all ANOVAs. Significant main and interaction effects were explored using Tukey's HSD for pairwise comparisons and simple effects analysis, respectively. Additionally, planned paired *t*-tests were completed for each difference score to examine whether mean scores significantly differed from zero (i.e., mean $\Delta \neq 0$), indicating significant differences between a BSE and the ND conditions.

All statistical analyses were performed using JMP Pro 16 (SAS, Cary, NC), with the restricted maximum likelihood (REML) method for the ANOVAs. No substantial deviations from parametric model assumptions were found, and statistical significance was determined when $p < 0.05$. Summary data are reported as medians (since there were some small deviations evident from normal distributions). Consistent with the purpose of our study, the subsequent presentation of results emphasizes the main and interactive effects of *Intervention* and *Experience Level.* While we found that several effects were statistically significant, many of these effects were relatively small in magnitude (|median Δ| < 1), and we considered such effects to be of limited practical importance. For completeness, all significant results are presented in Appendix C, but in the main text we emphasize the larger effects (i.e., |median Δ| ≥ 1).

3.0 Results

ANOVA results are summarized in Tables B1–B14 in Appendix B. There were significant main effects of *Intervention* on donning and doffing times and ease of donning and doffing. Main and/or interaction effects of *Intervention* were also observed for task completion time difference scores, physical effort difference scores, perceived discomfort difference scores, movement restrictions difference scores, and sense of imbalance difference scores. Detailed results are provided below. Of note, there were no substantial main or interaction effects of *Intervention* for any of the stationary tasks.

3.1 Donning and Doffing

There were significant differences in both donning and doffing times among the BSEs. Donning the BX took significantly longer (median = 42.2 seconds) compared to both HW (32.6 seconds) and PB (32.5 seconds). Doffing the HW was significantly faster (10.7 seconds) than both BX (17.5 seconds) and PB (14 seconds). However, ratings of ease of donning and doffing were comparable among all three BSEs.

3.2 Ambulatory Tasks

Material Stacking

Task completion time difference scores (ΔTC) were significantly affected by the *Intervention* × *Sex* × *Experience Level* interaction. In most cases, BSE use increased task completion time, with novice participants experiencing increases up to 8.1 s (23%) and experienced participants up to 5.2 s (14%; Figure 2). PB use among experienced female participants significantly increased task completion time, by 3.6 s (9%).

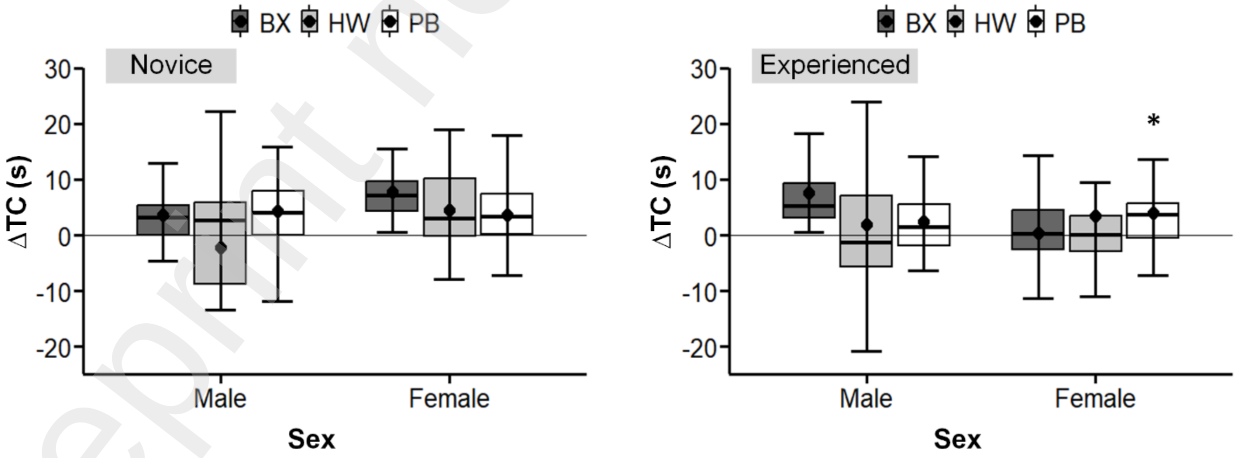

Figure 2: Box plots of difference scores for task completion time (ΔTC = BSE - ND) across BSE conditions, sexes, and experience levels during *Material Stacking*. In this and other figures below, the symbol * indicates a significant difference between a BSE and the ND condition (i.e., median Δ ≠ 0).

Stud Wall

Intervention had significant main effects on task completion time and perceived movement restriction difference scores (ΔQ3). All BSEs increased task completion time, compared to ND, with BX and PB use showing significant increases of 1.4 s (18%) and 1.9 s (22%), respectively. PB use also increased perceived movement restrictions (1.0) compared to both ND and HW (both 0.0). Perceived interference of BSE was significantly affected by the *Intervention* × *Sex* interaction. Among males, BX and HW use significantly reduced perceived interference compared to PB (BX: 1; HW: 0; PB: 2.5).

Scaffold Climbing

Intervention had significant main effects on task completion time, perceived physical effort (ΔQ1), and perceived sense of imbalance (ΔQ6) difference scores. Both BX and PB use significantly increased task completion time compared to ND (BX: 29 s; PB: 32 s; ND: 24 s). PB use significantly increased perceived physical effort compared to ND (3.5 vs. 3.0). Neither BSE significantly affected the perceived sense of imbalance compared to ND.

Perceived movement restriction difference scores were significantly affected by the *Intervention* × *Sex* interaction*.* Among males, BX and PB use significantly increased perceived movement restrictions compared to ND, by 2.8 and 3.8, respectively (Figure 3). Males also reported less perceived movement restrictions with HW than the PB, by 2.0 (50%). Among females, BX use significantly increased perceived movement restrictions, by 1.0 compared to ND.

A significant *Intervention* × *Sex* interaction was found on perceived interference. Among males, HW use led to smaller perceived interference values than PB (by 4.0), whereas females reported comparable interference values across BSEs (Figure 3).

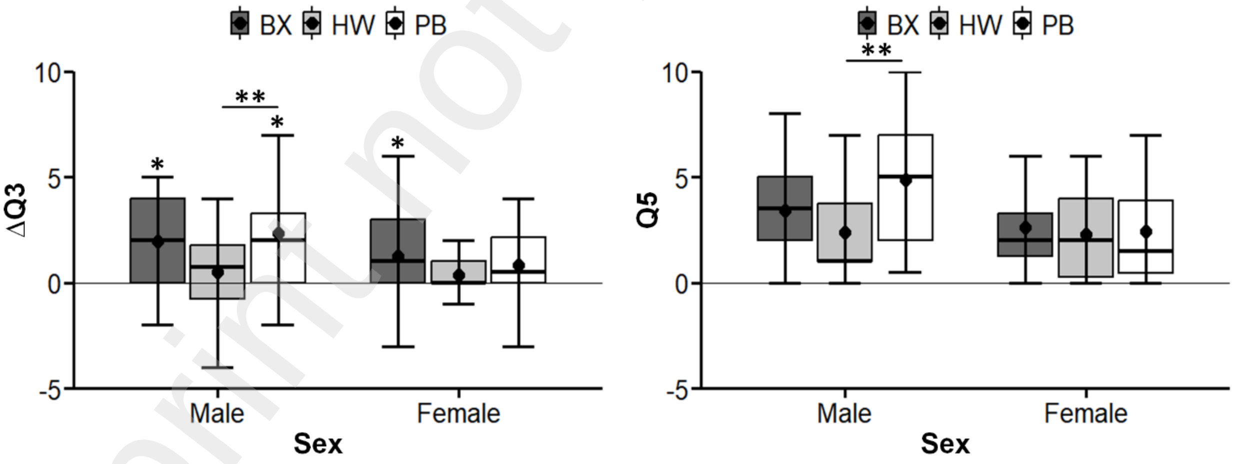

Figure 3: Box plots of difference scores for perceived movement restriction (ΔQ3**)** across BSE conditions and Sexes (Left), and perceived interference of BSEs (Q5) among males and females (Right) during *Scaffold Climbing*. For this and other figures below, levels with s bar and ** are significantly different between BSE levels.

Low Ceiling Crawl

There was a significant *Intervention* × *Experience Level* × *Support Setting* interaction effect on task completion time difference scores. Among novice participants, BX and PB use significantly increased task completion time vs. ND, with increases ranging from 3 to 6 seconds, and irrespective of whether support was off or on. With the BSE support on, however, HW use reduced task completion time among novices by 3 seconds (14%) more than PB. Among experienced participants, BX and PB use significantly increased task completion time vs. ND, by 2 – 3 seconds, when the support was on (Figure 4).

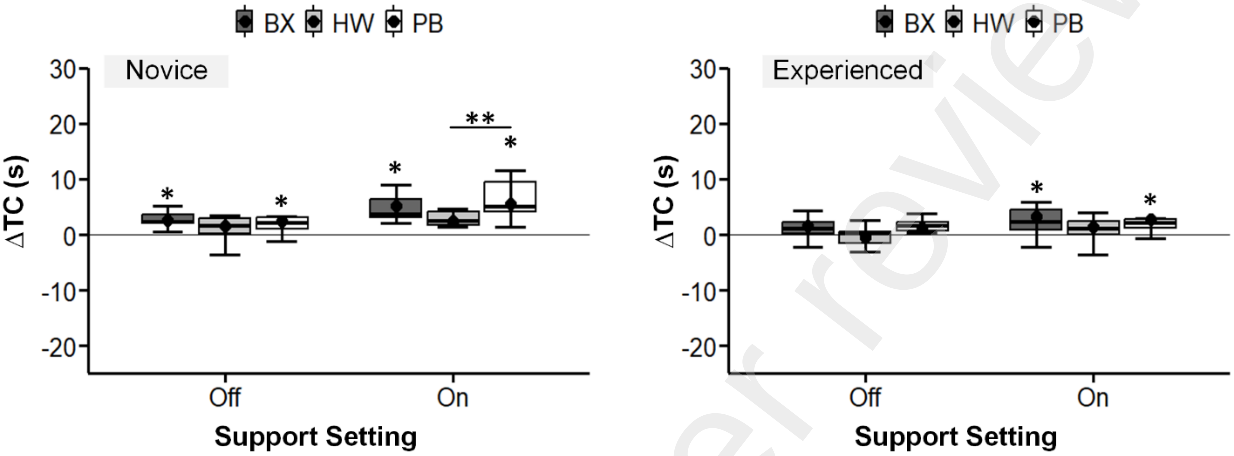

Figure 4: Box plots of difference scores for task completion time (ΔTC [s]) across BSE conditions, Experience levels, and Support settings during *Low Ceiling Crawl*.

Window Opening Crossing

Task completion time difference scores were significantly affected by the *Intervention* × *Experience Level* × *Support Setting* interaction. Among experienced participants, BX use led to significantly larger increases in task completion time than HW, though the magnitude was rather small (1.3 s; Figure 5).

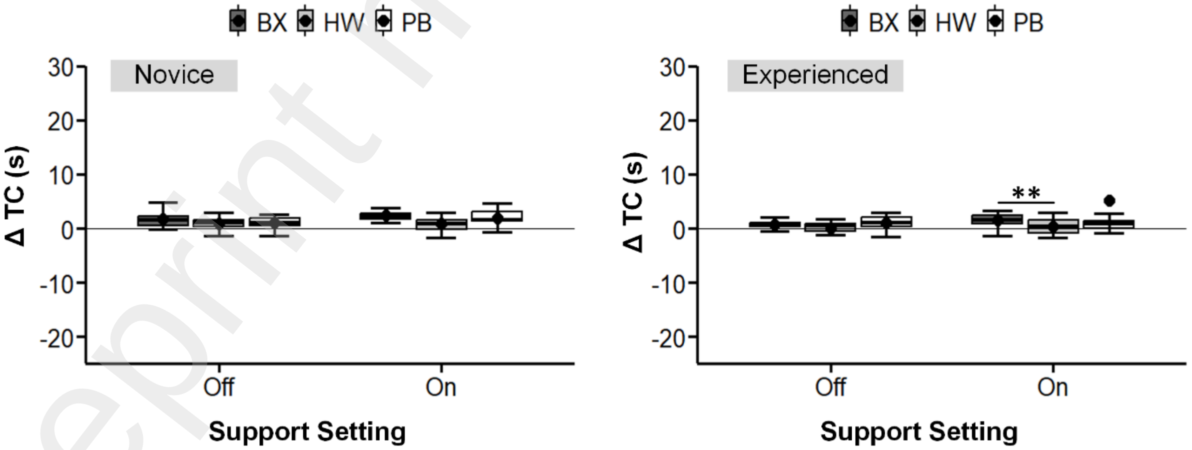

Figure 5: Box plots of difference scores for task completion time (ΔTC) across BSE conditions, support settings, and experience levels during *Window Opening Crossing*.

Perceived physical effort difference scores were significantly affected by the *Intervention* × *Sex* × *Experience Level* interaction. Among novice male participants, HW use led to significantly lower perceived physical effort, by 1.0 (70%) vs. ND, and resulted in a larger decrease in perceived physical effort than PB (-1.0 vs 0.0; Figure 6). In contrast, experienced participants exhibited no statistical differences in perceived effort across BSEs or between any BSE vs. ND.

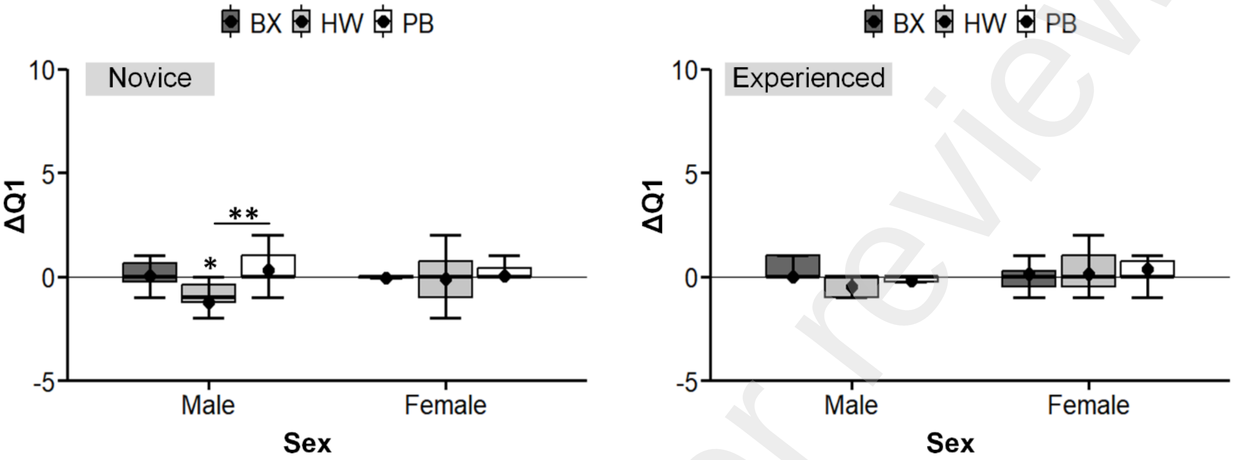

Figure 6: Box plots of difference scores for perceived physical effort (ΔQ1**)** between BSE conditions, sexes, and experience levels during *Window Opening Crossing*.

Intervention had significant main effects on perceived discomfort, perceived movement restriction, and perceived interference of BSEs difference scores. There was no significant difference in perceived discomfort with BSE use vs. ND. However, HW use caused significantly larger decreases in perceived discomfort than PB and BX (-0.31 vs. 0.17 and 0.14, respectively). BX and PB use significantly increased perceived movement restriction compared to ND (2.0 and 1.8 vs. 0.0). All BSEs significantly increased perceived interference during window opening crossing, with BX showing the largest increases (2.0), followed by PB (1.5), and HW (1.0).

Figure 8 Walk (F8W)

Task completion time difference scores were significantly affected by the *Intervention* × *Experience* × *Support Setting* interaction. When the support setting was off, novice participants exhibited significant increases in task completion time using the BX (by 3.2 seconds, 9.4%) and HW (by 2.6 seconds, 7.6%) vs. ND (Figure 7). With support on, BX use significantly increased task completion time for both novice participants by 2.9 (8.4%) and experienced participants by 2.18 (6.2%).

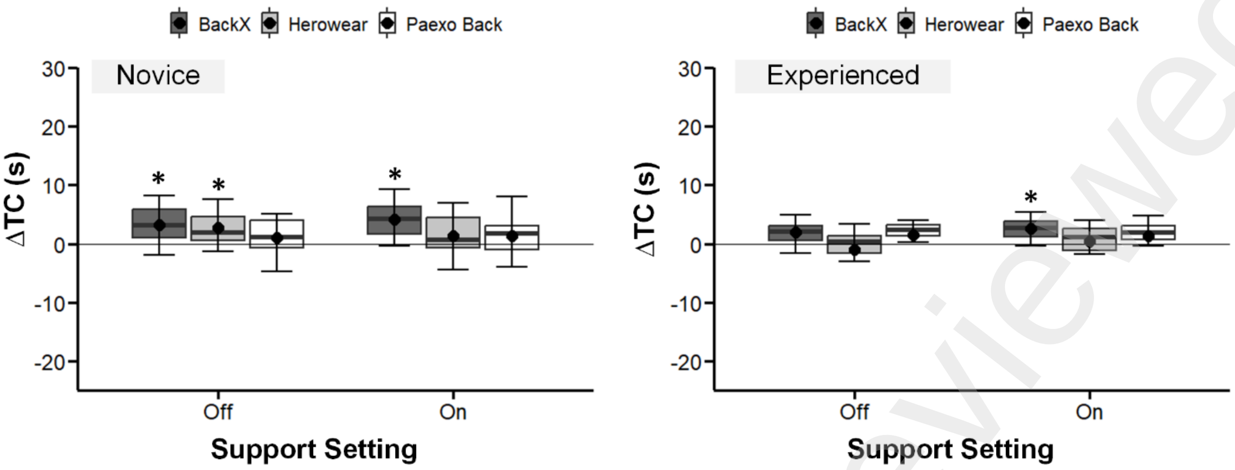

Figure 7: Box plots of difference scores for task completion time (ΔTC) between BSE conditions, support settings, and experience levels during *Figure 8 Walking.*

4.0 Discussion

We investigated the effects of using three different BSEs during diverse simulations of construction-relevant stationary and ambulatory tasks. Our results indicated that participants generally found donning and doffing the BSEs examined to be easy and straightforward. We also found that using BSEs increased task completion time and that the usability of a given BSE depends on the specific BSE design, task type (stationary *vs*. ambulatory), sex (male *vs*. female), and experience level (novice *vs*. experienced). Subsequent sub-sections discuss these results and their practical implications for BSE use in construction.

4.1 Effects of BSEs on Donning and Doffing

Donning and doffing any of the BSEs examined took a mean of 37 and 15 s respectively, suggesting participants completed these tasks relatively quickly. While not directly comparable due to differences in exoskeleton types, donning and doffing an arm-support exoskeleton led to a mean of 67.1 and 17.4 s, respectively (Kim et al., 2018). These BSEs seem easier to don, perhaps because of fewer or less complex connections to the user (e.g., straps), though their doffing times are comparable to those of arm-support exoskeletons. However, the durations may be limiting if donning and doffing need to be performed frequently or in cases of emergencies. Similarly, time to don and doff was also highlighted as an area needing improvement for potential application in manufacturing (Kim et al., 2022).

4.2 Effects of BSE use on Task Performance

Across the simulated tasks, using any of the BSEs increased task completion time (ΔTC = 2 – 8 seconds; see Figures 2, and 4 – 6). The magnitude of these increases was conditional on the specific task performed, with a larger increase generally observed among tasks (e.g., low ceiling crawl) involving movement restrictions (up to 8 seconds), compared to tasks with relatively less movement restriction (e.g., figure 8 walk; up to 3.2 seconds). This increase in task completion time with BSE use is consistent with earlier studies such as: a 2 – 8% increase during a test battery including box lifting, drilling, and stair climbing (Luger et al., 2023); a 0.4 – 1.7 s increase when a BSE was used for carrying, stair climbing, and ladder climbing (Baltrusch et al., 2018); and up to a 1.2 s increase when performing an assembly task (Madinei et al., 2020). While the changes in task performance were statistically significant, the magnitudes observed here were small to moderate, and their practical importance remains unclear. Such magnitudes could also have stemmed from the short duration of tasks and from participants needing a longer training period to develop an optimal work strategy specific to each BSE.

4.3 BSE effects on Perceived Physical Effort and Usability during the simulated tasks

BSE use had mixed effects on perceived physical effort, depending on the task and the specific BSE used. Specifically, using the PB increased perceived physical effort during scaffold climbing by 17%, while using HW reduced perceived physical effort by 70% during window opening crossing among novice participants (Figure 6). PB and BX also seemed to cause more perceived interference than the HW across the three tasks—stud wall, scaffold climbing, and window opening crossing.

We believe the mixed effects found here could be due to the characteristics of both the tasks and the BSEs. For example, the scaffold climbing task involved navigating confined spaces, whereas window crossing allows freer movement. Compared to the HW, the PB has a relatively bulky design with a high-profile frame and large thigh pads, which may limit ease of movement in confined spaces. As a result, participants might have taken extra care to avoid contact with the scaffold, thereby increasing perceived physical effort (Toxiri et al., 2019). Participants also mentioned that wearing the PB and BX in confined spaces made them conscious of their surroundings, while wearing the HW felt like wearing regular protective equipment.

However, it should be noted that Baltrusch et al. (2018) found minimal interference from a rigid BSE across various tasks. Specifically, they examined a different rigid BSE during stationary and ambulatory tasks, but not in confined spaces, reporting minimal interference. Similarly, minimal task interference was observed in another study (Naf et al., 2018) when using a different rigid BSE for tasks like stair climbing, ladder climbing, and lifting. Differences between our study and previous ones may stem from variations in task type and task simulation fidelity. It is possible that the interference from rigid BSEs is more pronounced in tasks performed in confined spaces. While we simulated stationary and ambulatory construction tasks with moderate fidelity, earlier studies often relied on less realistic simulations to assess perceived effort and task interference.

There were mixed effects of BSE use on perceived movement restriction during ambulatory tasks. HW did not increase ratings of perceived restriction, while PB and BX increased, particularly for tasks involving dynamic movement and confined spaces, such as window opening crossing. The increased perceived restriction associated with PB and BX use may be due to their design. Rigid BSEs have hip actuators aligned with the human hip joint (Schmalz et al., 2022), but misalignment often can happen during prolonged and/or repetitive use, especially in tasks requiring a large range of motion. (Junius et al., 2017). Misalignment may introduce unintended forces, compromising comfort and movement (Junius et al., 2017; Näf et al., 2018). Additionally, Park et al. (2022) found that using the BX can affect gait performance during level walking by decreasing step length and increasing swing time. Thus, the increase in movement restrictions here may have been due to participants adopting different hip postures due to the position of BX thigh cuffs placed anteriorly on the thigh and support mechanisms at the hips. Our findings are consistent with earlier reports (Baltrusch et al., 2019; Baltrusch et al., 2018), which indicated that BSE use can increase general discomfort and increased movement restriction while walking. In contrast, HW may not have hindered movement because, as an exosuit, it provided a more comfortable fit and allowed for greater hip freedom with or without support. The HW fitting instructions also include adjustment methods designed to minimize interference during walking.

4.4 Are the effects of BSE use consistent between novice and experienced participants?

We found a few cases where the effects of BSE use task completion time and BSE usability significantly differed between groups with differing levels of experience. For these cases, however, the actual magnitudes of the differences were generally small, leaving their practical importance unclear. However, there was an exception where HW use among novice male participants led to a 70% lower reported perceived physical effort, whereas experienced male participants reported no change in perceived physical effort. Our results were also in agreement with a recent study by Song et al. (2024), who found no significant differences in perceived task effort between participants with and without 1000 hours of construction experience. From these results, we suggest that future work could use results obtained from novice participants, as they may be easier to recruit, yet generalizing results to the actual worker population will still require some caution.

4.5 Limitations

Important limitations of the current study should be noted. First, our participants were relatively young and healthy and so did not represent the full range of the construction worker population. Thus, caution should be taken in generalizing the current results for older, injured, and/or obese workers. Second, participants had varying levels of construction experience, and the criterion we used (>1 year) may not have ensured that all workers were "experts." Third, although participants were familiarized with the BSEs, it remains unclear whether the duration of training was sufficient. Fourth, the tasks we simulated were relatively short in duration, and participants may need additional time to achieve steady-state outcomes when using BSEs. Fourth, the study was conducted under near-optimal conditions (e.g., in an air-conditioned environment with clean surfaces), and participants did not wear typical construction clothing or gear (e.g., tool belts, boots), which may affect the generalizability of our findings to real-world construction settings.

5.0 Conclusions

We evaluated the effects of three commercially available BSEs on task completion time and subjective assessments during construction-relevant tasks, considering experience levels. These BSEs were generally easy to don and doff, and participants completed donning and doffing somewhat fast. Using these BSEs led to minimal to moderate increases in task completion time, and these increases were larger during dynamic tasks. However, the magnitude of these changes was small, and the practical implications remain unclear. Our results also indicated that the effects of BSE use on perceived physical effort and movement restriction varied depending on the tasks. Nonetheless, using rigid BSEs increased perceived physical effort and movement restriction compared to using a soft exosuit. Overall, BSEs had distinct and task-specific effects on subjective outcomes, and experience level did not affect most outcomes, suggesting that the results from novices may, in many cases, be generalizable to experienced workers.

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