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# Passive back support exoskeletons do not effectively reduce physical demands during simulated floor tiling

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ABSTRACT

Back-support exoskeletons (BSEs) have the potential to reduce physical demands during many occupational tasks, but their effectiveness in flooring work remains underexplored. Eighteen participants performed simulated floor tiling work under three intervention conditions (HeroWear Apex™ = HW, Laevo Flex™ = LV, and no device = ND), across two tile sizes (small vs. large), and two task types (tiling vs. grouting). HW use increased back muscle activation by ~13–44 % compared to ND, while LV led to minimal changes. Some participants reported concerns with both BSEs, including movement restrictions, discomfort, and skin irritation. Significant interaction effects of intervention and tile size on muscle activity and subjective outcomes suggest the importance of considering task-specificity in BSE evaluations. Overall, the BSEs examined here did not effectively reduce physical demands during simulated floor tiling. Although we assessed BSE effects on tiling, our findings could also guide future implementation of exoskeletons in other similar construction tasks.

## 1. Introduction

Work-related musculoskeletal disorders (WMSDs) are a major concern in the workplace, comprising injuries, illnesses, and disorders to an individual's musculoskeletal system resulting from physical occupational activities. The construction sector has a relatively high prevalence of WMSDs, and construction work often exposes workers to strenuous physical activities (Bureau of Labor Statistics, 2023; CPWR - The Center for Construction Research, 2018). In a workforce of approximately 11.8 million construction workers in the U.S., WMSDs account for over 20 % of nonfatal injuries (CPWR, 2023), highlighting the critical need for managing and mitigating WMSDs in this industry sector. The back is the most frequently affected body area among construction worker, accounting for 39 % of all WMSD cases (Bureau of Labor Statistics, 2020a; 2020b).

Flooring tasks, particularly floor tiling, are associated with a high risk of WMSDs (Dong et al., 2019). Tile and terrazzo contractors, for instance, reported the highest rate of WMSDs among all construction trades (Dong et al., 2019). The elevated risk of WMSDs in floor tiling is largely due to the physically demanding nature of the work, requiring workers to adopt substantially non-neutral body postures—such as stooping, bending, and kneeling—and often maintain these postures for extended durations, imposing high physical demands on the low back, legs, and shoulders (Gajbhiye et al., 2021; Roja et al., 2018). Avoiding such postures, though, is difficult due to the inherent demands of floor tiling work. While automation has been explored for floor tiling, it remains challenging for tasks that require direct human involvement (Alzuheri et al., 2010; Hunter, 2001). Robotic systems developed for floor tiling remain rudimentary, having challenges with accuracy, adaptability to different environments, and operational consistency (De Hong Jung and Schwartz, 2014; Liu et al., 2018; Wang et al., 2021). Thus, integrating wearable technologies, such as occupational exoskeletons, presents a potential solution for controlling WMSDs in floor tiling.

Back-support exoskeletons (BSEs) are designed to reduce biomechanical demands on the low back by providing assistive forces or moments around the hips or low back (Toxiri et al., 2019), thus augmenting and supporting the physical capabilities of a worker (ASTM, 2020).

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Systematic reviews have highlighted the potential of BSEs to reduce physical demands across a variety of occupational tasks involving repetitive bending and lifting (Bär et al., 2021; Kermavnar et al., 2021). Given typical postural requirements while performing flooring tasks, BSEs are of particular interest here. A recent survey supported that the construction industry is open to adopting BSEs to reduce WMSD risks and improve performance (Gutierrez et al., 2024). Further, passive BSEs demonstrate clear potential to reduce physical demands on the back during tasks involving non-neutral trunk postures. For example, BSE use can reduce back muscle activity by up to 40 % during tasks that require prolonged trunk bending (e.g, Bosch et al., 2016; Koopman et al., 2019; Madinei et al., 2020b). However, the magnitude of these beneficial effects can vary depending on the task (Alemi et al., 2020). In some cases, BSEs may even lead to adverse effects, such as discomfort, slower task completion, or increased muscle activity (Luger et al., 2023), highlighting the importance of an effective match between BSE designs and specific job requirements.

Despite the potential of BSEs, there are no comprehensive studies evaluating their effectiveness for specific construction tasks, particularly floor tiling. Therefore, we aimed to assess the effects of BSEs on physical demands associated with floor tiling. We anticipated beneficial effects of passive BSEs, since several studies have indicated that BSE use can reduce the physical demands on the back during trunk forward bending and related tasks (Alemi et al., 2020; Goršič et al., 2021; Koopman et al., 2019). While our immediate goal was to evaluate how different BSEs affect physical demands, task performance, and usability aspects during floor tiling work, our findings could also guide more effective future implementations of exoskeletons for other flooring work in construction or otherwise.

## 2. Methods

### *2.1. Participants*

A convenience sample of 18 participants (9 males and 9 females) completed the study and were recruited from the local university and community using university listservs and posted flyers. Eligibility criteria required participants to be aged 18–60 years and with no history of low back injury, surgery, or musculoskeletal disorders in the past 12 months (which was confirmed through self-report). To ensure device fit and proper sensor placement with BSE use, participants were also required to be at least 165 cm tall and have a waist size of 66–117 cm. These criteria were stated on the recruitment flyer, confirmed through email communication with interested individuals, and included in the written consent document. The mean (SD) age, body mass, stature, and waist circumference were as follows: 27.2 (5.1) years, 85.8 (8.7) kg, 182.9 (6.4) cm, and 90.3 (6.0) cm for males; and 24.4 (5.9) years, 65.8 (10.6) kg, 170.1 (4.8) cm, and 85.7 (5.7) cm for females. Among all participants, 17 reported being right-handed, while one reported being left-handed. Our study adhered to the tenets of the Declaration of Helsinki, and the study protocol was approved by the Institutional Review Board at Virginia Tech (IRB# 23–024). Prior to the training session, written informed consent was obtained from all participants.

### *2.2. Task simulations*

Two tasks, *tiling* (installing tiles) and *grouting* (filling the spaces between tiles), were simulated in a laboratory setting using commercially available materials to replicate the typical biomechanical demands encountered in floor tiling work. The setup included porcelain tiles, premixed mortar, spacers, and premixed grout. Participants worked on 122 cm × 122 cm (48" × 48″) paperboard sheets, allowing us to reuse most tiles. For each trial of tiling and grouting, the working area was a 122 cm × 61 cm (48" × 24″) region (half of the paperboard sheet), which had chalked margin lines to ensure straight tile placement. Participants used 4.8 mm (or 3/16″) spacers to maintain consistent gaps between tiles. This approach ensured a consistent task area, while the number of tiles varied based on tile size (see details below): four large tiles or eight small tiles. During the tiling simulation, participants spread mortar on the paperboard sheet using a notched trowel, then lifted and positioned the tiles along pre-chalked margin lines. In the subsequent grouting simulation, participants applied grout to the spaces between pre-installed tiles using a rubber float and cleaned excess grout with a sponge. Participants were allowed to choose either a kneeling or stooping posture to perform the tasks, however all the participants opted to perform the tasks kneeling (Fig. 1). During both tiling and grouting tasks, participants wore minimal clothing on their torso and were provided with flooring knee pads (Model# KB-KP-100; Kobalt Ultra-Light Knee Pads; Lowe's, NC, USA) to minimize knee discomfort.

### *2.3. Experimental design and procedures*

All participants completed an initial training session (~1.5 h) and a subsequent experimental session (~3.5 h) on separate days within a week. During the training session, a member of our research team (AU, MR, or AO), who had previously been trained by professional tilers, demonstrated each step involved in floor tiling work. For tiling, demonstrations included spreading premixed mortar with a notched trowel and then lifting and positioning the tiles along pre-chalked margin lines. For grouting, the demonstration included applying grout between tiles, scraping off excess grout with a rubber grout float, and cleaning any residual grout using a sponge and water.

After demonstrating all the steps and addressing any questions, participants practiced tiling and grouting with both tile sizes (see below), starting without a BSE. During this practice, we provided guidance until both the participants and research team members were confident in the participant's skills. After completing a few tiling and grouting trials without any BSEs, participants were asked to try different support levels offered by each BSE. Participants selected a support level they deemed most suitable for both tiling and grouting (Appendix A; Figure A.1). They could change their choice of support level during the training session, but the selected level remained unchanged during the experimental session. During training, participants also practiced tiling and grouting tasks while wearing each BSE until they felt confident using the devices. As part of the training, participants were familiarized with the scales used for the subjective questions. For the Borg CR-10 scale (Borg, 1998), participants performed a 'wall sit' to their maximum endurance, providing intermittent ratings of perceived exertion (RPE) in their thighs every 10 s using this scale, until they reached a rating of 10. Participants were also familiarized with a balance rating scale (see below). Specifically, they completed a one-leg stand with their eyes closed, giving intermittent balance ratings until they needed to place their other leg on the floor (Schieppati et al., 1999). Although participants spent most of their time in kneeling postures during the simulation, we were interested in assessing perceived balance because they frequently moved and reached for different tools.

In the experimental session, each participant completed the simulations under 12 experimental conditions (3 *Interventions* × 2 *Tile sizes* × 2 *Task types*). The three *Intervention* levels were: 1) an exosuit BSE – HeroWear Apex-2 (HW; HeroWear, Nashville, USA); 2) a rigid BSE – Laevo Flex (LV; Laevo, Delft, Netherlands); and 3) the no device (ND) or control condition. Both BSEs are designed to fit the human body on the dorsal and ventral sides (Fig. 2), and HW and LV were selected based on evidence of their efficacy in alleviating physical demands in the low back region during activities involving prolonged and repetitive trunk flexion and similar postures (Goršič et al., 2021; Refai et al., 2024; Roentgen et al., 2024). Two *Tile size* levels were included—small (1.6 kg, 30.5 cm × 30.5 cm or 12" × 12″) and large (3.2 kg, 61 cm × 30.5 cm or 24" × 12")—representing common sizes used in U.S. residential construction. The two *Task types* were tiling vs. grouting. We counterbalanced the presentation order of *Intervention* conditions using 3 × 3 balanced Latin Squares, and within each *Intervention* condition we


**Fig. 1.** Illustrations of the tasks simulations: (a) tiling using the HeroWear Apex (HW); (b) grouting using the Laevo Flex (LV); and (c) tiling using No Device (ND).

alternated the order of *Tile size* conditions across participants. The order of *Task type* remained consistent for all participants, with tiling always preceding grouting. To minimize the development of fatigue, participants were provided with short rest breaks (~2 min) after each trial and at least one longer break (~10 min) around the midpoint of the experimental session; they were offered the option to take additional breaks at any time.

### *2.4. Instrumentation, data collection, and data processing*

Raw surface electromyography (EMG) was captured for the trunk extensor muscles using a telemetered system (TeleMyo Desktop DTS, Noraxon, AZ, USA). After skin preparation, pre-gelled, bipolar, disposable, dual EMG Ag/AgCl electrodes (20 mm interelectrode distance, Noraxon, AZ, USA) were placed bilaterally over two accessible trunk extensor muscles from the erector spinae muscle group—iliocostalis lumborum (IL) and longissimus thoracis (LT)—following earlier recommendations (Criswell, 2010; Hermens et al., 1999). The selected muscles were chosen for their relevance to prolonged or repetitive trunk bending tasks (Aspden, 1992; Henson et al., 2019; Mansfield and Neumann, 2019) and accessibility when participants were wearing the BSEs used in this study. A 3.5 mm thick foam-coated adhesive tape (MED-5634, Avery Dennison, OH, USA) was affixed over the EMG electrodes to prevent any potential movement of the electrodes on the skin.

Before performing the floor tiling tasks, participants completed two trials of maximum voluntary isometric contractions (MVICs) for their trunk extensor muscles, with at least a 60 s interval between the two trials. For the MVICs, participants were in a prone position on a Roman Chair for back extension; they extended their trunk against external manual resistance, while non-threatening verbal encouragement was provided. During the MVICs and experimental trials, raw EMG signals were recorded at a sampling rate of 1.5 kHz, and were subsequently band-pass filtered (25–450 Hz, 4th-order Butterworth, bidirectional). Root-mean-square values were obtained using a sliding window of 400 ms to create linear envelopes. Subsequently, processed EMG signals were normalized relative to the corresponding maximum values obtained during the MVICs. Two outcome measures were obtained—median (50th percentile) and peak (95th percentile) normalized EMG (nEMG) levels, respectively reflecting the typical and the maximum activity of trunk extensor muscles required during the tasks. Time-stamped videos were recorded for all experimental trials.

Upon completing each experimental trial, participants provided ratings of perceived exertion (RPEs) for the shoulder, low back, and leg, using a paper-based Borg CR-10 scale (Borg, 1998). For bilateral body parts, ratings were collected from the dominant side, and participants were encouraged to use fractional scores. Participants also rated their overall discomfort (resulting from their physical interaction with a BSE) on a 10-point analogue visual scale (ranging from 0 = no discomfort to 10 = extreme discomfort). To assess the cognitive demands associated with BSE use, we used specific subscales of NASA TLX (Hart, 1986) to record their task performance, effort, and frustration. Temporal and

**Fig. 2.** Participants wearing (a) HeroWear Apex (HW) and (b) Laevo Flex (LV) exoskeletons, a demonstration of how both BSEs fit the body on the dorsal and ventral sides.

physical demands were excluded due to the nature of the tasks and the use of RPEs. We recorded perceptions of balance on a scale of 0–10, where 0 indicated being perfectly balanced and 10 indicated being fully off balance (about to fall). To capture responses for each perceived measure, participants were given a hard copy of the questionnaire (see Appendix B.1) that included the relevant scale for each question. We read and explained each question aloud to ensure consistency. Participants then selected a number of their choice from the relevant scale. For all trials, task completion time (in seconds) was measured using time stamps from the video recording, with the start determined when the participant knelt on the floor to begin the task and the end when they completed the task and began to stand.

After completing all trials with a given BSE, participants answered questions regarding device usability and provided open-ended feedback on their perceptions (see Appendix B.2 for the complete set of questions). At the end of the experimental session, participants were also asked to share their general impressions of both BSEs, including their preferred intervention condition and their experiences performing the tasks with and without the BSEs (see Appendix B.3 for the complete set of questions).

### 2.5. Statistical analysis

Separate three-way, repeated measures analyses of variance (ANOVAs) were used to assess the main and interaction effects of *Intervention*, *Tile size*, and *Task type* on each of the objective (median and peak nEMG, and completion times) and subjective (RPEs, perceptions of BSE usability, overall discomfort, balance, performance, effort, and frustration) outcome measures. *Biological sex* and the order of trials were both included as blocking variables (order effects were not found to be statistically significant in any case). Parametric model assumptions were assessed, and median nEMG values for the right IL and peak nEMG values for both the right IL and left LT were transformed logarithmically to obtain a normal distribution of model residuals. Summary results were subsequently back-transformed to their original scales for presentation purposes. Significant main and interaction effects were followed by post-hoc pairwise comparisons using Tukey's HSD test and simple-effects tests, respectively, where relevant. EMG recordings from the first participant were excluded from data analysis due to changes in the data collection procedure afterward. Initially, a different setup was used for MVIC trials, which was later standardized for all subsequent participants. Additionally, 15 trials (among 216 total) were identified and excluded from EMG analysis due to obvious data collection errors, such as electrode movement, which occurred due to the extreme range of motion required for floor tiling simulations.

JMP Pro 16 (SAS, Cary, NC) was used to conduct the ANOVAs, using the restricted maximum likelihood (REML) approach. Statistical significance was determined when $p < 0.05$, and effect sizes were quantified using partial eta squared ($\eta_p^2$). Graphs are generated from the original data to illustrate our findings. Given the aims of the study, the presentation of results emphasizes the main and interaction effects of *Intervention*, whereas the effects of task-specific factors are only briefly noted.

## 3. Results

ANOVA results for median (50th percentile) nEMG values are provided in Table C.1 of Appendix C, while results for peak (95th percentile) nEMG values are provided in Table C.2. ANOVA results for RPE values, mental workload, perceived balance, general discomfort, and completion time are provided in Tables C.3 and C.4. Subsequent subsections summarize each of these groups of results in more detail.

### 3.1. Median nEMG

#### 3.1.1. Iliocostalis lumborum (IL)

*Intervention* had significant main effects on the median nEMG of the bilateral IL, with both values being higher when using HW vs. either LV or ND (Fig. 3). Interaction effects of *Tile size* × *Task type* and *Task type* × *Biological sex* were also significant for median nEMG of the left and right IL, respectively (Figure C.1). *Tile size* had a significant simple effect on left IL median nEMG during tiling, with the large tile size yielding higher levels than the small tile size. Male participants had higher median nEMG for the right IL during tiling compared to grouting, though the difference between tasks was not significant for females.

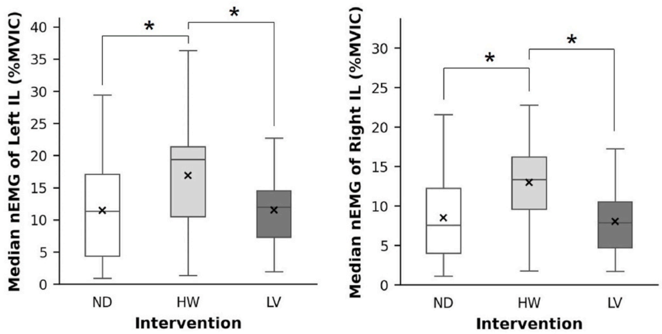


**Fig. 3.** Intervention main effects on median nEMG values of the left and right iliocostalis lumborum (IL). The symbol * (here and below) indicates a significant paired difference between conditions. ND= No Device (control condition); HW=HeroWear Apex; LV = Laevo Flex.

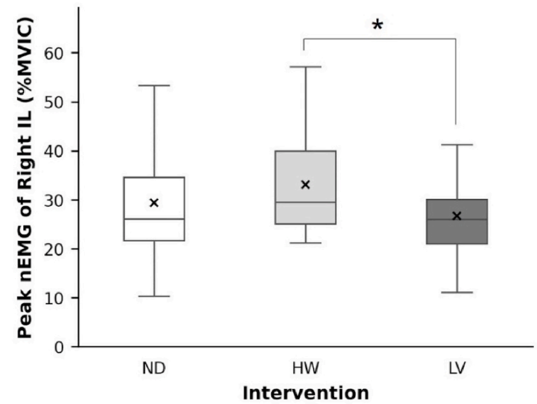


**Fig. 5.** Intervention main effect on peak nEMG values of the right iliocostalis lumborum (IL).

### 3.1.2. *Longissimus thoracis (LT)*

Main effects of *Intervention*, *Tile size*, and *Task type* were significant only on median right LT nEMG. Using HW led to the highest level of median nEMG for this muscle compared to both LV and ND (Fig. 4). Median right LT nEMG values were higher when using large vs. small tiles and during tiling compared to grouting (Figure C.2).

## 3.2. *Peak nEMG*

### 3.2.1. *Iliocostalis lumborum (IL)*

The main effect of *Intervention* on peak right IL nEMG values was significant, with higher values found for HW compared to LV (Fig. 5). Peak nEMG values for both the left and right IL were significantly affected by the interaction effect of *Task type* × *Biological sex* (Figure C.3). *Task type* had a significant simple effect on peak nEMG values of both the left and right IL for only male participants, though pairwise comparisons were not statistically significant.

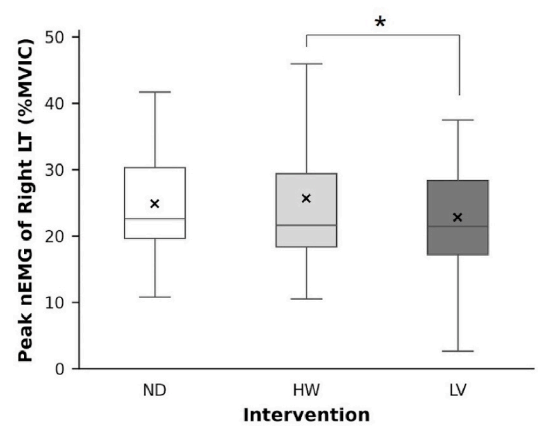


**Fig. 6.** Intervention main effect on peak nEMG values of the right longissimus thoracis (LT).

### 3.2.2. *Longissimus thoracis (LT)*

Peak right LT nEMG was significantly affected by the *Intervention* main effect (Fig. 6) and the *Tile size* × *Task type* interaction effect (Figure C.4). Specifically, using HW yielded higher peak right LT nEMG values than using LV. Peak right LT nEMG values were higher during tiling compared to grouting, but only when using the large *Tile size*.

## 3.3. *Perceived exertion, mental workload, overall discomfort, and completion time*

*Intervention* × *Tile size* interaction effects were significant for shoulder RPE, overall discomfort, perceived balance, perceived task performance, and completion time. *Intervention* had a significant simple effect on shoulder RPE when using the large tile size ($p = 0.02$) but pairwise comparisons were not statistically significant. Although *Tile size* had a significant simple effect on shoulder RPE when using HW and LV, post-hoc analysis revealed significant differences only for LV, for which participants reported higher shoulder RPE with small vs. large tile size (Fig. 7). *Tile size* also had a significant simple effect on other subjective measures. When using HW, participants reported higher overall discomfort with small vs. large tile size. For LV, participants reported higher perceived imbalance and a higher sense of failure in perceived task performance using small vs. large tile size (Fig. 8).

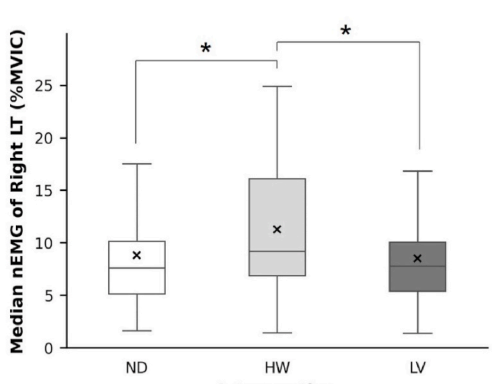


**Fig. 4.** Intervention main effect on median nEMG values of the right Longissimus Thoracis (LT).

We also found significant main effects of *Task type* on perceived frustration and perceived task performance. Participants reported higher frustration and a greater sense of failure in perceived task performance for grouting vs. tiling. The overall mean (SD) task completion time was 7.2 (2.7) minutes, and there was no significant main effect of *Intervention* on completion times using either small or large tile sizes, and there were no significant differences in completion times across *Interventions* for a given *Tile size* (Figure C.5). However, *Task type* and *Biological sex* had significant main effects on completion time, with females having longer completion times compared to males, and tiling requiring more time compared to grouting.

## 3.4. *BSE preference, usability, and general feedback*

A plurality of participants (44 %) preferred the LV, followed by ND (31 %), and the fewest (25 %) preferred the HW. Specific feedback

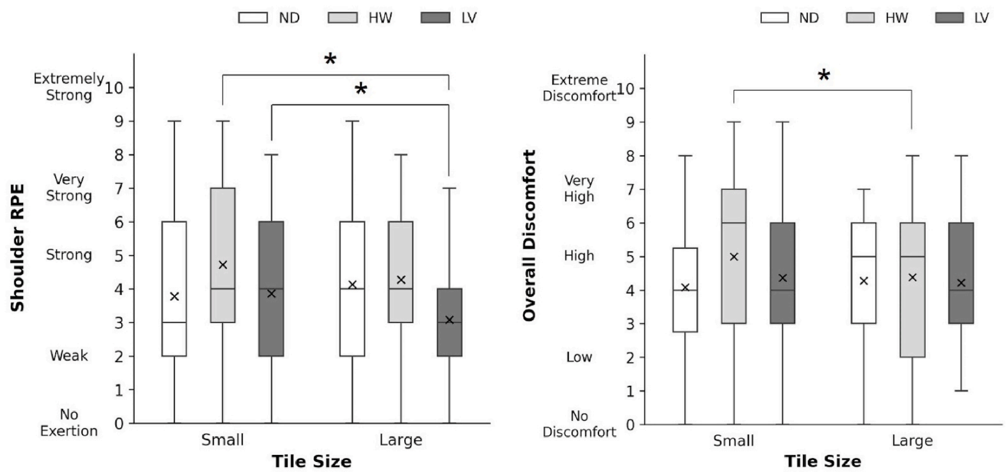


**Fig. 7.** Intervention x Tile Size interaction effects on shoulder ratings of perceived exertion (RPE; left) and overall discomfort (right).

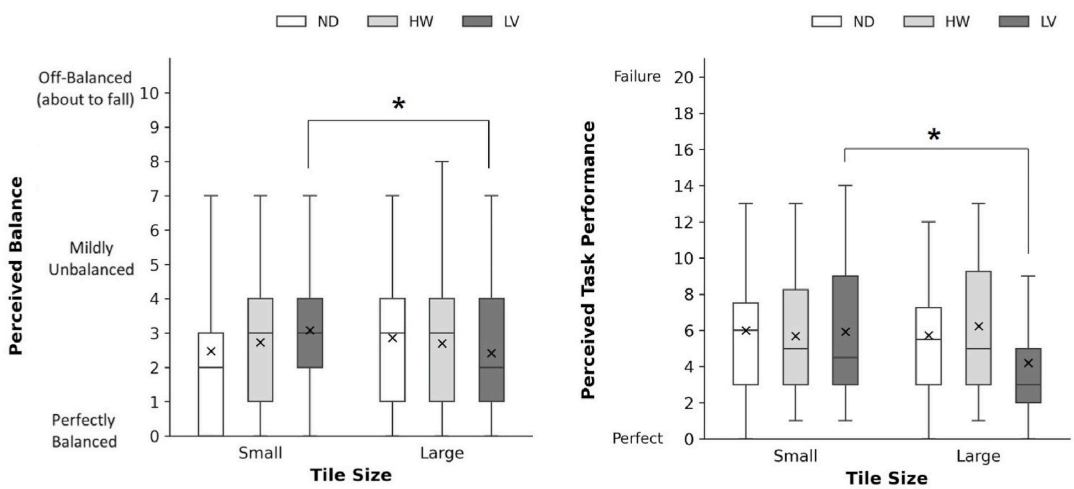


**Fig. 8.** Intervention x Tile Size interaction effects on perceived balance (left) and perceived task performance (right).

indicated that HW use increased frustration and required additional time for adjustments. Roughly a quarter (28 %) of participants found both BSEs helpful, offering comments such as: *I feel less load on my back. It was less effort doing the task with BSEs*. Yet, another 28 % reported negative experiences, such as: *I think the exoskeleton is making me tired, pushing the muscles, the legs. It makes me very tired*. Many of the participants (~44 %) reported mixed views on BSEs, mentioning that although the BSEs provided support, the devices also restricted movement. One participant explained: *With the exoskeleton, I felt a bit easier to perform the task as in terms of load, how much I was getting the load. But it was a bit restraining when compared to no exoskeleton*. Participant feedback on each BSE varied, with 28 % liking HW, 28 % disliking it, and 44 % expressing mixed opinions. For LV, 33 % of participants were evenly split among liking, disliking, and having mixed opinions. Common reasons for disliking the BSEs included discomfort and movement restrictions, with 17 % of participants reporting skin irritation associated with HW use. Some (17 %) participants also reported that HW made their movements easier, though more (33 %) indicated this same feedback for LV. In contrast, 39 % stated that HW made their movements harder, and most participants (56 %) reported the same for LV. Additionally, 44 % indicated that movement ease with HW depended on the type of movement, compared to only 11 % for LV. Roughly 39 % of participants reported changes in their natural movements or movement timings with the HW, compared to nearly 72 % who noted similar problems with LV. Finally, about 83 % of participants indicated that both BSEs became more familiar with continued use.

## 4. Discussion

We investigated the effects of two different BSEs on physical demands, task performance, and usability aspects during medium-high fidelity tiling and grouting tasks, involving different tile sizes and task types. Our primary aim was to assess whether wearing BSEs reduced physical demands on the low back compared to no device (ND). However, our findings did not support this expectation, as indicated by multiple outcome measures, including trunk extensor muscle activity, perceived exertion, and overall discomfort. Our results instead showed that using the rigid BSE (LV) did not meaningfully change muscle activation levels in the IL or LT muscles, and the exosuit or soft BSE (HW) caused higher muscle activation levels compared to both ND and the LV. In parallel, subjective outcomes including low-back RPE, perceived task performance, and overall discomfort were not improved when using either BSE. In addition to our main focus on BSE effects, we also examined the effect of task-specific factors on physical demands to confirm that these manipulations created distinct demands, which in turn can help guide future experimental designs. The following sections discuss the effects of BSEs on muscle activity and subjective outcomes, as well as how task-specific factors influenced physical demands.

### 4.1. Effects of BSEs on muscle activity and subjective outcomes

Neither of the BSEs reduced muscle activity or improved subjective outcomes during the simulated tiling and grouting tasks, which contrasts with some relevant findings from earlier studies. Specifically, the LV here did not affect IL and LT muscle activation levels, while the HW increased activation levels in both muscle groups (see Figs. 3–6). Earlier studies have determined BSE effects during lifting, lowering, or stooped postures (Goršič et al., 2021; Kang et al., 2023; Kim et al., 2024; Madinei et al., 2020b; Nuesslein et al., 2023; Schnieders et al., 2023), making direct comparisons difficult. Nonetheless, while these studies typically found a reduction in muscle activity with BSE use, some showed increased muscle activity. For example, Madinei et al. (2020b) reported higher trunk extensor muscle activity when using BSEs during below-floor-level work, wherein participant postures involved substantial trunk flexion, similar to those in floor tiling. Importantly, our study closely replicated actual floor tiling, requiring participants to complete various steps in tiling and grouting tasks while maintaining physically demanding postures. This approach differs from studies previously reported that often focused on isolated task segments. Our results, in fact, align more closely with industrial field studies. In these studies, BSE use often caused minimal reductions or even increases in muscle activity (Amandels et al., 2019; Motmans et al., 2019).

Previous work indicates that BSEs can be less effective during asymmetric tasks (Kranenborg et al., 2023; Madinei et al., 2020a; Raghuraman et al., 2024), potentially explaining why our results, stemming from tasks that inherently included trunk lateral bending and rotations, did not yield the expected reductions in muscle activity. BSEs typically provide support based on the trunk-thigh angles in the sagittal plane (Baltrusch et al., 2018, 2019). However, differences in BSE design—such as variations in mechanical structures, support mechanisms, and materials—could influence how effectively these devices alleviate physical demands. The two BSEs used here differed in their support mechanisms: HW used elastic elements to generate torque and delivered without rigid structures whereas LV used gas springs to generate torque, which is delivered via rigid structures. These differences, in turn, may have affected whether each BSE provided consistent support during asymmetric movements, with HW offering greater flexibility while also resulting in variable force delivery depending on posture. Indeed, tiling work involves complex combinations of movements (e.g., simultaneous axial rotation, flexion, and/or lateral bending). Future research should investigate how specific BSE designs affect the level of support provided in asymmetric postures, with a focus on understanding how specific postural deviations affect the engagement and effectiveness of the muscle groups supported by the BSE.

Although BSEs did not significantly affect any of the subjective outcomes we obtained—such as shoulder RPE, overall discomfort, perceived balance, or task performance—the relatively lower preference for HW may be attributed to participants perceiving it as inefficient and insufficient for floor tiling. Participant feedback highlighted that while both BSEs provided support, these devices also increased their frustration and restricted their movements. The latter adverse effects were likely due to the added mechanical constraints imposed on hip and low back movements, aligning with previous studies that identified similar limitations associated with BSEs (Kermavnar et al., 2021; Riemer and Wischniewski, 2023).

### 4.2. Role of task-specific factors on muscle activity and subjective outcomes

We found significant differences in muscle activity between handling small and large tiles, as well as between tiling and grouting tasks (Figures C.1–C.4). Specifically, higher muscle activity was required when using large vs. small tiles, consistent with many previous reports of increased muscle activity with heavier loads (e.g., Aghazadeh et al., 2012; Chen et al., 2013; Kamarudin et al., 2014). Higher muscle activity in the tiling task vs. grouting may be attributed to the relatively higher precision demands of placing tiles, as opposed to grouting, performed on already-placed tiles. Similarly, several prior studies reported higher muscle activity during tasks requiring greater precision(Alabdulkarim et al., 2019; Joseph et al., 2014; Mehta et al., 2015). Interestingly, despite lower muscle activity and shorter completion times during the grouting task (Figures C.2 and C.5), participants reported ~13 and 21 % higher perceptions of failure and frustration, respectively. These adverse perceptions may be due to the detailed nature of grouting, such as removing grout from tiles and cleaning it using a rubber sponge, which we suspect increased cognitive demands.

Furthermore, participants reported higher shoulder RPE, overall discomfort, and perceived task failure (Figs. 7 and 8) despite lower trunk extensor muscle activity (Figures C.1 and C.2) with small vs. large tiles. One possible explanation is that it took longer to complete tasks using the small tiles across all intervention conditions (Figure C.5), since a more prolonged task duration is associated with increased subjective discomfort and frustration (Kee and Lee, 2012; Szalma et al., 2004). Additionally, while EMGs were recorded only for the trunk extensor muscles, participants likely engaged other muscle groups (e.g., shoulders, arms) during the tasks, and managed potential challenges (e.g., movement restrictions, task precision requirements). We believe these aspects help to explain why participants experienced an increased overall frustration using small vs. large tiles, and, more broadly, the disconnect we found between BSE effects on muscle activity and subjective perceptions. Overall, our outcomes emphasize the importance of evaluating BSEs for a specific task of interest, rather than for more generic task demands, while considering a range of actual task parameters and a range of outcome measures, to help determine the most effective applications of exoskeletons.

### 4.3. Limitations

Our study had a few limitations that should be acknowledged. First, participants were predominantly young (mean age = 27.5 years), which may not represent the broader age range of actual flooring workers, whose mean age is approximately 40 years (Data USA, 2022). Therefore, caution is necessary when generalizing these results, especially for older workers. Second, most participants wore minimal clothing on the upper body to allow access for EMG sensors. Since BSEs are typically worn over clothing, our approach might have caused unrealistically high localized discomfort, due to direct contact between the BSE and the skin. Third, to ensure the feasibility of training and data collection within a reasonable timeframe, we provided participants with a limited familiarization time compared to the durations recommended by some manufacturers. A longer adaptation period may have influenced biomechanical and perceived outcomes. Fourth, our participants were not experienced tiling workers. Consequently, the applicability of these findings to other user groups may be limited. Fifth, while the task simulations were realistic and extended in duration, they did not account for the effects of prolonged or frequent BSE use (e.g., over full workdays or across multiple workdays). Future studies might reveal different outcomes when BSEs are worn for more extended periods. Finally, despite our attempts to achieve reasonable floor tiling simulations, the study was conducted in a laboratory environment, lacking factors such as environmental conditions or dynamic events found on actual construction sites. These potential influences need further investigation, particularly given evidence suggesting that lab-based results may not always align with real-world conditions and demands in the construction industry (Bennett et al., 2023). Future studies should also incorporate advanced modeling approaches to better understand spine stability during BSE use. Examining the interplay between task asymmetry, BSE assistance, and muscle coactivation may provide useful findings for optimizing BSE design and implementation.

## 5. Conclusions

Construction tasks such as floor tiling require workers to maintain physically demanding, non-neutral postures for extended durations, increasing the risk of WMSDs. Due to the impracticality of modifying working postures, alternative intervention approaches are of growing interest in such cases. We examined the effects of two BSEs, one rigid (LV) and one soft (HW), on physical demands, task performance, and usability aspects during medium-high fidelity simulations of tiling and grouting with varying tile sizes. Using the LV did not affect muscle activity, while HW increased muscle activity vs. either the LV or no device (ND). Our results emphasize the importance of including specific conditions or simulations when considering BSE use in practice, as the BSEs used in this study did not effectively alleviate the physical demands of floor tiling work. Given the differing outcomes found between two distinct BSEs, further investigation is warranted to explore how different BSEs affect diverse outcomes. Furthermore, our results indicate that BSE effectiveness can vary depending on the BSE used (e.g., soft vs. rigid structure) and the specific task conditions, which reinforces the need to tailor BSE applications. Adopting a more task-specific approach to BSE selection and implementation could enhance the benefits of this technology, potentially leading to wider adoption and more effective mitigation of WMSDs in the construction industry, whether for tiling specifically or for other tasks involving prolonged/repetitive trunk flexion.

## CRediT authorship contribution statement

**Ahmad Raza Usmani:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mohammad Sadra Rajabi:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Aanuoluwapo Ojelade:** Writing – review & editing, Methodology, Conceptualization. **Sunwook Kim:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Carisa Harris-Adamson:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Alan Barr:** Writing – review & editing, Methodology, Conceptualization. **Maury A. Nussbaum:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors received financial support provided by a grant from The Center for Construction Research and Training.

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## Appendix A. Supplementary data

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