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Rigid and soft back-support exoskeletons affect biomechanical and perceptual demands, but in different ways, during simulated shingle installation

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ABSTRACT

Passive back-support exoskeletons (BSEs) are promising but underexplored interventions to reduce the high physical demands of roofing shingling. Eighteen participants performed simulations of shingle installation tasks under 12 different conditions. These conditions included all combinations of three BSE levels (Rigid, Soft, and no BSE), two task orientations (peak-facing vs. side-facing), and two roof slopes (18° vs. 26°). Using the rigid BSE significantly reduced lumbar muscle activation (11–17%) compared to no BSE, without altering trunk flexion. In contrast, the soft BSE reduced trunk flexion (~4%) without altering lumbar muscle activation. Both BSEs reduced perceived low back exertion (~16%); however, the rigid BSE increased leg discomfort (~26%), and the soft BSE increased shoulder exertion (~19%). Our results suggest that using BSEs can be beneficial for shingle installation tasks but also highlight the importance of considering device-specific biomechanical benefits and associated trade-offs to ensure effective application.

1. Introduction

Roofing is among the most physically demanding trades in the construction industry (Fredericks et al., 2005; NRCA, 2022). More than 50% of roofing workers (roofers) annually experience at least one work-related musculoskeletal disorder (WMSD); they also had the second highest rate of low back injuries, with an incident rate ~40% higher than the mean across other construction subsectors (Welch et al., 2009; NSC, 2024; BLS, 2024). This high risk of back-related WMSDs among roofers is largely attributed to the inherent nature of roofing work, which requires roofers to spend over 75% of their working hours in physically strenuous postures such as prolonged and repetitive trunk flexion, as well as in kneeling, crouching, or crawling (Dong et al., 2010; CPWR, 2018). Notably, a one-year longitudinal study found that roofers with WMSDs were eight times more likely to leave the roofing trade than those without WMSDs, primarily due to physical difficulties in performing roofing tasks (Welch et al., 2010).

Roofing tasks, shingling in particular, present unique ergonomic challenges due to the physical demands of working on sloped surfaces. Performing shingling tasks on steeper slopes (e.g., 30°) is associated with increased activation of lumbar and knee extensor muscles, likely due to forward flexion and more constrained hip and knee postures (Wang et al., 2017; Dutta et al., 2020; Breloff et al., 2019). Steeper slopes also increase demands for balance control (Simeonov et al., 2009; Lin and Nussbaum, 2012; Breloff et al., 2020b).

Various ergonomic interventions have been introduced to reduce physical demands in roofing. Material handling systems, such as ladder hoists, platform lifts, and powered carts or loaders, are commonly used to move shingles and equipment onto rooftops. While these aids can reduce the physical burden associated with manual lifting and carrying (HSE, 2012; Mungroo and Choi, 2018; Zhang et al., 2021), they primarily support material staging and do not assist with shingle installation or trunk-intensive tasks that involve prolonged and repetitive trunk flexion on sloped surfaces. More recently, robotic and semi-automated systems have been applied in roofing to assist with tasks such as shingle placement (RCS, 2024) and nail driving (McAlpine, 2019). However, these technologies are still in early development, are often costly, and appear not yet scalable or adaptable to the complex geometries and

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dynamic conditions of residential roofing sites.

One emerging approach to mitigate occupational physical demands is the use of passive exoskeletons (e.g., Nussbaum et al., 2019; Bär et al., 2021; De Bock et al., 2022). Back-support exoskeletons (BSEs), in particular, provide external supportive torque to the low back and hips, and these devices can reduce physical demands during tasks requiring prolonged or repetitive trunk flexion (e.g., Kermavnar et al., 2021; Zhu et al., 2021; Babalola et al., 2023; Moreira et al., 2025). The magnitude of such benefits, though, varies with task-specific demands and BSE designs (e.g., Alemi et al., 2020; Schwartz et al., 2021; Reimeir et al., 2023). Existing commercial BSEs are available in different designs: rigid BSEs, which use structured frames and spring-loaded mechanisms for supportive torque generation; and soft BSEs (or exosuits), which use textile-based elastic elements to generate supportive force while maintaining flexibility (Ali et al., 2021). These design approaches differ both in their mechanical structures and in how they interact with the body, leading to distinct biomechanical effects depending on the wearer's postures and tasks (Schwartz et al., 2021; Refai et al., 2024). For instance, Schwartz et al. (2021) found that using rigid BSEs increased low back muscle activation at 75–100% of full trunk flexion, while using soft BSEs reduced muscle activation at 50–75%. These results emphasize the importance of selecting designs that align with task-specific demands.

Despite the growing body of research on BSEs in various occupational settings (e.g., Golabchi et al., 2023; Okpala and Nnaji, 2024; Gonsalves et al., 2024; Kim et al., 2025), we are not aware of any evidence related to BSE use for roofing work. The goal of our current study was to evaluate the effects of using BSEs on biomechanical demands and subjective responses during roof shingle installation. We focused on this specific task, given that it is a physically demanding component of roofing. We hypothesized that using BSEs would reduce biomechanical demands and perceived exertion during shingle installation. Given that rigid and soft BSEs differ in their support mechanisms, we further hypothesized that these effects would differ between the rigid and soft BSEs.

2. Methods

2.1. Participants

Eighteen participants (14 males and 4 females) completed the study and were recruited from the local university and community. Roofing experience was not considered for inclusion, and none of the participants reported such experience. There were no restrictions to participation related to biological sex, though relatively few females volunteered. Respective means (SDs) of age, stature, and body mass were 26.7 (5.5) years, 173.9 (6.5) cm, and 69.9 (9.6) kg. Inclusion criteria required participants to be between 18 and 60 years and to self-report no musculoskeletal problems within the previous 12 months at the time of recruitment. To ensure proper fit of the BSEs used, only individuals taller than 160 cm and with a waist circumference of 66–116.8 cm were included. Participants provided written consent prior to any data collection, and the study procedures were approved by the Institutional Review Board at Virginia Tech.

2.2. Experimental tasks, design, and procedures

A repetitive shingling task was simulated in a laboratory environment to examine the effects of two types of BSEs (see below) under different shingling conditions. Participants performed trials of the shingling task on a platform (Fig. 1), with each trial requiring approximately 1 min. The task was completed using architectural shingles (98.5 $\times$ 33.5 cm, 1.8 kg) and a pneumatic nail gun (mass = 2.7 kg). They were instructed to place six shingles in sequence, guided by numbered markers (arranged in three rows and two columns). For each shingle, participants performed four simulated nailing motions by tapping the tip of the nail gun on the shingle while holding the trigger (see Fig. 1). At the beginning of each trial, shingles were positioned at the top center of the working area, with the nail gun placed on the right. Four nailing points were indicated on each shingle, and the nail gun was connected to an air hose with nails loaded; however, no air pressure was applied to prevent the nails from firing. To minimize slipping during the trials, anti-slip tape and four courses of shingles were applied to the roof platform on which participants worked.

Participants performed trials of the shingling task in each of four combinations of two task *Orientations* and two roof *Slopes*. The two *Orientations* were peak-facing and side-facing, reflecting whether participants faced toward the roof peak or worked laterally across the roof. These orientations were selected through discussions with roofing experts and our observations of professional roofers using different working methods and postures depending on the shingle installation location (e.g., bottom row vs. middle row). The two roof *Slopes* were 18° (4/12 pitch) vs. 26° (6/12 pitch), representing common roof designs for residential buildings (ICC, 2021).

Participants used two types of BSEs (Fig. 2): one rigid (FLEX, Laevo, Rijswijk, The Netherlands) and one soft (Apex 2, HeroWear, TN, USA). The rigid BSE has a mass of approximately 4.2 kg and consists of upper-body components (e.g., front vest, vest frame, and torso structure) and a hip joint structure (e.g., pelvic frame, actuator spring, and leg pads). The soft BSE is a textile-based BSE (or exosuit) with a mass of approximately 1.5 kg. This device includes upper-body components (e.g., shoulder strap, strap frame, and clutch) and lower-body components (thigh

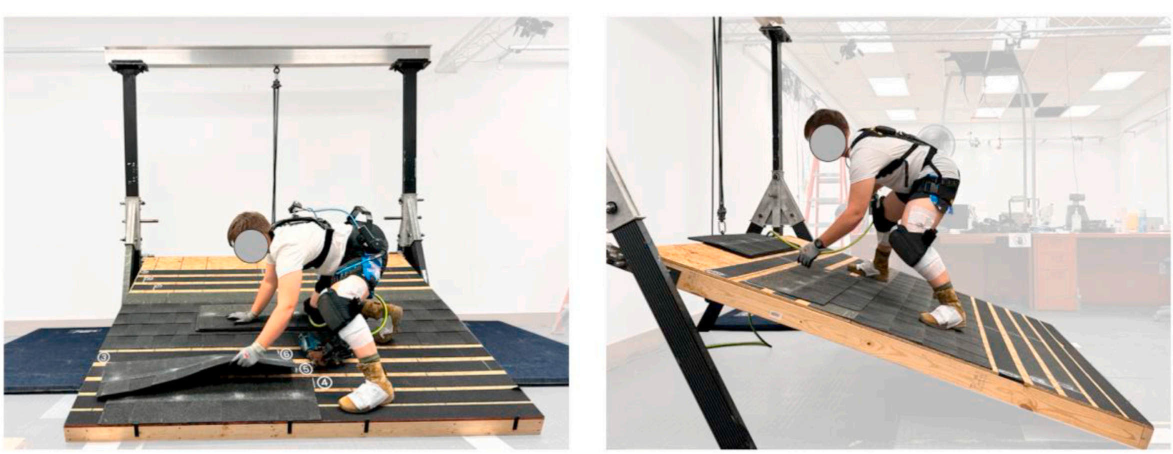

Fig. 1. Simulated shingling tasks being completed in two different task orientations at the 18° slope: (Left) side-facing orientation and (Right) peak-facing orientation.

Fig. 2. The two back-support exoskeletons (BSEs) included in the study: (Left) a rigid BSE, Laevo FLEX and (Right) a soft BSE, HeroWear Apex 2.

sleeves) connected by elastic bands.

Each participant completed a single session lasting approximately 3.5 h, which included preparation and practice (~2 h) followed by task performance (~1.5 h). Knee pads and gloves were provided and were worn by all participants throughout the task performance portion of the session. Participants first received an overview of the experimental protocol. They watched short video clips showing professional roofers performing shingling tasks and then practiced these tasks following demonstrations by the lead author. Participants practiced the shingling trials at least once for both task orientations on the 26° slope (which was used since it posed greater physical challenges than the 18° slope). Participants were next fitted with each BSE according to manufacturer's instructions, which specified the recommended component size and support levels. Lastly, participants selected their preferred support levels after briefly experiencing different levels while completing activities such as shingling trials, trunk flexion, and squatting (selected support levels are summarized in Appendix A).

Participants completed 24 shingling trials, involving two replications of each of the 12 factorial combinations of two *Orientations*, two *Slopes*, and three *Interventions* (i.e., Rigid = FLEX, Soft = Apex 2, and no BSE = control). To minimize the potential for order-related confounding effects, the presentation orders of *Orientation* and *Slope* were each counter-balanced within a given *Intervention*, and the order of *Intervention* was counter-balanced using multiple 3 × 3 Latin squares. Between trials and conditions, brief rest opportunities (~2 min) occurred during experimental adjustments and the collection of subjective outcomes. Participants were also allowed to take additional rest upon request.

During the shingling trials, participants were instructed to remain on the roof platform for all tasks and to maintain specific task orientations. These orientations were determined from observing professional roofers: facing uphill for the middle row and facing sideways for the bottom row. For middle row trials, participants stood on pre-installed shingles and placed three courses of shingles on the left side, followed by three courses on the right side (Fig. 1, Right). For bottom row trials, they placed three courses of shingles on the left side while working on the right side, then moved to the left side and continued placing shingles on the right side (Fig. 1, Left). After completing the first three shingles on the left side, we removed these shingles to prevent slipping. Working posture was not restricted for trials on either of the rows, except for maintaining the required orientation.

2.3. *Instrumentation, data collection, and Processing*

Prior to practicing the shingling task, and after appropriate skin preparation, four EMG electrodes (pre-galled bipolar Ag/AgCl electrodes with a 2 cm inter-electrode distance) were attached over trunk extensor muscles in the thoracic and lumbar regions, following earlier recommendations (Criswell, 2010; Hermens et al., 2000). Specific muscle groups monitored were the bilateral thoracic erector spinae (TES_L and TES_R) and bilateral lumbar erector spinae (LES_L and LES_R). These muscles were selected both because of the task demands (i.e., requiring prolonged and repetitive trunk flexion) and since they were accessible using surface electrodes while wearing either of the BSEs.

To normalize EMG signals, maximum voluntary isometric contractions (MVICs) were completed prior to the shingling trials. During these MVICs, participants exerted and held maximal trunk extension for 3-s while their lower body was secured in a Roman Chair and their upper body was connected to a sufficiently heavy load (~100 kg) via a chest harness. Non-threatening verbal encouragement was provided throughout the MVICs. Participants performed a total of three MVICs with 1-min rest periods between exertions.

During MVICs and each shingling trial, muscle activations were captured at 1500 Hz using a surface electromyography (EMG) system (TeleMyo Desktop DTS, Noraxon, AZ, USA). Raw EMG data were band-pass filtered (20–450 Hz) and then low-pass filtered (5 Hz cut-off frequency, 4th order Butterworth) to create linear envelopes (De Luca et al., 2010). Processed EMG data were then normalized (nEMG) relative to the corresponding maximum values obtained during MVICs. Mean nEMG values during the shingling trials were used as outcome measures (Wang et al., 2017).

Trunk and lower body joint kinematics were monitored during the shingling trials at 100 Hz using an inertial motion capture system (MVN Awinda, Xsens Technologies, Enshede, The Netherlands). Eight inertial measurement units (IMUs) were attached according to the manufacturer's guidelines: one each on the sternum and pelvis, and bilaterally on the upper legs, lower legs, and feet. After attaching the IMUs, a calibration procedure was performed following instructions provided by the Xsens Analyze software (i.e., a 4-s N-pose and a 15-s walk).

Joint kinematic data were low-pass filtered (5 Hz cut-off frequency, 4th order Butterworth), and the standard rotation sequence recommended by the ISB (ZXY; Wu et al., 2002) was used to determine the location of the thoracic spine (i.e., trunk relative to pelvis). Two outcome measures were derived from peak values (95th percentile) in each trial: 1) peak trunk flexion angle with respect to the vertical axis (*trunk flexion*), representing the extreme posture used; and 2) peak included angle between the trunk and thighs (*T-T flexion*), calculated using the bilateral mean of thigh flexion angles, which was used to represent postures associated with greater BSE deformation and potential assistive support.

After completing the two replications in each condition, participants provided ratings of perceived exertion (RPE) for the shoulders, low back, and legs using the Borg (1990) CR-10 scale. They also gave ratings of perceived wearing discomfort (RPWD) for the same body regions using a 100 mm visual analogue scale (VAS), in which 0 mm represented "no discomfort at all" and 100 mm represented "extreme discomfort" (McCormack et al., 1988; Baltrusch et al., 2018). Participants were instructed that RPWD reflected discomfort associated with wearing the BSE, including physical irritation, pressure, or fit-related issues, rather than muscular exertion or fatigue experienced during task performance. For both RPEs and RPWDs, participants provided a single overall rating for bilateral body parts. Perceived whole-body balance was also assessed using a 100 mm VAS, with 0 mm indicating "perfectly balanced" and 100 mm indicating "off balanced" (Schieppati et al., 1999; Usmani et al., 2025). After completing all four conditions using a given BSE, participants rated BSE usability using 7-point Likert scales, ranging from 1 (strongly agree) to 7 (strongly disagree). The usability assessment comprised four questions that addressed (Finstad, 2010): 1) effectiveness (the BSE met my requirements); 2) satisfaction (using the BSE was a frustrating experience); 3) efficiency, in terms of ease (the BSE was easy to use); and 4) efficiency, in terms of time (I spent too much time correcting problems with the BSE). After completing all shingling trials, participants were asked to provide any additional comments and to rank the three BSE conditions in order of preference (BSE preference). A complete listing of subjective instruments is provided in Appendix B.

2.4. Statistical analyses

Separate repeated-measures analyses of variance (ANOVA) were conducted to assess the effects of *Intervention, Orientation*, and *Slope* on each outcome measure (i.e., muscle activation, joint kinematics, RPE and RPWD, and perceived balance). One-way repeated-measures ANOVAs were used for usability ratings, with the independent variable of *Intervention* (with two levels, representing the two BSEs). Biological sex and presentation order were included as blocking effects in these ANOVAs. Parametric model assumptions (e.g., normality and homoscedasticity) were evaluated, and Johnson transformations were applied when necessary to achieve normally-distributed residuals (Farnum, 1996; Chou et al., 1998). Summary results were subsequently back-transformed to their original scale to improve interpretability. All subjective measures, including usability ratings and Likert-type scale data, were analysed using parametric methods, given evidence of the robustness of parametric analysis for such data (Rickards et al., 2012; Mircioiu and Atkinson, 2017). A Friedman test was conducted to evaluate whether there were significant differences in ranked preferences across the three *Interventions*.

ANOVA models were fit using the restricted maximum likelihood (REML) method, with statistical significance concluded when $p < 0.05$. Effect sizes were reported using partial eta-squared (η_p^2). Significant main effects were further explored using *post-hoc* comparisons using Tukey's HSD (Montgomery, 2017). All statistical analyses were performed using JMP Pro 18 (SAS, NC, USA) and R 4.2.1 (RStudio Desktop, MA, USA). Given the purpose of this study, the results and discussion focus on the main and interactive effects of *Intervention*. Summaries of ANOVA model results are provided in Appendix C for muscle activation (Table C.1), kinematics (Table C.2), and usability ratings (Table C.3).

3. Results

3.1. Muscle activation

Intervention had significant main effects on the LES_L and LES_R (Table C.1). Compared with the no BSE condition, using the rigid BSE significantly reduced mean nEMG in the LES_L and LES_R muscles, with respective reductions of ~17% and ~11% (Fig. 3). For the LES_L, mean nEMG was ~12% smaller when using the rigid vs. soft BSE (Fig. 3). Note, though, that these decreases were rather small (representing less than ~3% of %MVIC), and were consistent across *Orientations* and *Slopes*. Using the soft BSE did not significantly affect mean activation levels of the bilateral LES muscles relative to no BSE.

3.2. Postural kinematics

Intervention had significant main effects on both peak trunk flexion and peak T-T flexion (Table C.1). Using the soft BSE significantly reduced trunk flexion by up to 4% vs. using the rigid BSE and no BSE (Fig. 4). T-T flexion increased by ~5% when using the soft BSE compared with the no BSE condition (Fig. 4). In contrast, no significant differences were observed between the rigid and no BSE conditions.

3.3. RPE and RPWD

Intervention had significant main effects on RPE and RPWD for all body regions assessed, except for RPE in the leg (Table C.2). Using the soft BSE significantly increased shoulder RPE vs. both the no BSE condition (by ~24%) and the rigid BSE (by ~35%); it also led to significantly higher shoulder RPWD (by ~29%) compared to the rigid BSE (Fig. 5). At the low back, both BSEs significantly reduced RPE (by up to 16%) relative to no BSE, but the rigid BSE resulted in significantly higher RPWD (by ~26%) compared to the soft BSE (Fig. 6). In the legs, the rigid BSE led to significantly higher RPWD (by ~34%) compared to the soft BSE (Fig. 7).

3.4. Perceived balance, usability ratings, and BSE preference

No significant main or interaction effects of *Interventions* were found for perceived balance (Table C.2). Respective medians (IQRs) of balance ratings were 20 (8.8–46.3) for no BSE, 25 (10–38.3) for the rigid BSE, and 26 (8.8–59.3) for the soft BSE.

Usability ratings tended to be neutral to negative across both BSEs (Fig. 8). Among the usability ratings, a significant effect was found only for time efficiency (Table C.3). Participants reported spending less time correcting fit or functionality problems using the rigid BSE compared to the soft BSE (Fig. 8). The rigid BSE was indicated as easier to use, although this difference only approached significance ($p = 0.061$; Table C.3).

The Friedman test revealed no significant differences in ranked BSE preferences ($p = 0.68$). However, 13 preferred using a BSE (seven favoring the soft BSE and six the rigid BSE), while five preferred working without a BSE. Participants who preferred using a BSE commonly stated that the BSEs reduced low back demands, provided a sense of physical support, and decreased the effort of maintaining trunk-flexed postures for longer periods. Participants favoring the rigid BSE often noted that it enhanced postural stability by pressing against the thighs and helping anchor the lower body on the slope. Those who preferred using the soft BSE often highlighted its flexibility and greater freedom of movement. They noted that it allowed them to move more naturally during task performance while still supporting the low back. On the other hand, participants who preferred not to use BSEs expressed concerns about movement restriction and reduced balance. They specifically reported that the BSEs interfered with their natural range of motion and made it more difficult to coordinate their body. Five participants noted that wearing a BSE led to perceptions of imbalance and an increased risk of

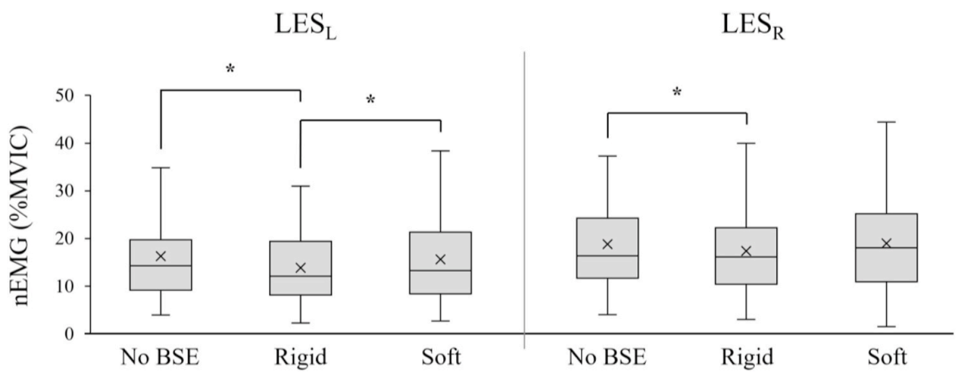

Fig. 3. *Intervention* main effects on mean normalized muscle activation (nEMG) in the bilateral lumbar erector spinae (LES). Asterisks (*) indicate significant paired differences.

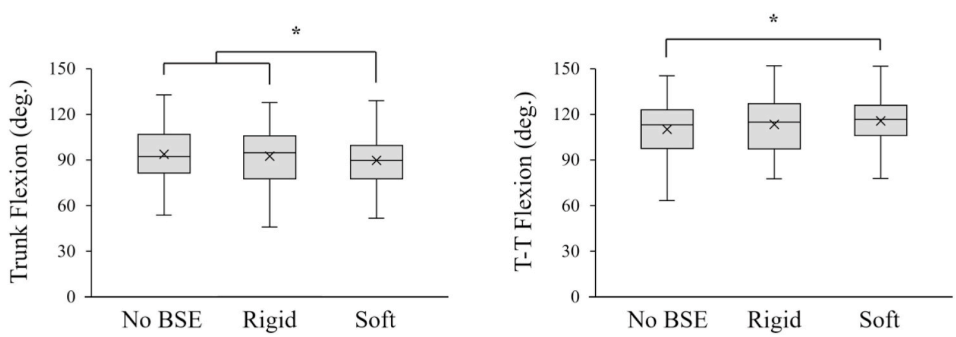

Fig. 4. *Intervention* main effects on peak trunk flexion (Left) and peak T-T flexion (Right). Asterisks (*) indicate significant paired differences.

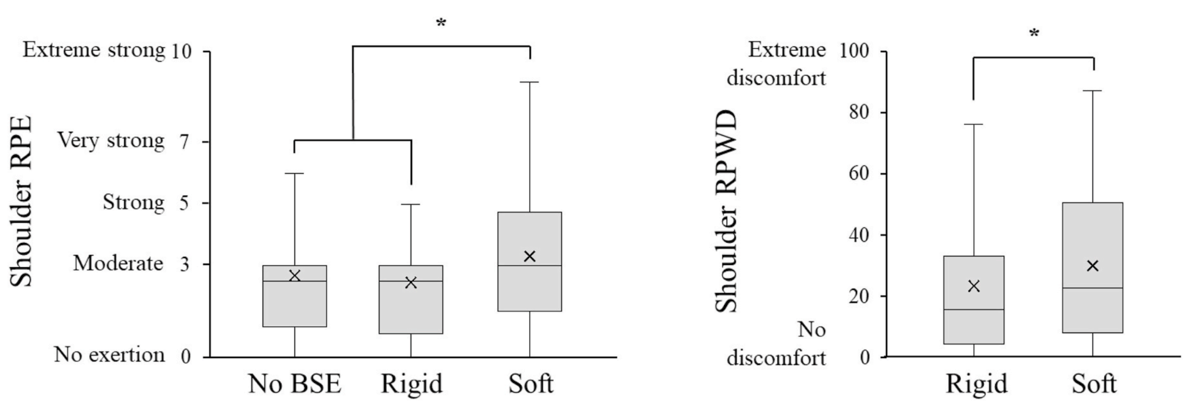

Fig. 5. *Intervention* main effects on ratings of perceived exertion (RPE, Left) and ratings of perceived wearing discomfort (RPWD, Right) at the *shoulder*. Asterisks (*) indicate significant paired differences.

falling. Additionally, three participants mentioned that performing tasks was easier and more efficient without the constraints of the BSEs.

4. Discussion

We investigated the effects of a rigid BSE and a soft BSE in simulated shingling tasks. Although this study was conducted in a laboratory setting, we designed shingling tasks to achieve a modest fidelity by incorporating representative roof surfaces, tools, and materials. Several prior studies restricted participants to standardized postures such as stooping or kneeling (Choi and Fredericks, 2008; Wang et al., 2017; Breloff et al., 2019, 2020a; Dutta et al., 2020). In contrast, we allowed participants to use self-selected movements, only constraining the facing orientation to reflect typical practices observed among professional roofers.

Despite these methodological differences, we observed outcomes that were generally similar to earlier work. For example, we found the main effects of *Slope* and *Orientation*, with greater biomechanical demands when working on the steeper slope and on the bottom row (Appendix D). These results were consistent with prior research (Lin and Nussbaum, 2012; Wang et al., 2017; Dutta et al., 2020; Breloff et al., 2020a), suggesting that our task design reasonably captured the fundamental ergonomic challenges of shingling tasks.

More specific to our current goals, our first hypothesis was partially supported. Using the rigid BSE significantly reduced lumbar muscle activation and using the soft BSE significantly reduced trunk flexion. Both BSEs decreased perceived low back exertion. Our second hypothesis was also supported, since the two BSEs produced distinct effects in terms of muscle activation, trunk posture, and regional discomfort. The following sections discuss these outcomes in more detail.

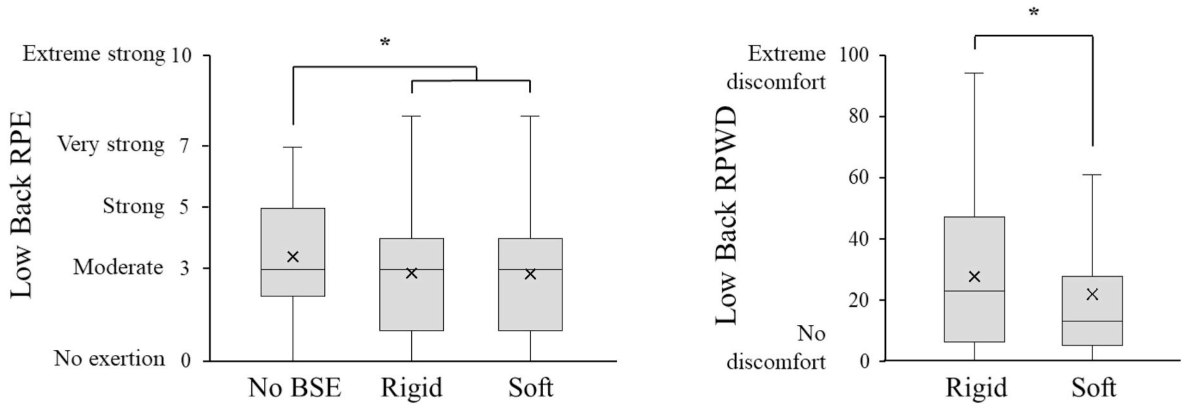

Fig. 6. *Intervention* main effects on ratings of perceived exertion (RPE, Left) and ratings of perceived wearing discomfort (RPWD, Right) at the *low back*. Asterisks (*) indicate significant paired differences.

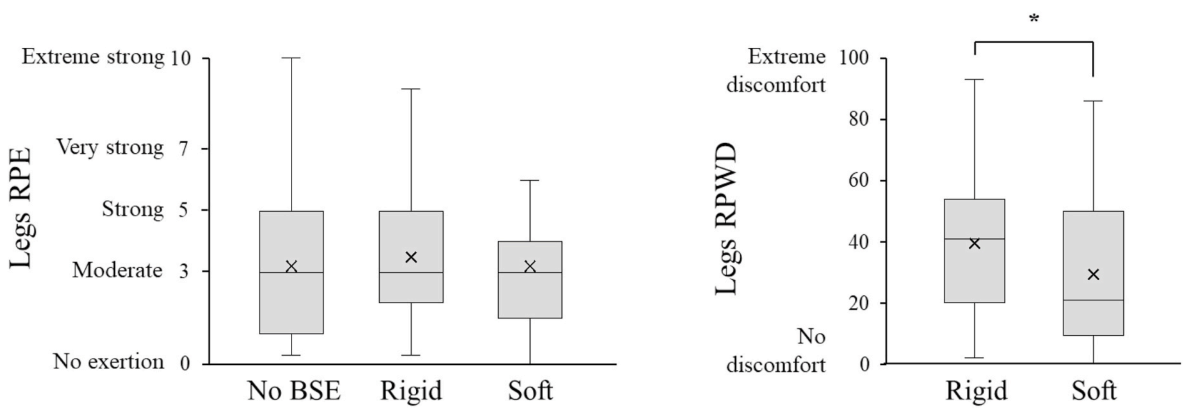

Fig. 7. Effects of *Intervention* on ratings of perceived exertion (RPE, Left) and ratings of perceived wearing discomfort (RPWD, Right) at the *legs*. The asterisk (*) indicates a significant paired difference.

4.1. Muscle activation and postural kinematics

Using the rigid BSE significantly reduced LES muscle activity (by 11–17%) but did not significantly affect trunk flexion and T-T flexion angles compared to no BSE (Figs. 3 and 4). These effects together suggest that the mechanical support provided by the rigid BSE reduced demands on the back extensor muscles without significantly altering trunk posture. Similar findings have been reported in previous studies, which demonstrated reduced low back muscle activation without corresponding changes in trunk kinematics (e.g., Koopman et al., 2019; Baltrusch et al., 2020; Reimeir et al., 2023). A recent study among logistics workers also identified reductions in LES muscle activity without substantial changes in posture, when a rigid BSE was used during standardized lifting tasks (Schrøder Jakobsen et al., 2024). Multiple field studies have also reported reduced LES activation (e.g., Amandels et al., 2019; Motmans et al., 2019; Thamsuwan et al., 2020; Ciccarelli et al., 2024), suggesting that rigid BSEs can alleviate muscular demands in real occupational settings.

Using the soft BSE significantly decreased trunk flexion (~9%) and increased T-T flexion (~5%) compared to the no BSE condition, but it did not significantly affect activation levels of any of the monitored muscles (Figs. 3 and 4). The change in posture could be beneficial, since reduced trunk flexion can mitigate low back loading by decreasing spinal compression and shear forces (Adams and Hutton, 1982; McGill, 2015). Additionally, the concurrent reduction in trunk flexion and increase in T-T flexion indicate that participants adopted slightly more kneeling or squat-like postures, rather than a stooped posture, when using the soft BSE. Previous evidence suggests that a kneeling posture is preferable to stooping for reducing low back loading during shingling tasks (Wang et al., 2017).

Despite these kinematic changes, a corresponding reduction in LES activation was not observed when using the soft BSE. Our results in this aspect differ from multiple previous studies that evaluated the effects of soft BSEs, which often reported decreased LES activation during repetitive lifting tasks (e.g., Lamers et al., 2018; Reimeir et al., 2023; Nueslein et al., 2023; Thevenot et al., 2025). However, several similar reports indicate no significant reductions in LES muscle activity when trunk kinematics were altered (e.g., Goršič et al., 2022; Favennec et al., 2024). This evidence suggests that the effectiveness of soft BSEs in reducing muscular demand may depend on the specific postural demands of the task. Koopman et al. (2020) similarly observed no changes in LES activation while trunk flexion was reduced when using a BSE, and interpreted these findings based on the muscle force–length relationship. Using a reduced trunk flexion angle with a BSE may have positioned the lumbar extensors closer to their optimal length, allowing these muscles to produce greater active force with similar levels of neural input.

The distinct torque-generation characteristics of the soft and rigid BSEs provide another potential explanation for the different effects observed between these two BSE designs (i.e., reduced muscle activity versus reduced trunk flexion). The rigid BSE we used provided relatively consistent or slightly decreasing supportive torque from ~30° of trunk flexion to full flexion, indicating that users receive fairly consistent kinetic assistance regardless of how far they bend forward (Koopman et al., 2020; Van Harmelen et al., 2022; Johns et al., 2024; Eskandari et al., 2025). This consistency likely contributed to the observed reduction in LES activation, but without necessitating changes in lumbar flexion posture. In contrast, the soft BSE we used provided torque that

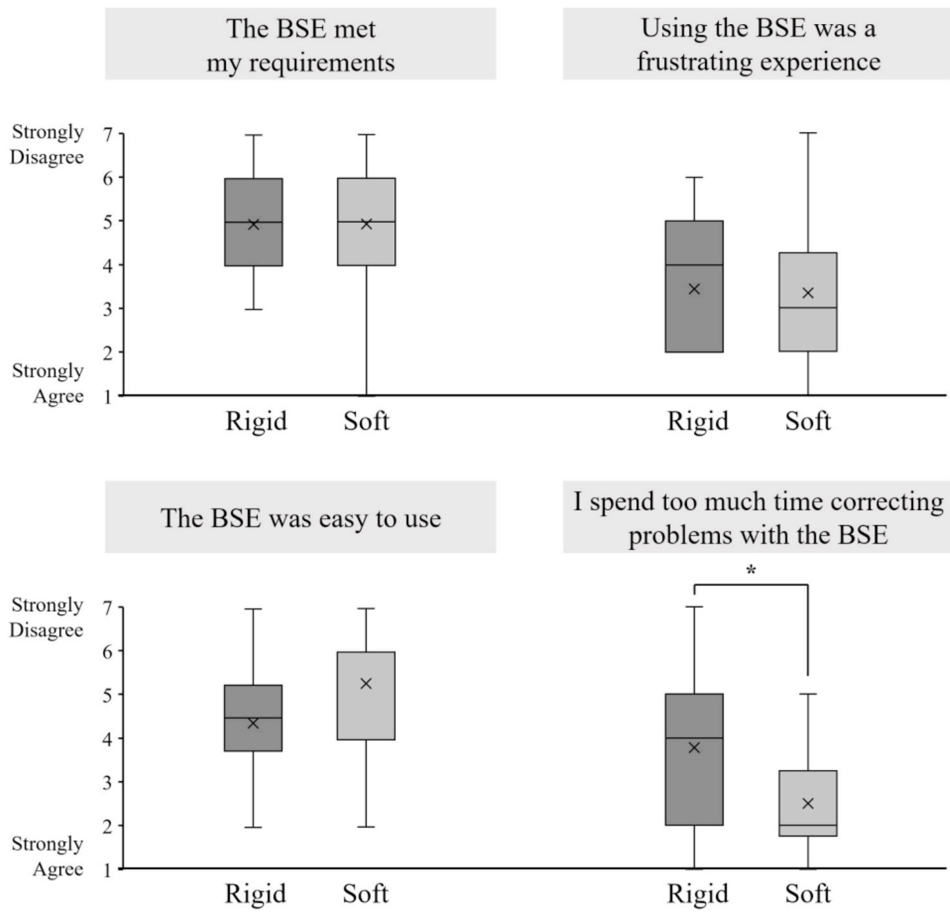

Fig. 8. Reponses to usability questions about effectiveness (Top left), satisfaction (Top right), efficiency in terms of ease (Bottom left), and efficiency in terms of time (Bottom right). The asterisk (*) indicates a significant paired difference.

increases with trunk flexion, resulting in progressively greater support as users bend forward (Lamers and Zelik, 2021; Van Harmelen et al., 2022; Nuesslein et al., 2023). This increasing torque could impose more substantial resistance as trunk flexion angle increases, potentially restricting trunk flexion and thereby limiting reductions in muscle activation. Future research is still needed to investigate whether observed trunk posture changes stem from mechanical constraints imposed by the soft BSE or from voluntary adaptations to perceived support, and to assess how these mechanisms interact to influence muscle activations across different task demands.

4.2. Subjective responses

Participants reported greater shoulder RPE and RPWD when using the soft BSE than either the rigid BSE or no BSE (Fig. 5). Participants reported greater shoulder RPE when using the soft BSE than either the rigid BSE or no BSE, and higher shoulder RPWD than using the rigid BSE (Fig. 5). This effect could be due to increased BSE tension during trunk flexion, which applied force on the shoulder region (Lamers et al., 2018; Toxiri et al., 2019). In the low back, using both BSEs significantly reduced RPE (Fig. 6), suggesting reduced strain in the lumbar region (Crewe et al., 2008; Williams, 2017). The soft BSE also significantly reduced low back RPWD compared to the rigid and no BSE conditions, indicating less perceived wearing discomfort. This outcome may be attributed to the absence of hip pads in the soft BSE; in contrast, the rigid BSE included structural components near the lower back and pelvis. But the rigid BSE led to significantly higher low back RPWD compared to the soft BSE conditions, indicating higher perceived wearing discomfort. This outcome may be attributed to the presence of hip pads and other structural components near the lower back and pelvis in the rigid BSE, which were absent in the soft BSE. Leg RPWD was significantly greater when using the rigid BSE (Fig. 7). We suspect this greater discomfort stemmed from pressure applied to the thighs during task performance and/or friction caused by the thigh pads contacting participants' skin, as all participants wore shorts.

Overall, using both BSEs reduced perceived low back exertion, but our findings also revealed localized wearing discomfort—particularly at the shoulders with the soft BSE and at the thighs with the rigid BSE. Previous studies in other task scenarios have also found increases in discomfort when using the BSEs, especially during tasks requiring substantial trunk and hip flexion (Baltrusch et al., 2018; Kim et al., 2020). Taken together, these findings emphasize the importance of carefully considering task-specific physical demands when selecting BSEs.

Regarding usability, ratings on the item "I spend too much time correcting problems" were significantly higher for the soft BSE than for the rigid BSE (Fig. 8). Participants also indicated that the rigid BSE was easier to use than the soft BSE. They occasionally reported that the thigh straps on the Apex 2 (i.e., soft BSE) shifted upward or rotated to the side during task performance. These strap displacements required manual readjustment, which may have led to the lower usability ratings.

4.3. Limitations

Some limitations of this study should be acknowledged. First, the participants were relatively young, healthy, and had no prior roofing experience. In contrast, professional roofers are typically older, have specific experience, and often perform work tasks while managing chronic or acute musculoskeletal pain (Data USA, 2022). These differences may limit the generalizability of the present findings to the target occupational population. Second, although roofing is a predominantly male occupation (BLS, 2025), the limited representation of female participants in this study may further constrain the broader generalizability of the results. Third, the familiarization period provided for BSE use was shorter than the durations recommended by manufacturers due to the practical time constraints of training and data collection. Insufficient adaptation time may have influenced our biomechanical and subjective outcomes. Fourth, despite our attempt to achieve reasonable fidelity of roofing simulations, the study was conducted in a laboratory setting and so cannot fully capture the dynamic situations roofers face on actual job sites. Future studies should incorporate field-based evaluations to understand how BSEs influence biomechanical demands and subjective perceptions in real-world environments. Lastly, the relatively short duration of each trial limits the interpretation of the perceived exertion results, since RPE measured during brief, controlled laboratory tasks may not directly extrapolate to longer task durations. Future studies are needed to examine how perceived exertion and related outcomes may differ over extended exposure periods under more prolonged conditions.

5. Conclusions

Our findings indicate that passive back-support exoskeletons (BSEs) can affect biomechanical and perceptual demands during shingle installation tasks, but their effectiveness depends on the BSE design (rigid vs. soft). Rigid and soft BSEs provided different forms of assistance and introduced distinct trade-offs, highlighting the importance of considering device-specific biomechanical benefits and associated trade-offs when selecting BSEs for roofing and other occupations involving repetitive trunk flexion on sloped surfaces. Selecting BSEs based solely on their ability to reduce low-back loading may overlook unintended effects on other body regions, such as the legs or shoulders, which could influence user acceptance and sustained use. Future research should extend the current work to longer task durations and field-based settings, and to experienced workers, to better understand how these device-specific trade-offs influence fatigue, usability, and long-term adoption in real-world roofing operations.

CRediT authorship contribution statement

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

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Declaration of competing interest

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

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Appendix A. Supplementary data

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References

Adams, M.A., Hutton, W.C., 1982. Prolapsed intervertebral disc: a hyperflexion injury. Spine 7 (3), 184–191.
Alemi, M.M., Madinei, S., Kim, S., Srinivasan, D., Nussbaum, M.A., 2020. Effects of two passive back-support exoskeletons on muscle activity, energy expenditure, and subjective assessments during repetitive lifting. Human factors 62 (3), 458–474.
Ali, A., Fontanari, V., Schmoelz, W., Agrawal, S.K., 2021. Systematic review of back-support exoskeletons and soft robotic suits. Front. Bioeng. Biotechnol. 9, 765257.
Amandels, S., Eyndt, H.O.H., Daenen, L., Hermans, V., 2019. Introduction and testing of a passive exoskeleton in an industrial working environment. In: Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20. Springer International Publishing, pp. 387–392.
Babalola, A., Urhal, P., Manu, P., Bartolo, P.J.D.S., Cheung, C., Yunusa-Kaltungo, A., Perera, S., Gao, S., Francis, V., Paton-Cole, V., 2023. Application of exoskeletons for occupational safety and health management in construction: a systematic review. Handbook of Construction Safety, Health and Well-being in the Industry 4.0 Era 249–264.
Baltrusch, S.J., Van Dieën, J.H., Van Bennekom, C.A.M., Houdijk, H., 2018. The effect of a passive trunk exoskeleton on functional performance in healthy individuals. Appl. Ergon. 72, 94–106.
Bär, M., Steinhilber, B., Rieger, M.A., Luger, T., 2021. The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton–A systematic review and meta-analysis. Appl. Ergon. 94, 103385.
BLS – Bureau of Labor Statistics, 2024. Occupational Injuries and Illnesses Resulting in Musculoskeletal Disorders (MSDs). U.S. Department of Labor. https://www.bls.gov/iif/factsheets/msds.htm.
BLS – Bureau of Labor Statistics, 2025. Labor Force Statistics from the Current Population Survey. U.S. Department of Labor. https://www.bls.gov/cps/cpsaat11.htm.
Borg, G., 1990. Psychophysical scaling with applications in physical work and the perception of exertion. Scand. J. Work. Environ. Health 55–58.
Breloff, S.P., Carey, R.E., Dutta, A., Sinsel, E.W., Warren, C.M., Dai, F., Wu, J.Z., 2020a. Kneeling trunk kinematics during simulated sloped roof shingle installation. Int. J. Ind. Ergon. 77, 102945.
Breloff, S.P., Carey, R.E., Wade, C., Waddell, D.E., 2020b. Inclination angles during cross-slope roof walking. Saf. Sci. 132, 104963.
Breloff, S.P., Dutta, A., Dai, F., Sinsel, E.W., Warren, C.M., Ning, X., Wu, J.Z., 2019. Assessing work-related risk factors for musculoskeletal knee disorders in construction roofing tasks. Appl. Ergon. 81, 102901.
Choi, S.D., Fredericks, T.K., 2008. Surface slope effects on shingling frequency and postural balance in a simulated roofing task. Ergonomics 51 (3), 330–344.
Chou, Y.M., Polansky, A.M., Mason, R.L., 1998. Transforming non-normal data to normality in statistical process control. J. Qual. Technol. 30 (2), 133–141.
Ciccarelli, M., Tonelli, S., Terlizzi, S., Scoccia, C., Papetti, A., Germani, M., 2024. A preliminary experimentation of passive back-support exoskeleton in a real industrial context. In: 2024 20th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA). IEEE, pp. 1–8.
CPWR – The Center for Construction Research and Training, 2018. The Construction Chart Book: the U.S. Construction Industry and Its Workers, sixth ed. CPWR, Silver Spring, MD.
Crewe, H., Tucker, R., Noakes, T.D., 2008. The rate of increase in rating of perceived exertion predicts the duration of exercise to fatigue at a fixed power output in different environmental conditions. Eur. J. Appl. Physiol. 103, 569–577.
Criswell, E., 2010. Cram's Introduction to Surface Electromyography. Jones & Bartlett Publishers.
Data USA, 2022. Roofers. Data USA carpet. https://datausa.io/profile/soc/roofers.
De Bock, S., Ghillebert, J., Govaerts, R., Tassignon, B., Rodriguez-Guerrero, C., Crea, S., Veneman, J., Geeroms, J., Meeusen, R., De Pauw, K., 2022. Benchmarking occupational exoskeletons: an evidence mapping systematic review. Appl. Ergon. 98, 103582.
De Luca, C.J., Gilmore, L.D., Kuznetsov, M., Roy, S.H., 2010. Filtering the surface EMG signal: movement artifact and baseline noise contamination. J. Biomech. 43 (8), 1573–1579.
Dong, X.S., Wang, X., Herleikson, B., 2010. Work-Related Fatal and Nonfatal Injuries Among US Construction Workers, pp. 1992–2008.
Dutta, A., Breloff, S.P., Dai, F., Sinsel, E.W., Warren, C.M., Carey, R.E., Wu, J.Z., 2020. Effects of working posture and roof slope on activation of lower limb muscles during shingle installation. Ergonomics 63 (9), 1182–1193.
Eskandari, A.H., Ghezelbash, F., Shirazi-Adl, A., Arjmand, N., Larivière, C., 2025. Effect of a back-support exoskeleton on internal forces and lumbar spine stability during low load lifting task. Appl. Ergon. 123, 104407.
Farnum, N.R., 1996. Using JOHNSON curves to describe non-normal ROCESS data. Qual. Eng. 9 (2), 329–336.

Favennec, A., Frère, J., Mornieux, G., 2024. Changes in human motor behavior during the familiarization with a soft back-support occupational exoskeleton. Appl. Sci. 14 (3), 1160.
Finstad, K., 2010. The usability metric for user experience. Interact. Comput. 22 (5), 323–327.
Fredericks, T.K., Abudayyeh, O., Choi, S.D., Wiersma, M., Charles, M., 2005. Occupational injuries and fatalities in the roofing contracting industry. J. Construct. Eng. Manag. 131 (11), 1233–1240.
Golabchi, A., Riahi, N., Fix, M., Miller, L., Rouhani, H., Tavakoli, M., 2023. A framework for evaluation and adoption of industrial exoskeletons. Appl. Ergon. 113, 104103.
Gonsalves, N., Akanmu, A., Shojaei, A., Agee, P., 2024. Factors influencing the adoption of passive exoskeletons in the construction industry: industry perspectives. Int. J. Ind. Ergon. 100, 103549.
Goršič, M., Song, Y., Dai, B., Novak, V.D., 2022. Short-term effects of the Auxivo LiftSuit during lifting and static leaning. Appl. Ergon. 102, 103765.
Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10 (5), 361–374.
HSE – Health and Safety Executive, 2012. Health and Safety in Roof Work.
ICC – International Code Council, 2021. 2021 International Residential Code (IRC) – chapter 9: roof assemblies. https://codes.iccsafe.org/content/IRC2021P2/chapter-9-roof-assemblies.
Johns, J., Schultes, I., Heinrich, K., Potthast, W., Glitsch, U., 2024. Biomechanical analysis of different back-supporting exoskeletons regarding musculoskeletal loading during lifting and holding. J. Biomech. 168, 112125.
Kermavnar, T., de Vries, A.W., de Looze, M.P., O'Sullivan, L.W., 2021. Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review. Ergonomics 64 (6), 685–711.
Kim, S., Madinei, S., Alemi, M.M., Srinivasan, D., Nussbaum, M.A., 2020. Assessing the potential for "undesired" effects of passive back-support exoskeleton use during a simulated manual assembly task: muscle activity, posture, balance, discomfort, and usability. Appl. Ergon. 89, 103194.
Kim, S., Porto, R., Nussbaum, M.A., 2025. User experiences and adoption factors for a back-support exosuit in automotive logistics: results from field testing up to 18 months. IISE Transactions on Occupational Ergonomics and Human Factors 1–9.
Koopman, A.S., Kingma, I., Faber, G.S., de Looze, M.P., van Dieën, J.H., 2019. Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks. J. Biomech. 83, 97–103.
Koopman, A.S., Näf, M., Baltrusch, S.J., Kingma, I., Rodriguez-Guerrero, C., Babič, J., de Looze, M.P., van Dieën, J.H., 2020. Biomechanical evaluation of a new passive back support exoskeleton. J. Biomech. 105, 109795.
Lamers, E.P., Zelik, K.E., 2021. Design, modeling, and demonstration of a new dual-mode back-assist exosuit with extension mechanism. Wearable Technologies 2, e1.
Lamers, E.P., Yang, A.J., Zelik, K.E., 2018. Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 65 (8), 1674–1680.
Lin, D., Nussbaum, M.A., 2012. Effects of lumbar extensor fatigue and surface inclination on postural control during quiet stance. Appl. Ergon. 43 (6), 1008–1015.
McAlpine, K., 2019. Roofing drone nails down shingles. Aerospace Engineering, University of Michigan. https://aero.engin.umich.edu/2019/09/20/roofing-drone-nails-down-shingles/.
McCormack, H.M., Horne, D.J.D.L., Sheather, S., 1988. Clinical applications of visual analogue scales: a critical review. Psychol. Med. 18 (4), 1007–1019.
McGill, S., 2015. Low Back Disorders: Evidence-Based Prevention and Rehabilitation. Human Kinetics.
Mircioiu, C., Atkinson, J., 2017. A comparison of parametric and non-parametric methods applied to a Likert scale. Pharmacy 5 (2), 26.
Montgomery, D.C., 2017. Design and Analysis of Experiments. John wiley & sons.
Moreira, T.T., Leite, H., Campos, D.P., 2025. The impact of exoskeletons on industrial operations: a review of the knowledge and future research directions. Cognit. Technol. Work 1–16.
Motmans, R., Debaets, T., Chrispeels, S., 2019. Effect of a passive exoskeleton on muscle activity and posture during order picking. In: Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20. Springer International Publishing, pp. 338–346.
Mungroo, S., Choi, S.D., 2018. Ergonomic assessment of work-related musculoskeletal risks among construction roofers in central Trinidad. J. Saf. Health Environ. Res 14, 322.
NRCA – National Roofing Contractors Association, 2022. Musculoskeletal disorders are prevalent in the construction industry. https://www.nrca.net/RoofingNews/musculoskeletal-disorders-are-prevalent-in-the-construction-industry-.1-27-2022.10222/details/story.
NSC – National Safety Council, 2024. Work Safety: Most Dangerous Industries - Injury Facts. https://injuryfacts.nsc.org/work/industry-incidence-rates/most-dangerous-industries.
Nuesslein, C., Bhakta, K., Fernandez, J., Davenport, F., Leestma, J., Kim, R., Lee, D., Mazumdar, A., Sawicki, G., Young, A., 2023. Comparing metabolic cost and muscle activation for knee and back exoskeletons in lifting. IEEE Transactions on Medical Robotics and Bionics 6 (1), 224–234.
Nussbaum, M.A., Lowe, B.D., de Looze, M., Harris-Adamson, C., Smets, M., 2019. An introduction to the special issue on occupational exoskeletons. IISE Transactions on Occupational Ergonomics and Human Factors 7 (3–4), 153–162.
Okpala, I., Nnaji, C., 2024. Insidious risks of wearable robots to worker safety and health: a scoping review. J. Saf. Res. 88, 382–394.
RCS – Roofing Contractor Staff, 2024. Introducing Rufus, the automated roofing robot from renovate robotics, roofing Contractor. https://www.roofingcontractor.com/articles/99133-introducing-rufus-the-automated-roofing-robot-from-renovate-robotics.
Refai, M.I.M., Moya-Esteban, A., van Zijl, L., van der Kooij, H., Sartori, M., 2024. Benchmarking commercially available soft and rigid passive back exoskeletons for an industrial workplace. Wearable technologies 5, e6.
Reimeir, B., Calisti, M., Mittermeier, R., Ralfs, L., Weidner, R., 2023. Effects of back-support exoskeletons with different functional mechanisms on trunk muscle activity and kinematics. Wearable Technologies 4, e12.
Rickards, G., Magee, C., Artino Jr, A.R., 2012. You can't fix by analysis what you've spoiled by design: developing survey instruments and collecting validity evidence. Journal of graduate medical education 4 (4), 407–410.
Schieppati, M., Tacchini, E., Nardone, A., Tarantola, J., Corna, S., 1999. Subjective perception of body sway. J. Neurol. Neurosurg. Psychiatr. 66 (3), 313–322.
Schrøder Jakobsen, L., Samani, A., Desbrosses, K., De Zee, M., Madeleine, P., 2024. In-Field training of a passive back Exoskeleton changes the biomechanics of logistic workers. IISE transactions on occupational ergonomics and human factors 12 (3), 149–161.
Schwartz, M., Theurel, J., Desbrosses, K., 2021. Effectiveness of soft versus rigid back-support exoskeletons during a lifting task. Int. J. Environ. Res. Publ. Health 18 (15), 8062.
Simeonov, P., Hsiao, H., Hendricks, S., 2009. Effectiveness of vertical visual reference for reducing postural instability on inclined and compliant surfaces at elevation. Appl. Ergon. 40 (3), 353–361.
Thamsuwan, O., Milosavljevic, S., Srinivasan, D., Trask, C., 2020. Potential exoskeleton uses for reducing low back muscular activity during farm tasks. Am. J. Ind. Med. 63 (11), 1017–1028.
Thevenot, C., Pierre, X., Mornieux, G., 2025. Effects of an Occupational soft-back Exoskeleton During Order Picking: a Field Study in Logistics. Ergonomics, pp. 1–14.
Toxiri, S., Näf, M.B., Lazzaroni, M., Fernández, J., Sposito, M., Poliero, T., Monica, L., Anastasi, S., Caldwell, D.G., Ortiz, J., 2019. Back-support exoskeletons for occupational use: an overview of technological advances and trends. IISE Transactions on Occupational Ergonomics and Human Factors 7 (3–4), 237–249.
Usmani, A.R., Rajabi, M.S., Ojelade, A., Kim, S., Harris-Adamson, C., Barr, A., Nussbaum, M.A., 2025. Passive back support exoskeletons do not effectively reduce physical demands during simulated floor tiling. Appl. Ergon. 128, 104549.
Van Harmelen, V., Schnieders, J., Wagemaker, S.J., 2022. Measuring the Amount of Support of Lower Back Exoskeletons. Laevo White Paper.
Wang, D., Dai, F., Ning, X., Dong, R.G., Wu, J.Z., 2017. Assessing work-related risk factors on low back disorders among roofing workers. J. Construct. Eng. Manag. 143 (7), 04017026.
Welch, L., Haile, E., Boden, L.I., Hunting, K.L., 2009. Musculoskeletal disorders among construction roofers—physical function and disability. Scand. J. Work. Environ. Health 56–63.
Welch, L.S., Haile, E., Boden, L.I., Hunting, K.L., 2010. Impact of musculoskeletal and medical conditions on disability retirement—a longitudinal study among construction roofers. Am. J. Ind. Med. 53 (6), 552–560.
Williams, N., 2017. The Borg rating of perceived exertion (RPE) scale. Occup. Med. 67 (5), 404–405.
Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D D'Lima, D., Cristofolini, L., Witte, H., Schmid, O., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. J. Biomech. 35 (4), 543–548.
Zhang, Z., Lin, K.Y., Lin, J.H., 2021. Factors affecting material-cart handling in the roofing industry: evidence for administrative controls. Int. J. Environ. Res. Publ. Health 18 (4), 1510.
Zhu, Z., Dutta, A., Dai, F., 2021. Exoskeletons for manual material handling–A review and implication for construction applications. Autom. ConStruct. 122, 103493.