International Journal of Occupational Safety and Ergonomics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tose20

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INTERNATIONAL JOURNAL OF OCCUPATIONAL SAFETY AND ERGONOMICS (JOSE)
2024, VOL. 30, NO. 4, 1226–1233
https://doi.org/10.1080/10803548.2024.2383077

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Evaluation of a passive back-support exoskeleton during in-bed patient handling tasks

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ABSTRACT
This study evaluated the effects of a back-support exoskeleton on the trunk and hip joint angles, lower back muscle activity and heart rate during four patient handling tasks: assisting a patient from sitting to lying, laterally repositioning the patient and turning the patient in two directions. Eight participants performed these tasks with and without the exoskeleton. Results demonstrated a significant reduction in the lower back muscle activity, but less pronounced effects for other tasks involving minimal trunk flexion. Hip flexion angles were reduced for all tasks when the exoskeleton was worn. The amount of reduction in the muscle activity and changes in the trunk and hip angles varied by task. The exoskeleton did not affect the heart rate across all tasks. The exoskeleton appeared to be more effective in tasks requiring substantial trunk flexion, indicating its potential benefits for reducing lower back muscle strain during such activities.

KEYWORDS
patient handling; back-support exoskeleton; musculoskeletal disorders; electromyography; heart rate

1. Introduction

Musculoskeletal disorders (MSDs) have been a primary concern for healthcare workers. For nursing assistants in the USA, the total number of MSD cases was 17,240 and the incidence rate was reported to be 140.5 per 10,000 full-time workers [1]. Among the various localized regions, the lower back and shoulders were the two most frequently affected areas [2]. One of the major risk factors of MSDs for healthcare workers is patient handling [3], which refers to a variety of physical maneuvers involving overexertion and awkward postures, such as patient lifting/lowering, transferring and repositioning and assisting in patient walking [3–5]. The variable size, weight, shape and behavior of patients that caregivers handle could be additional risk factors [6–8].

Industrial exoskeletons have gained attention as an innovative and emerging ergonomic intervention. Passive exoskeletons have been more widely adopted in the field setting compared to powered exoskeletons due to the lightweight design, simplicity and technological maturity [9,10]. Depending on the targeted body regions, exoskeletons could be categorized as back-support, upper-extremity, lower-extremity or whole-body exoskeletons. In the context of the healthcare setting, upper-extremity exoskeletons have been investigated for their potential application in surgical activities that involve upper-body movements [11,12]. However, for patient handling activities that involve bending, back-support exoskeletons appear to be a more appropriate solution for reducing the risk of back injuries among caregivers.

Several recent studies have investigated the effectiveness of back-support exoskeletons during patient handling [8,13,14]. One study found that back-support exoskeletons reduced lower back muscle activities during patient transfer between a wheelchair and a bed [13]. However, the exoskeleton increased trunk and shoulder flexion angles compared to performing those tasks with no exoskeleton. Another study designed a new passive exoskeleton, focusing on assisting torso twist among nurses [14]. It is important to note that the effectiveness of exoskeletons was found to be task-dependent [10,13]. This suggests that a wide range of patient handling activities should be thoroughly tested before adopting exoskeletons to assist healthcare workers with patient handling tasks.

In-bed patient handling activities are one of the most frequent activities performed by healthcare workers [5,15,16]. This typically involves repositioning supine patients, such as repositioning up in bed (boosting), lateral repositioning and turning [17,18]. The initial friction of the patient against the bed could increase the risk of overexertion while caregivers are pushing or pulling their patients [5,6,19]. Additionally, a caregiver may substantially bend their torso and elevate their arms while repositioning the patient away from them, the effect of which could be magnified with increasing patient size [6,16,20].

Despite the high-risk nature of in-bed patient handling activities, there is a significant gap in the literature regarding the potential benefits and limitations of back-support exoskeletons for caregivers in these types of tasks. Therefore, the primary objective of this study was to assess the effects of a back-support passive exoskeleton (Laevo V2.5) on joint angles of the trunk and hip, lower back muscle activity and heart rate during four different in-bed patient handling tasks. Our hypotheses were that the back-support exoskeleton would reduce the aforementioned measures compared to no exoskeleton and that the amount of reduction of these measures by use of the exoskeleton would differ across in-bed patient handling tasks. This study aimed to fill the gap in

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knowledge regarding the effectiveness of exoskeletons during in-bed patient handling tasks, which could inform future interventions to reduce the risk of musculoskeletal injuries among healthcare workers.

2. Methods

2.1. Participants

A total of eight participants (five males and three females) were recruited for this study. The mean and standard deviation height and weight are presented in Table 1. All participants were university students who reported no musculoskeletal pain in the past 7 days, were not taking medication associated with MSDs and had no restrictions in physical activities. For the simulated patient, we recruited a male participant of height 177 cm and weight 84 kg. The experimental protocol was approved by the University Institutional Review Board (HS22-0131), and all participants provided written consent after reviewing the protocol prior to data collection.

2.2. Passive back-support exoskeleton

Laevo V2.5 (Delft, the Netherlands) back-support exoskeletons in small and large size were used for this study based on the participant's height and a sizing table and guidelines provided from a manufacturer. This back-support exoskeleton is lightweight (2.9 kg) and consists of gas springs and anchors to support the back, and distributes the external load to multiple body segments, e.g., chest, waist and thighs. For proper fit, each participant was instructed to adjust the engagement angle built into the exoskeleton. The Laevo exoskeleton was selected in this study due to its broad potential applications in different industrial sectors, including the healthcare industry. For example, this device has been tested in various sectors, including the automotive industry [21], manual material handling [22–24], intensive care units [25], surgical department [26] and geriatric care [27].

2.3. In-bed patient handling tasks

Four different in-bed patient handling tasks were simulated. These in-bed patient handling tasks were chosen based on the previous studies showing that repositioning patients in bed could increase the risk of the MSDs [5,16,19,20]. For instance, hand forces and spine compressive forces exceeded the safe limits while repositioning patients with draw sheets [5]. The participants were instructed to perform the standardized in-bed patient handling tasks as described previously [28]. The description of each task is presented in Table 2 and an example of the data collection in a controlled laboratory setting is shown in Figure 1. The draw sheet was positioned underneath the patient to set up consistent surface friction for all tasks. For task 1, the bed height was set as the lowest height of the bed to ensure a safe and stable initial sitting position for the patient.

Table 1. Participant information.

Anthropometric measure	Males ($n = 5$)	Females ($n = 3$)	Total ($n = 8$)
Height (cm)	177.9 (5.45)	164.33 (7.09)	172.75 (8.94)
Weight (kg)	78 (13.02)	62.33 (2.52)	72.13 (12.82)

Note: Values presented as mean (standard deviation). n = number of participants.

Table 2. Description of in-bed patient handling tasks.

Task number	Name	Description
1	Sitting to lying	The participant repositioned the patient from sitting on the bed to a supine position. The participant held onto the patient's shoulder and thigh
2	Repositioning toward the caregiver	The participant laterally repositioned the supine patient from the middle of the bed to the bedside near the participant. The participant grasped the draw sheet to reposition the patient
3	Turning toward the caregiver	The participant turned the supine patient toward the caregiver. The patient was repositioned to face the participant, with the participant holding onto the patient's right shoulder and knee
4	Turning away from the caregiver	The participant turned the supine patient away from themselves. The participant held the patient's left shoulder and knee to perform the task

For tasks 2, 3 and 4, the bed height was set at the caregiver's knuckle height [29]. The simulated patient was instructed to provide minimal assistance and effort to the caregiver during the tasks. The order of the exoskeleton condition was counterbalanced, and the order of different patient handling tasks were randomized to reduce the order effect.

2.4. Apparatus and outcome measures

2.4.1. Joint angles

The kinematic data of the participants were recorded using an optical motion capture system with eight cameras (Flex 13, Optitrack; Natural Point, USA). The participant's movements were captured at a sampling rate of 50 Hz during the task. A total of 39 reflective markers were attached to the head, torso, arms, hands, pelvis, legs and feet of the participants. The motion capture software Motive version 2.0 was utilized to record and process the kinematic data of participants. The biomechanical analysis software Visual3D (Version v2020.08.3) was utilized to compute the joint angles in the sagittal plane of the trunk and bilateral hips with respect to the local coordinate system using the XYZ Euler rotation sequence. The torso (four thorax markers) and pelvis (four pelvic markers) markers were used to calculate the relative angle of the trunk compared to the pelvis. The upper legs (six markers) and pelvis markers were considered to compute the bilateral hip angles relative to the pelvis. The positive values indicate trunk extension and bilateral hip flexion, whereas the negative values indicate trunk flexion and hip extension. The peak (90th percentile) and median (50th percentile) flexion and extension angles of each task were extracted for statistical analysis. This assessment aimed to evaluate the risk of overexertion and determine the median physical demands during the patient transfer period. The minimum values (10th percentile) for trunk flexion and hip extension were excluded from the analysis. This decision was based on their proximity to the neutral standing postures of the caregivers, and the brief duration of this period was not deemed indicative of an overexertion event [13].

2.4.2. Muscle activity

A wireless electromyography (EMG) system (Delsys Trigno; Delsys Inc., USA) at a sampling rate of 2000 Hz was used to collect

Figure 1. Experimental set-up of in-bed patient handling tasks: (a) task 1, sitting to lying; (b) task 2, repositioning toward the caregiver laterally; (c) task 3, turning toward the caregiver; (d) task 4, turning away from the caregiver.

the muscle activities of bilateral erector spinae. The lower back region of the erector spinae was chosen because previous studies showed that this muscle was highly affected by different patient transfer methods and various engineering controls [3,13,16]. Skin preparation and electrode placements were performed per the European recommendation for surface EMG [30]. Isometric maximum voluntary contractions (MVCs) were conducted for each participant to normalize the muscle activities [31]. The participant used a Roman chair to incline and maintain an unsupported torso for 5 s [32,33]. The MVC tasks were repeated three times with 2-min resting periods between the tasks.

The EMG signals were band-pass filtered (20–450 Hz) by the Delsys system's EMGworks version 3.0. The signals were then rectified and smoothed (a window size of 0.025 s) using the root mean square (rms). The 95th percentile values of MVCs of individual muscles were used to normalize the muscle activities of each task (%MVC). The peak (90th percentile) and median (50th percentile) values were summarized for statistical analysis [34].

2.4.3. Heart rate

The heart rate monitor chest strap (Polar H10; Polar Electro Oy, Finland) was utilized to collect the electrocardiogram (ECG) signals of each participant during the task. The validity and reliability of this device have been confirmed by previous studies [35,36]. The elastic heart rate monitor strap, moistened with room-temperature water, was placed at the participant's chest level. After recording the ECG data, the number of heart rate as beats per minute (bpm) was processed. The average heart rate was extracted for each task for further statistical analysis.

2.5. Statistical data analysis

The outcome measures included the trunk flexion/extension and hip flexion angles (°), normalized muscle activities (%MVC) of bilateral erector spinae and heart rate (bpm). The non-parametric Wilcoxon signed-rank test was employed to analyze the peak (90th percentile) and median (50th percentile) values of trunk flexion/extension and hip extension angles, as well as the normalized muscle activities for bilateral erector spinae. This choice was made due to the non-normal distribution of the measures, rendering the normality assumption unsatisfied. The statistical significance was determined as $p < 0.05$. The Cohen's effect size (d) was summarized for each measure.

3. Results

3.1. Joint angles

3.1.1. Trunk flexion and extension angles

The back-support exoskeleton did not significantly affect the trunk flexion and extension angles for all patient handling tasks, as presented in Table 3.

3.1.2. Hip flexion angles

As shown in Figure 2, the back-support exoskeleton significantly reduced the left and right median and peak hip flexion angles of all tasks ($p < 0.04$; $|d| < 1.783$) except the median

Table 3. Mean (standard error), percentage difference, statistical significance and Cohen's effect sizes of peak and median trunk flexion (negative) and extension (positive) angles with and without the exoskeleton.

Task	Variable	No exoskeleton, mean (standard error)	Exoskeleton, mean (standard error)	Percentage difference (%)	Statistical significance (*p*)	Cohen's *d* effect size
1	Peak trunk extension	3.66 (2.84)	8.59 (3.39)	80.49	0.231	0.394
	Peak trunk flexion	−29.34 (6.23)	−23.48 (4.24)	−22.19	0.821	0.275
	Median trunk angle	−14.73 (2.09)	−10.93 (4.51)	−29.62	0.175	0.270
2	Peak trunk extension	6.84 (2.75)	5.49 (3.37)	−21.90	0.821	−0.110
	Peak trunk flexion	−15.35 (1.8)	−9.97 (2.84)	−42.50	0.144	0.566
	Median trunk angle	−10.98 (1.96)	−5.2 (3.05)	−71.45	0.495	0.564
3	Peak trunk extension	11.71 (2.6)	12.49 (2.62)	6.45	0.403	0.075
	Peak trunk flexion	− 3.53 (1.59)	−6.44 (3.41)	58.38	0.940	−0.273
	Median trunk angle	1.93 (1.69)	2.36 (2.92)	20.05	0.900	0.045
4	Peak trunk extension	8.32 (2.25)	7.47 (2.53)	−10.77	0.211	−0.089
	Peak trunk flexion	−11.92 (2.17)	−5.87 (2.22)	−68.02	0.940	0.689
	Median trunk angle	−3.02 (1.88)	1.09 (2.47)	30.58	0.211	0.468

Note: Peak values indicate 90th percentile, and median values indicate 50th percentile. Task 1 = sitting to lying; task 2 = repositioning toward the caregiver; task 3 = turning toward the caregiver; task 4 = turning away from the caregiver.

right hip flexion of task 2 (repositioning toward the caregiver laterally).

3.2. *Muscle activity*

The back-support exoskeleton significantly reduced the muscle activities of the median left erector spinae ($p = 0.003$; $|d| = 0.569$) and peak right erector spinae ($p = 0.029$; $|d| = 0.343$) of task 1 (sitting to lying), as shown in Figure 3.

3.3. *Heart rate*

The heart rate was not significantly affected by use of the exoskeleton for all tasks ($p > 0.463$; $|d| < 0.267$), as presented in Table 4.

4. Discussion

This study investigated the effects of a back-support exoskeleton on trunk and hip postures, lower back muscle activities and heart rate during four in-bed patient handling tasks. Our findings indicated that the exoskeleton significantly reduced the hip flexion angles for all four tasks. Nevertheless, the influence of the exoskeleton on trunk angles did not reach statistical significance. Furthermore, the impact on lower back muscle activities exhibited variability contingent on the specific tasks involved in in-bed patient handling. Notably, the exoskeleton was more effective in reducing lower back muscle activities in the task that required substantial trunk flexion (task 1, sitting to lying) compared to the other tasks. On the other hand, no significant effect was observed on the heart rate with and without the exoskeleton.

Regarding trunk postures, the impact of the back-supported exoskeleton on trunk flexion and extension angles during in-bed patient handling tasks was minimal. This finding contrasts with the results of a previous study, which reported a significantly larger trunk forward flexion, averaging 13°, when working with the exoskeleton [37]. Discrepancies in results may stem from variations in the types of patient handling tasks examined in these studies. Nevertheless, taken together, the implication is that back-support exoskeletons may not positively influence trunk posture during patient handling activities. Given the asymmetric and complex nature of body movements in patient handling tasks, the feasibility of back-support exoskeletons in affecting trunk motions appears to be inconclusive.

For the hip posture, consistent reduction of the hip flexion angles was found for all tasks with the back-support exoskeleton, with the amount of reduction dependent on the task. Sitting to lying (task 1) showed the greatest reduction, whereas turning away from the caregiver (task 4) revealed a moderate reduction when using the exoskeleton. Sitting to lying (task 1) demanded the greatest hip flexion angles (66–74°) among all tasks, and the anchor points placed on thighs could play a more significant role in adjusting the hip postures. Conversely, turning away from the caregiver (task 4) required the lowest hip flexion angles (41–43°) among all tasks, which could result in the moderate impact of the exoskeleton. These results were similar to a previous study reporting that the back-support exoskeleton assisted the hip extension and reduced the hip flexion angles by 11% during symmetric and asymmetric lifting tasks [38]. The findings suggest that the subjects tend to adjust hip flexion angles while wearing the back-support exoskeleton during in-bed patient handling tasks.

The back-support exoskeleton significantly reduced the median muscle activities of the left erector spinae and peak muscle activities of the right erector spinae during sitting to lying (task 1), and the reduction was more substantial in the right side of the erector spinae (by 9%MVC). This asymmetric difference could be related to the asymmetric exertions required for the task simulated in this study. The patient's upper body was handled by the participant's right-hand side and the participant was required to do an asymmetric movement to his/her right side to reposition the patient securely. The patient's upper body accounted for a greater proportion of the total weight compared to the lower body, potentially requiring increased muscular exertion, particularly on the right side, from the caregiver. Sitting to lying (task 1) showed the highest muscle activities (40–57%MVC) and the greatest trunk flexion angle (29°) among all tasks without the exoskeleton. The back-support exoskeleton's gas springs were designed to provide greater assistant force when wearers were bending forward, thus the participants could have more supportive torque on the back during sitting to lying tasks. This trend was consistent with the previous study finding that high-demanding wheelchair-to-bed transfer methods showed the greatest reduction of the lower back muscle activities with the back-support exoskeleton [13].

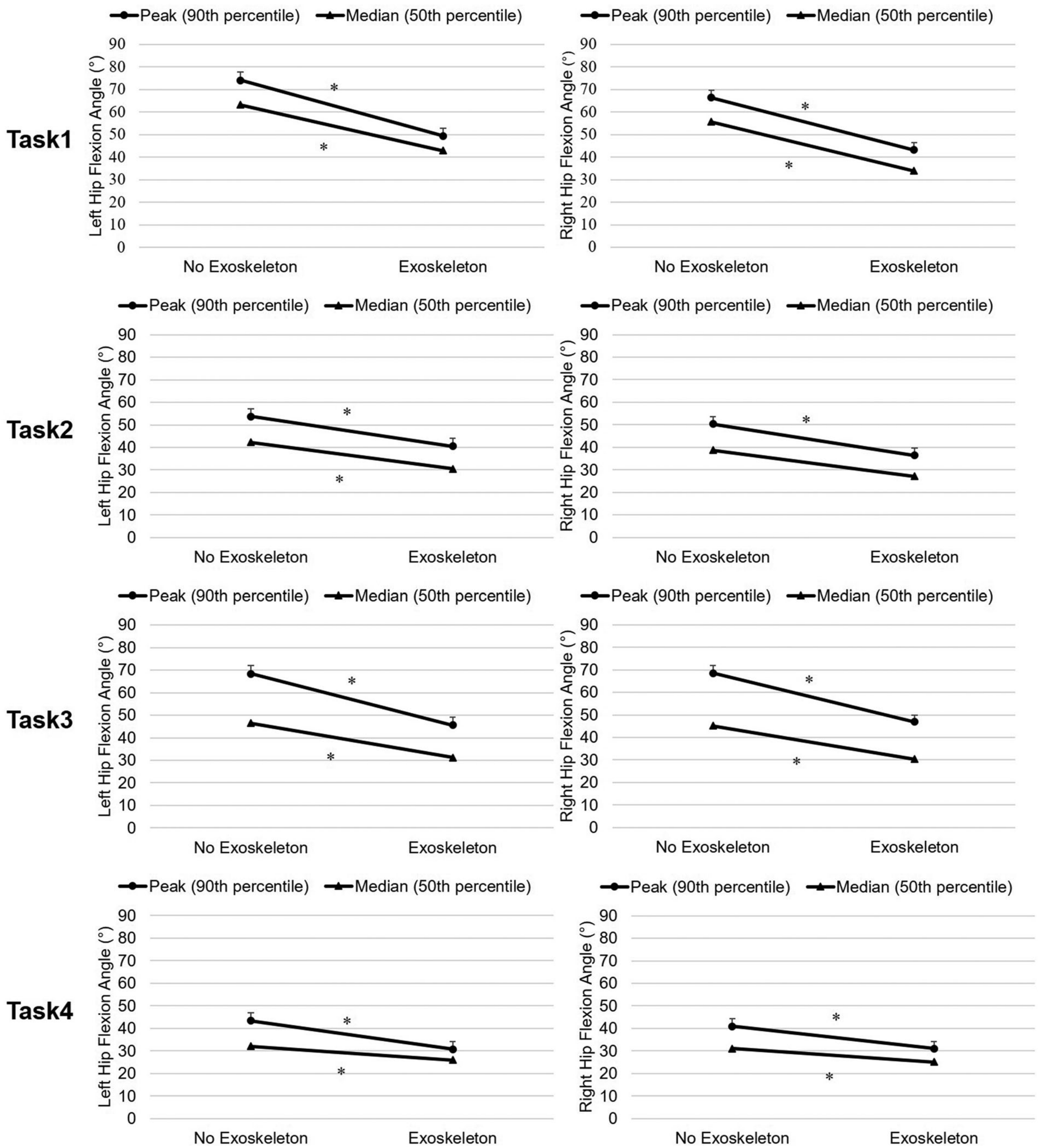

Figure 2. Mean and standard error of peak (90th percentile) and median (50th percentile) flexion angles of the left and right hip. *Significant difference ($p < 0.05$) with and without the exoskeleton. Note: task 1 = sitting to lying; task 2 = repositioning toward the caregiver; task 3 = turning toward the caregiver; task 4 = turning away from the caregiver.

While a consistent reduction in bilateral hip angles was noted across all tasks when utilizing back-support exoskeletons, a decrease in back muscle activity was observed only during the transition from sitting to lying (task 1). This phenomenon might be linked to minimal alterations in trunk flexion and extension angles, with and without the back-support exoskeleton, throughout all patient handling tasks examined in this study. This suggests that the use of exoskeletons adjusted caregivers' postures by decreasing hip angles while maintaining trunk angles. In a prior study, it was discovered that wearing the exoskeleton partially mitigated lower back moments during the lowering phase of patient transfer tasks. However, undesired effects such as altered joint kinematics and center of mass displacement were observed [39]. While the alteration of posture with back-support exoskeletons did not significantly impact the lower back muscle activity in the majority of tasks, it might influence caregivers' perceived comfort. Therefore, future studies could investigate the modification of trunk and hip postures and its repercussions on biomechanical loading, subjective discomfort and perceived exertions across various patient handling tasks.

Heart rate was not significantly affected by the back-support exoskeleton during all in-bed patient handling tasks. A previous study found that Borg's rating of perceived exertion (RPE) scale showed a high correlation with the heart rate ($r = 0.847$) of healthcare workers [40]. Therefore, it was expected that the back-support exoskeletons could reduce the heart rate during in-bed patient handling tasks. The lack of difference in heart rates found in this study could be related to the short duration of the tasks that were tested, which was supported by a previous study demonstrating that short-duration tasks might not alter cardiovascular strain [41].

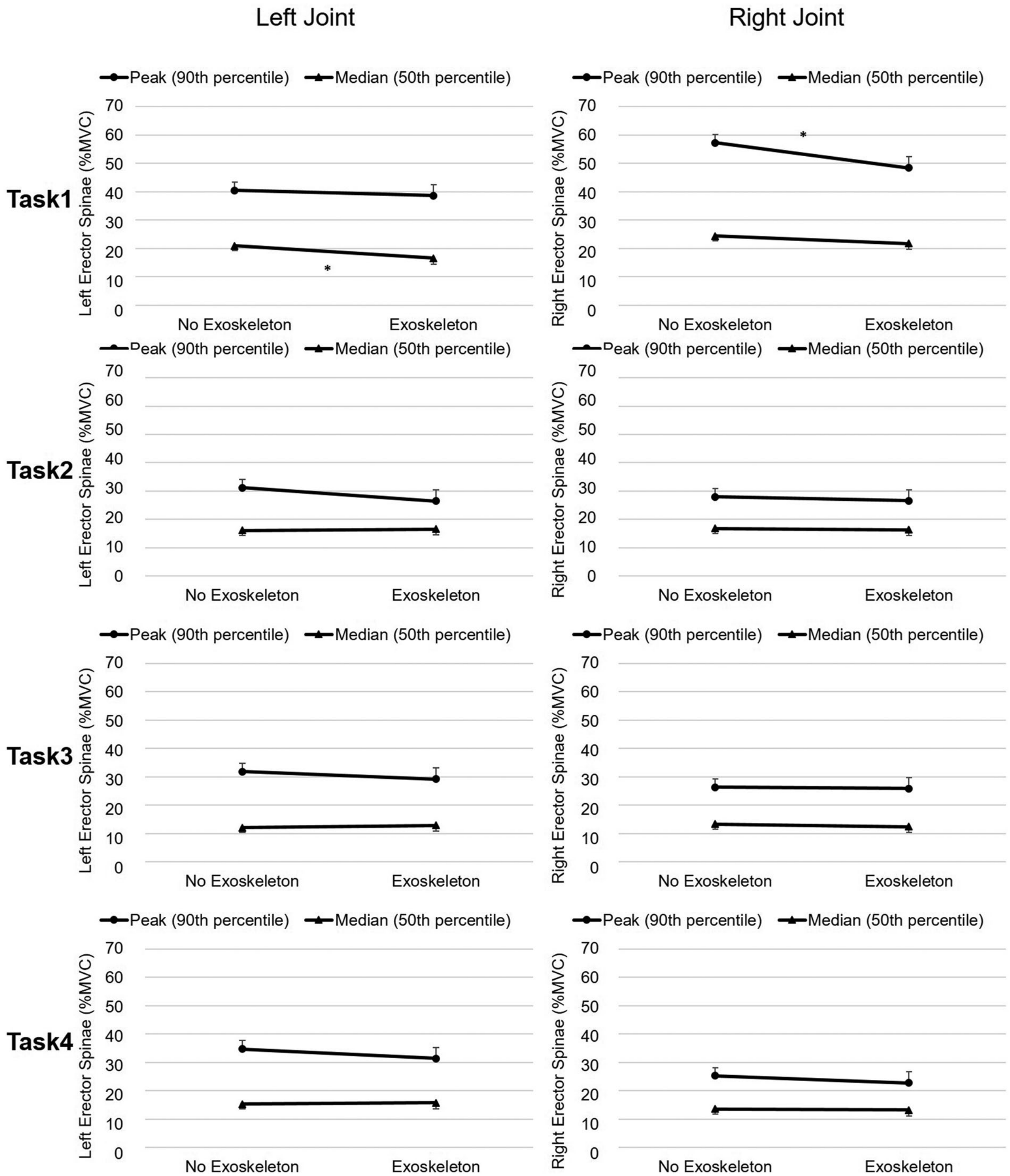

Figure 3. Mean and standard error of peak (90th percentile) and median (50th percentile) normalized muscle activities (%MVC) of the left and right erector spinae. *Significant difference ($p < 0.05$) with and without the exoskeleton. Note: MVC = maximum voluntary contraction; task 1 = sitting to lying; task 2 = repositioning toward the caregiver; task 3 = turning toward the caregiver; task 4 = turning away from the caregiver.

Although not statistically significant, sitting to lying (task 1) increased the heart rate by 10 bpm with the back-support exoskeleton (to 111 bpm). This reached the endurance limit of physical exertion (105–110 bpm), which could be associated with a risk to cardiovascular health [41]. Given conflicting findings about the cardiovascular impact of back-support exoskeletons [24,38,41], more studies are needed in both the laboratory and field settings.

In the present study, notable distinctions emerge among various treatment combinations with respect to certain variables. Despite the relatively small size of our sample, it is crucial to emphasize that the detection of statistically significant differences indicates that there was sufficient statistical power to discern such variations. This suggests that our study was adequately powered to identify meaningful differences despite the limitations in sample size. The study meticulously incorporates the calculated effect sizes for each variable, offering a lucid understanding of the treatment combinations and variables conducive to potential modifications through the implementation of engineering controls, specifically lift devices. The significance of these findings lies in their contribution to the broader scientific community, providing researchers with a foundational framework for subsequent investigations. Each evaluated variable is accompanied by an estimate of the effect size, coupled with an assessment of the variability surrounding these measures. This information is pivotal for advancing

Table 4. Mean (standard error), statistical significance and Cohen's effect sizes of mean heart rate (bpm) with and without the exoskeleton.

Task	No exoskeleton, mean (standard error)	Exoskeleton, mean (standard error)	Statistical significance (p)	Cohen's d effect sizes
1	100.47 (5.37)	111 (12.9)	0.348	0.267
2	99 (12.7)	98.16 (9.86)	0.944	−0.018
3	94.13 (4.65)	91.5 (8.1)	0.68	−0.1
4	92.46 (9.15)	96.08 (6.91)	0.13	0.112

Note: Task 1 = sitting to lying; task 2 = repositioning toward the caregiver; task 3 = turning toward the caregiver; task 4 = turning away from the caregiver.

the exploration of these devices in future studies, serving as a valuable resource for robust power calculations and aiding in the judicious selection of treatment conditions. In essence, this study furnishes essential insights into the utilization of lift devices, delineating pathways for future research endeavors and contributing to the progressive evolution of this pivotal field.

Although the study design was carefully considered and conducted, several limitations were noted. First, professional caregivers were not recruited for the study. Given the pandemic and shortage of hospital workers, it was very challenging to invite field healthcare workers to the laboratory; instead, university students were recruited for this study. We used a multimedia learning source to properly educate each participant before conducting the in-bed patient-handling tasks. Second, the short-term effect of back-support exoskeletons was assessed in the laboratory setting. Prolonged use of the back-support exoskeletons in the hospital setting may affect discomfort, fatigue and efficiency. This should be investigated in the future. Third, shoulder postures and muscle activities were not assessed in this study. There might be trade-offs if the exoskeleton reduces the trunk flexion and hip flexion, possibly resulting in increased shoulder flexion and muscle activities. This could be explored in future studies. Fourth, this study exclusively measured the erector spinae. Subsequent research endeavors could encompass the rectus abdominis and oblique muscles to evaluate the activation of both agonist and antagonist muscles during exoskeleton use. This additional analysis would contribute to discerning whether the exoskeleton induces heightened coactivation of the trunk muscles. Lastly, only one type of back-support exoskeleton model was tested in this study. We chose the Laevo V2.5 exoskeleton because it is commonly used and studied in laboratory and field settings and would allow us to compare our findings with those of previous studies to provide additional insights. Nevertheless, our findings may not be transferable to other types of back-support exoskeletons. Subsequent research endeavors may find value in exploring alternative back-support exoskeleton options tailored for patient handling, including soft exoskeletons constructed from elastic materials and powered exoskeletons crafted from rigid materials [42,43].

5. Conclusion

This study evaluated the effects of a back-support exoskeleton on the trunk and hip angles, lower back muscle activity and heart rate during four different in-bed patient handling tasks. The exoskeleton significantly reduced the hip flexion angles for all four tasks. The effects of the exoskeleton on trunk flexion and lower back muscle activities were dependent on the tasks. The exoskeleton demonstrated a significant reduction of trunk flexion during repositioning toward the caregiver (task 2) and turning away from the caregiver (task 4). Sitting to lying (task 1) required greater trunk flexion of caregivers compared to other tasks and the greatest reduction of lower back muscle activity occurred with the exoskeleton. The heart rate and the risk of adverse cardiovascular health effects were not significantly different with and without the exoskeleton. Our findings indicate that back-support exoskeletons are more effective in assisting in-bed patient handling tasks that require substantial trunk flexion to reposition patients. Future studies are needed to explore the long-term impact of back-support exoskeletons in a hospital setting.

Acknowledgements

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH/CDC.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by NIOSH/CDC.

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