Applied Ergonomics 93 (2021) 103373

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: http://www.elsevier.com/locate/apergo

Effects of passive back-support exoskeletons on physical demands and usability during patient transfer tasks

Jaejin Hwang [a,*], Venkata Naveen Kumar Yerriboina [a], Hemateja Ari [a], Jeong Ho Kim [b]

[a] Department of Industrial and Systems Engineering, Northern Illinois University, DeKalb, IL, USA
[b] School of Biological and Population Health Sciences, Oregon State University, Corvallis, OR, USA

ARTICLE INFO

Keywords:
Patient handling
Healthcare ergonomics
Electromyography
Hand pull force
Musculoskeletal disorders
Low back demand

ABSTRACT

The objective of this study was to evaluate and compare the effects of three passive back-support exoskeletons (FLx ErgoSkeleton, V22 ErgoSkeleton, and Laevo V2.5) and patient transfer methods on physical demands in the low back and shoulders during patient transfer. Twenty professional caregivers (17 females and 3 males) performed a series of simulated patient transfer tasks between a wheelchair and a bed with three different patient transfer methods including the squat pivot, stand pivot, and scoot with two directions (wheelchair to bed and vice versa). The passive exoskeletons (FLx ErgoSkeleton, V22 ErgoSkeleton, and Laevo V2.5) significantly affected trunk postures (forward flexion and lateral flexion), shoulder postures (flexion and abduction), hand pull forces, muscle activities of erector spinae and middle deltoid (p-values < 0.01). The muscle activities of the erector spinae were significantly lower (up to 11.2%) with the FLx and V22 ErgoSkeletons compared to no exoskeleton condition (p-values < 0.002). However, the trunk and shoulder flexion angles with the passive exoskeleton use were greater (up to 77.3%) than those without the exoskeletons (p-values < 0.03). The biomechanical benefits and usability varied by passive exoskeleton designs (p-values < 0.01). The lower muscle activities of the erector spinae suggest that the back-support exoskeletons may be a viable intervention to reduce the low back strain during patient transfer tasks. More research would be needed to reduce the adverse effects of back-support exoskeletons on the postures such as increased trunk and shoulder flexions during patient handling.

1. Introduction

Work-related musculoskeletal disorders (WMSDs) are highly prevalent among healthcare workers. A total number of the documented WMSD cases and their incidence rate among nursing assistants in the U. S. were 17,240 and 140.5 per 10,000 full time workers, respectively, and the primarily affected body parts was the low back followed by the shoulders (Bureau of Labor Statistics, 2018; Davis and Kotowski, 2015). Patient handling activities including patient lifting, transferring, and repositioning pose various physical risks associated with WMSDs (Budarick et al., 2019; Hwang et al., 2019b; Sun et al., 2018; Wiggermann et al., 2020). These WMSD-related risk factors consist of high force (overexertion), awkward postures (e.g., bending, twisting, and reaching), and variable patient behavior (e.g., unpredictable behavior and level of coordination) (Marras et al., 1999; Nagavarapu et al., 2016; Nelson et al., 2003).

Exoskeletons have recently gained attention as an innovative intervention to reduce the aforementioned physical risk factors by providing postural support and enhancing workers' physical capabilities. Commercially-available passive exoskeletons have been introduced and evaluated in several industries including shipbuilding, automotive, agricultural, and aerospace manufacturing (Alemi et al., 2020; Bosch et al., 2016; Picchiotti et al., 2019). Previous studies found that back-support exoskeletons reduced trunk muscle activities and energy expenditure during repetitive lifting and manual assembly tasks (Alemi et al., 2020; Madinei et al., 2019).

Despite these promising benefits, other studies have shown potential adverse effects (or limitations). Briefly, some of the aforementioned benefits of the exoskeletons were found to be dependent on task and exoskeleton (i.e., design and mechanism) (Alemi et al., 2020; Madinei et al., 2020). Moreover, passive exoskeletons could adversely affect body posture and self-reported discomfort (Kim et al., 2020), transfer load and related discomfort to other body parts (Hensel and Keil, 2019), increase the spine compression force due to increased abdominal muscle activities (Koopman et al., 2019), and adversely affect joint kinematics and gait performance (DeBusk et al., 2017).

* Corresponding author. Department of Industrial and Systems Engineering, Northern Illinois University, 590 Garden Road, EB230.
E-mail address: jhwang3@niu.edu (J. Hwang).

https://doi.org/10.1016/j.apergo.2021.103373
Received 6 August 2020; Received in revised form 14 January 2021; Accepted 17 January 2021
Available online 27 January 2021
0003-6870/

Given these potential benefits and limitations, it is important to evaluate the feasibility and efficacy of the exoskeletons in patient handling, especially because inadequate applications of exoskeletons can compromise the health and safety of both caregivers and patients. There have been a few studies investigating the efficacy of passive exoskeletons in a healthcare setting. A recent qualitative study identified the facilitators and barriers for the upper extremity exoskeleton implementation in the operating room by determining four themes including the individual characteristics, perceived benefits, environmental/societal factors, and intervention characteristics (Cha et al., 2019). Although this qualitative study identified urgent needs and potential viability for passive exoskeleton application for healthcare (primarily, surgeons), there has been a lack of quantitative studies to evaluate the biomechanical benefit and drawbacks of back-support exoskeletons in patient handling tasks.

Therefore, the objective of this study was to evaluate the effect of three different back-support passive exoskeletons (FLx ErgoSkeleton, V22 ErgoSkeleton, and Laevo V2.5) on the postures, muscle activities of the trunk and shoulders, and usability during patient transfer tasks (wheelchair-to-bed). The passive back-support exoskeletons were chosen in this study due to the maturity of the technologies, and they were commercially-available for the adoptions. The FLx and V22 ErgoSkeletons from StrongArm Technologies were selected as potential candidates due to their simple design and usability. A recent survey study of nurses indicated that perceived usefulness, ergonomics, and enjoyment of use were important factors for exoskeleton adoptions in healthcare settings (Turja et al., 2020). We also considered Laevo V2.5 as another candidate because it was one of the commonly tested and used passive back-support exoskeletons in various industrial settings. We hypothesized that the passive exoskeletons would lower physical demands in the low back during patient transfer tasks compared to no exoskeleton condition. We also hypothesized that biomechanical benefits and usability would be various by different passive exoskeleton designs.

2. Methods

2.1. Participants

Twenty professional caregivers (17 females and 3 males) were recruited for this study. The eligibility criteria included: 1) at least 6 months of caregiving experience, 2) no musculoskeletal pain in the past 7 days, 3) no current medication related to MSDs, and 4) no restrictions in physical activities. The sample size was determined based on previous studies showing that 20 participants detected the practical differences of measures in patient handling (Hwang et al, 2019b, 2020). Demographic and anthropometric information of participants is summarized in Table 1. One research assistant was designated to act as the simulated patient (age: 24 years; height: 181 cm, weight: 84 kg, and BMI: 25.6) throughout the experiment for all the participants.

2.2. Passive exoskeletons tested

As shown in Fig. 1, three different passive back-support exoskeletons were tested in this study: (a) FLx ErgoSkeleton (size medium, length 40.7–48.8 cm, mass 1.08 kg, StrongArm TechnologiesTM, Brooklyn, NY), (b) V22 ErgoSkeleton (size medium, length 41.9–52.1 cm, mass 1.29 kg, StrongArm TechnologiesTM, Brooklyn, NY), and (c) Laevo V2.5 (size small to large, mass 2.90 kg, Delft, The Netherlands). These passive exoskeletons are designed to reduce the force and torques on the low back region while stooping, bending, or lifting weights with minimal disruption of body movement (Bosch et al., 2016; Picchiotti et al., 2019). These selected passive exoskeletons had different mechanisms to unload the external load acting on the back. FLx ErgoSkeleton, consisting of a rigid rod that is aligned with the back with the straps for the torso and hip, is designed to prevent extensive flexion and twisting of the trunk. V22 ErgoSkeleton is similar to FLx ErgoSkeleton but includes the cables connecting from shoulders to the hands (via effectors). Laevo V2.5 uses gas springs for generating a torque, and body anchor points are designed at the chest, waist, and thighs to distribute the external load. The engagement angle of Laevo V2.5 was adjusted for individual participant's preferences. The training session was initially given until each participant became familiarized with each passive exoskeleton. The order of passive exoskeleton conditions was randomized to minimize the systematic bias due to the order.

Table 1
Mean and standard deviation of age, height, weight, and caregiving experience of participants.

	Age (years)	Height (cm)	Weight (kg)	Experience (years)
Average	24.7	163.4	64.0	3.5
Standard deviation	6.0	7.1	8.9	2.9

2.3. Patient transfer tasks

Simulated patient transfers between a wheelchair and a bed were used to evaluate the passive exoskeletons with three different task methods (squat pivot, stand pivot, and scoot) based on a previous study (Hess et al., 2007) as seen in Fig. 2. The simulated patient wore a transfer belt at his waist throughout the session. Regardless of different methods, the participants initially placed their one knee between the patient's knees and squatted with upright back postures (Fig. 2). The participants grasped the handles attached to two force transducers instead of directly grasping the transfer belt. The height of the wheelchair and the bed was set as 47 cm and 67.3 cm, respectively. The distance between the bed and the wheelchair was 91 cm. The wheelchair was placed at a 90° angle to the bed. Prior to the main data collection, participants were instructed on how to perform each patient transfer method consistently across tasks.

- Squat pivot: the participants gently swung the simulated patient to the destination (wheelchair or bed) so their feet pivoted. The participant used forward-backward rocking motions to create momentum to pivot the simulated patient. The simulated patient relaxed and slightly leaned forward to the participant. The participants helped the patient to aim his bottom to the middle of the seat or to the surface of the bed.
- Stand pivot: the participants lifted the simulated patient to a standing position and pivoted with two steps to be in front of the destination. The simulated patient relaxed his arms on his side during the transfer. The participants lowered the patient to the destination.
- Scoot, the participants lifted the patient 1–2 inches from the origin (called scoots) and gradually transferred the simulated patient toward the destination. Two scoots were performed to transfer the simulated patient. The participant applied small forward-backward rocking motions to create momentum. During the transfer, the simulated patient relaxed and slightly leaned forward to the participant.

2.4. Apparatus and measures

2.4.1. Kinematic and kinetic data

An 8-camera optical motion capture system (Flex 13; Optitrack; Natural Point, OR) with a sample rate of 100 Hz was utilized to measure the participants' movement during patient transfer tasks. A total of 27 reflective markers were placed on the head, torso, arms, hands, and the pelvis of the participants via the biomechanics marker set in the motion capture software (Motive 2.0; Optitrack; Natural Point, OR). Three-dimensional (3-D) angles of the trunk were computed based on the

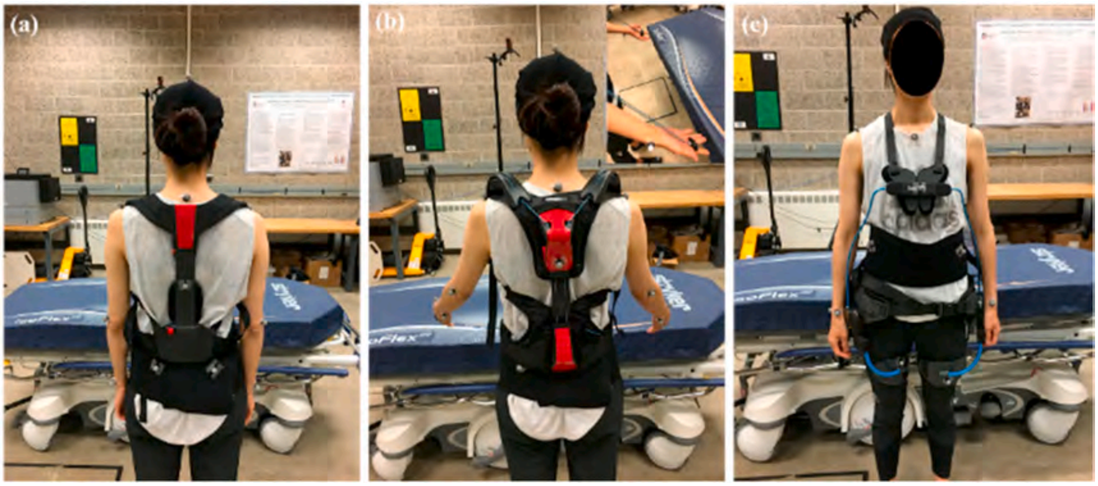

Fig. 1. Passive back support exoskeletons: (a) FLx ErgoSkeleton, (b) V22 ErgoSkeleton, and (c) Laevo V2.5.

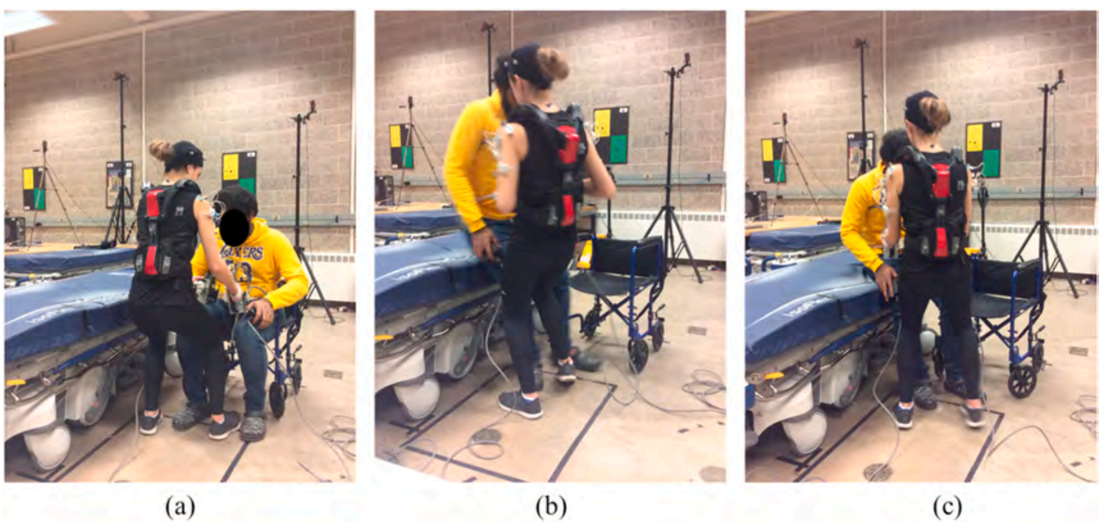

Fig. 2. Example of patient transferring tasks from wheelchair to bed: (a) squat pivot, (b) stand pivot, and (c) scoot.

rotation matrix between the local coordinate system of the torso and the ground. The 3-D angles of the shoulders were calculated between the local coordinate system of the torso and upper arms. The peak (95th percentile) angles of the trunk flexion and lateral flexion, and the shoulder flexion and abduction were summarized. The peak angles were chosen because overexertion due to the awkward posture has been known as a primary factor for the WMSDs among nurses.

The bilateral 3-D hand pull forces were measured using two 6-degrees-of-freedom force transducers at 1000 Hz (PY6; Bertec, Columbus, OH). Hand pull forces were measured as surrogated measures to identify whether wearing passive exoskeletons transfer different amount of forces to the hand. The handles were attached to the force transducers, so participants grasped the handles during patient transfers. The other sides of the force transducers were secured onto the transfer belt at the simulated patient's waist. The peak (95th percentile) magnitude of the resultant force at each hand was computed based on 3-D force components.

2.4.2. *Electromyography*

The muscle activities of the low back and shoulders were recorded using a wireless data logger (WBA; Mega Electronics; Kupio, Finland) at 1000 Hz. The Ag/AgCl surface electrodes (Blue Sensor N; Ambu; Ballerup, Denmark) were placed bilaterally on six muscle sites: 1–2) lumbar erector spinae (iliocostalis lumborum) (ES), 3–4) anterior deltoids (AD), and 5–6) middle deltoids (MD). Previous studies showed that these muscle groups were highly active during patient turning, pushing, pulling, and transferring activities (Hwang et al, 2019a, 2019b; Sun et al., 2015). Skin preparation and identification of the electrode locations followed the European Recommendation for Surface Electromyography (Hermens et al., 1999). To normalize muscle activities, a series of the maximum voluntary contractions (MVC) and the reference voluntary contractions (RVC) were collected. For the RVC of ES, participants maintained 30° trunk flexion postures for 3 s (Soderberg and Knutson, 2000). For the MVC of AD and MD muscles, participants performed two different exertions: 1) the shoulder abduction (90°) with the internal rotation by resisting the downward force at the wrist (i.e., empty can), and 2) the shoulder flexion (125°) by resisting the downward force at the elbow (Boettcher et al., 2008). Each MVC/RVC exertions were performed three times with a 2-min break.

The band-pass filter (10–350 Hz) was applied to the raw EMG data, and then the root mean square EMG was computed using a 125-milisecond moving window via MegaWin software (Mega Electronics; Kupio, Finland). Processed EMG data of each task were normalized by the peak values (95th percentile) of MVC or RVC of individual muscle (%MVC or %RVC). The Amplitude Probability Density Function was employed to extract the peak normalized EMG (nEMG) values (90th percentile) of each task (Jonsson, 1982). The peak nEMG values were chosen to evaluate the risk of overexertion injuries in patient transfers.

2.4.3. Usability

After using each passive exoskeleton, the participants rated the usability based on the System Usability Scale (SUS) (Bangor et al., 2009). The SUS consisted of ten statements (a mixture of 5 positive and 5 negative statements) with a 10-point scale ranged from strongly disagree to strongly agree. The SUS has been used to evaluate the usability of passive exoskeletons (Cha et al., 2019; Huysamen et al., 2018a, 2018b). Specific questions are described in Table 2. Acceptable usability was considered if a SUS score was greater than 70 out of 100. The acceptable usability was further divided into three levels including good (70–80), excellent (80–90), and best imaginable (90–100).

2.5. Statistical analysis

The independent variables were the passive exoskeleton conditions (no exoskeleton, FLx ErgoSkeleton, V22 ErgoSkeleton, and Laevo V2.5) and the patient transfer methods (squat pivot, stand pivot, and scoot). The dependent variables included the trunk flexion and lateral flexion angles; shoulder flexion and abduction angles; hand pull forces; muscle activities of the low back and shoulders; and the usability ratings. The normality of the dependent variables was diagnosed prior to formal statistical modeling. For the normally-distributed data, two-way repeated-measures analysis of variance (ANOVA) was conducted to evaluate the main effect and two-way interaction effects of the passive exoskeletons and patient transfer methods. The passive exoskeleton and patient transfer method were set as fixed effects and the participant was set as a random effect. Due to their skewed distributions, the joint angle, hand pull force, and muscle activity data were transformed using either logarithm, Johnson, or square root transformations. The transformed data were analyzed in the same ways as the normal data as described earlier. Because the usability data violated the normality assumptions even after transformation, they were analyzed by *Friedman* tests (a non-parametric test equivalent to repeated-measures ANOVA). The post-hoc pairwise tests (*Tukey* HSD or *Wilcoxon* signed rank) were further conducted when statistical significance was found (i.e., $p < 0.05$). The effect sizes (Cohen's d) were calculated to assess the pairwise differences in dependent variables among passive exoskeleton conditions.

3. Results

3.1. Kinematic and kinetic data

3.1.1. Trunk postures

As shown in Table 3, Fig. 3, and Appendix Table 1, the back-support exoskeletons significantly affected the trunk flexion and lateral flexion angles (p-values < 0.001). All three passive exoskeletons significantly increased the trunk flexion angle by (mean difference: up to 9.7°; p-values < 0.001; effect size = 0.36 to 0.98) and right lateral flexion angle (mean difference: 10.4°; p-values < 0.002; effect size = 0.26 to 0.94) compared to no exoskeleton condition. The Laevo V2.5 exoskeleton showed greater left lateral trunk flexion angle relative to no exoskeleton condition (mean difference: 2.9°; $p < 0.001$; effect size = 0.34).

There were significant two-way interaction effects between the passive exoskeletons and transfer methods on the trunk flexion and lateral flexion angles (p-values < 0.006). For the trunk flexion and right lateral flexion, V22 ErgoSkeleton showed 7.7°–11.4° higher angles compared to other passive exoskeleton conditions, especially in the scoot method (Fig. 3). For the trunk left lateral flexion, the scoot method showed different patterns among passive exoskeleton conditions compared to squat and stand pivot methods.

3.1.2. Shoulder postures

As shown in Table 3, Fig. 4, and Appendix Table 1, the bilateral shoulder flexion and abduction angles were significantly affected by the passive exoskeletons ($p < 0.001$). The passive exoskeletons showed higher bilateral shoulder flexion angles (up to 4.3°) than no exoskeleton condition (p-values < 0.03; effect size = 0.17 to 0.35). The Laevo V2.5 exoskeleton showed 5.1° greater left shoulder abduction angle than no exoskeleton condition ($p < 0.001$; effect size = 0.42). The V22 ErgoSkeleton and Laevo V2.5 exoskeletons showed higher right shoulder abduction angles (up to 3.8°) compared to no exoskeleton condition (p-values < 0.001; effect size = 0.28–0.32). No significant two-way interaction between the passive exoskeletons and transfer methods were found (p-values > 0.29).

3.1.2.1. Hand pull force. The bilateral hand pull forces were significantly different among passive exoskeletons (p-values < 0.001) as shown in Table 3, Fig. 5, and Appendix Table 1. The Laevo V2.5 exoskeleton showed greater (up to 11.2N) bilateral hand pull forces than no exoskeleton condition (p-values < 0.001; effect size = 0.16 to 0.27). The V22 ErgoSkeleton showed 8.3N lower right hand pull force than no exoskeleton condition ($p = 0.004$; effect size = −0.21). There were no significant two-way interaction effects between the passive exoskeletons and the transfer methods (p-values > 0.12).

3.2. Electromyography (EMG)

3.2.1. Effects of passive exoskeletons on nEMG

The passive exoskeletons significantly affected the erector spinae (ES) muscle activities (p-values < 0.01) as shown in Table 3, Fig. 6, and Appendix Table 1. The FLx ErgoSkeleton exoskeleton showed significantly lower Left ES (LES) muscle activity (mean difference: 15.2%RVC) whereas the V22 ErgoSkeleton showed greater LES muscle activity (mean difference: 6.6%RVC) compared to no exoskeleton condition (p-values < 0.01; effect size = −0.11 to 0.05). The Right ES (RES) muscle activity was significantly lower (mean difference: up to 40.4%RVC) with the FLx ErgoSkeleton and V22 ErgoSkeleton compared to no exoskeleton condition (p-values < 0.002; effect size = −0.26 to −0.14). The passive exoskeletons had a significant effect on the muscle activities of the right anterior deltoid (RAD) and bilateral middle deltoid (right: RMD; left: LMD) (p-values < 0.01). The V22 ErgoSkeleton showed lower RAD muscle activity (mean difference: 1.6%MVC) than no exoskeleton condition ($p = 0.02$; effect size = −0.14). The Laevo V2.5 exoskeleton showed higher LMD muscle activity (mean difference: 4.1%MVC) compared to no exoskeleton condition ($p < 0.001$; effect size = 0.45).

3.2.2. Interaction effects between the passive exoskeletons and patient transfer methods on nEMG

There were significant two-way interactions (passive exoskeleton x transfer method) on muscle activities bilaterally in the ES and MD muscles (p-values < 0.01). This indicates that the efficacy of passive exoskeletons may depend on tasks. All three passive exoskeletons reduced the LES muscle activity (mean difference: up to 106.8%RVC)

Table 2
Description of system usability scale questions.

Number	Question
1	I think that I would like to use this product frequently
2	I found the product unnecessarily complex
3	I thought the product was easy to use
4	I think that I would need the support of a technical person to be able to use this product
5	I found the various functions in the product were well integrated
6	I thought there was too much inconsistency in this product
7	I imagine that most people would learn to use this product very quickly
8	I found the product very awkward to use
9	I felt very confident using the product
10	I needed to learn a lot of things before I could get going with this product

Table 3
Mean (standard error) and p-values of trunk and shoulder postures, bilateral hand pull forces, and normalized muscle activities of four different passive exoskeleton conditions.

	Measure	No Exoskeleton	FLx	V22	Laevo	p-value
Joint angle	Trunk flexion (°)	12.6 (0.6)	15.6 (0.4)	22.4 (0.7)	18.7 (0.6)	<0.001
	Trunk left lateral flexion (°)	5.4 (0.3)	5.8 (0.3)	6.2 (0.5)	8.3 (0.7)	<0.001
	Trunk right lateral flexion (°)	21 (0.6)	23.4 (0.6)	31.3 (0.8)	23.8 (0.7)	<0.001
	Left shoulder flexion (°)	33 (0.7)	35.1 (0.6)	35.9 (0.8)	34.9 (0.7)	<0.001
	Right shoulder flexion (°)	32.3 (0.7)	34.2 (0.6)	36.6 (0.9)	35 (0.7)	<0.001
	Left shoulder abduction (°)	23.7 (0.7)	25.1 (0.7)	25.1 (0.7)	28.8 (0.9)	<0.001
	Right shoulder abduction (°)	28.2 (0.7)	28.8 (0.7)	31.6 (0.8)	32 (0.8)	<0.001
Force	Left hand pull force (N)	61.3 (2.5)	58.8 (3.1)	61.6 (2.9)	67.3 (2.4)	<0.001
	Right hand pull force (N)	74.6 (2.8)	70.4 (2.4)	66.3 (2.4)	85.8 (2.6)	<0.001
EMG	Left erector spinae (%RVC)	162.6 (9.5)	147.4 (9.2)	169.3 (7.9)	161 (11.1)	<0.001
	Right erector spinae (%RVC)	172.6 (11.9)	150.5 (8.9)	132.2 (8.1)	156.5 (7.3)	<0.001
	Left anterior deltoid (%MVC)	11.7 (0.8)	11.7 (0.8)	12.3 (0.8)	10.8 (0.7)	0.383
	Right anterior deltoid (%MVC)	11.2 (0.8)	11.3 (0.8)	9.6 (0.7)	10.4 (0.7)	0.010
	Left middle deltoid (%MVC)	11.1 (0.5)	11 (0.5)	11.7 (0.5)	15.1 (0.7)	<0.001
	Right middle deltoid (%MVC)	13.2 (0.6)	12.2 (0.5)	13.1 (0.7)	14.1 (0.7)	0.004

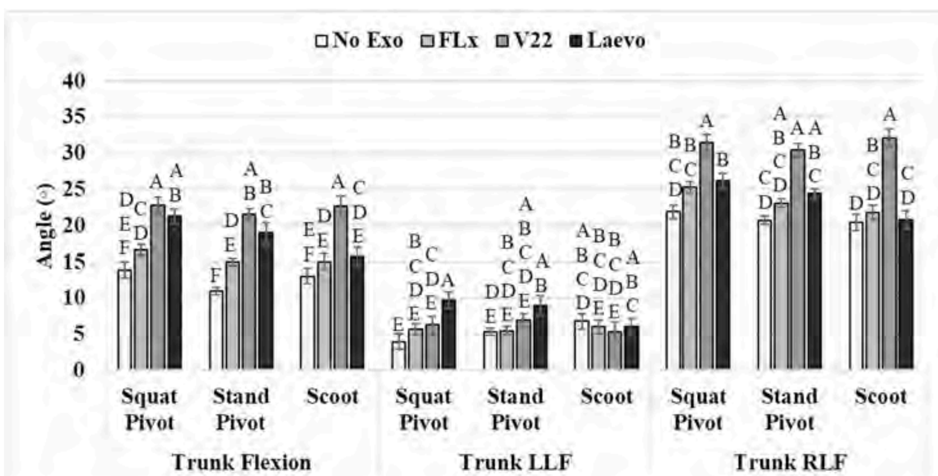

Fig. 3. Peak (95th percentile) trunk flexion, left lateral flexion (LLF), right lateral flexion (RLF) angles by four different passive exoskeleton conditions (FLx ErgoSkeleton, V22 ErgoSkeleton, Laevo V2.5, and no Exo) and three different transfer methods (squat pivot, stand pivot, and scoot methods). Alphabet letters indicate a significant difference among the combination of the exoskeleton and patient transfer methods for each measure.

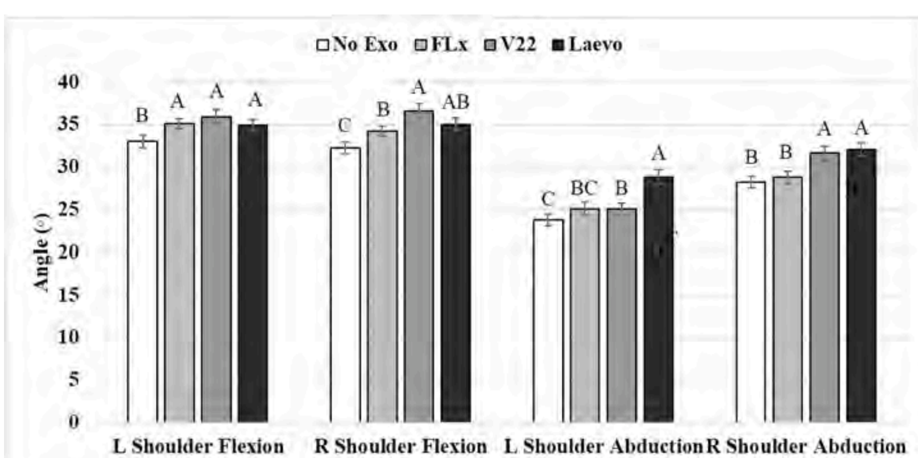

Fig. 4. Peak (95th percentile) left (L) shoulder flexion, right (R) shoulder flexion, left shoulder abduction, and right shoulder abduction angles by four different passive exoskeleton conditions (FLx ErgoSkeleton, V22 ErgoSkeleton, Laevo V2.5, and no Exo). Alphabet letters indicate a significant difference among exoskeleton conditions.

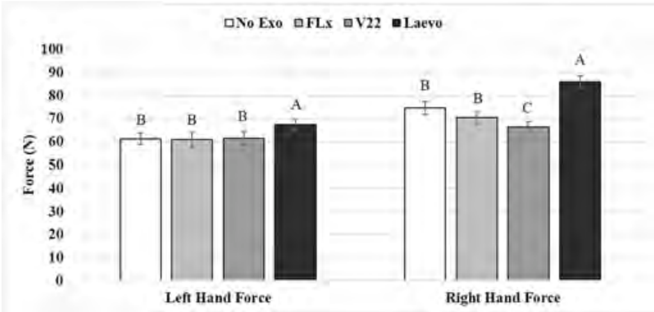

Fig. 5. Peak (95th percentile) left and right hand pull forces by four different passive exoskeleton conditions (FLx ErgoSkeleton, V22 ErgoSkeleton, Laevo V2.5, and no Exo). Alphabet letters indicate a significant difference among exoskeleton conditions.

relative to no exoskeleton condition when using the scoot transfer method; however, the LES muscle activity was higher with the passive exoskeletons (mean difference: up to 89.8%RVC) compared to no exoskeleton when the squat pivot method was used. All three passive exoskeletons lowered the RES muscle activities (mean difference: up to 83.5%RVC) relative to no exoskeleton condition during transferring the patient with the squat and stand pivot method. During transferring the patient via the scoot method, however, the RES muscle activities were higher with the passive exoskeletons (mean difference: up to 18.2%RVC) compared to no exoskeleton condition.

The FLx ErgoSkeleton exoskeleton reduced the LMD muscle activities (mean difference: up to 3.5%MVC) during the stand pivot and scoot transfer whereas all three passive exoskeletons increased the LMD muscle activities (mean difference: up to 4.1%MVC) with the squat pivot method compared to no exoskeleton. The FLx ErgoSkeleton and V22 ErgoSkeleton reduced the RMD muscle activities (mean difference: up to 4.7%MVC) during the squat and stand pivot transfer whereas all three passive exoskeletons increased the RMD muscle activities (mean difference: up to 8.3%MVC) during the scoot transfer compared to no exoskeleton.

3.3. Usability

Most usability measures (8 of 10) were significantly affected by passive exoskeletons (p-values < 0.01) (Table 4 and Appendix Table 2). The participants preferred the FLx ErgoSkeleton exoskeleton compared to the other exoskeletons due to the easiness of use and minimal effort to learn (questions 2, 3, 4, 7, 8, and 10) (effect size $= -1.61$ to 0.85). Little difference was found in the usability measures between the V22 ErgoSkeleton and Laevo V2.5 exoskeleton. The overall SUS score was significantly higher with the FLx ErgoSkeleton exoskeleton compared to the other exoskeletons (p-values < 0.001; effect size $= 1.08$ to 1.24).

4. Discussion

This study evaluated the effect of three passive exoskeletons and patient transfer methods on physical demands in the low back and shoulders as well as usability. The passive exoskeletons significantly affected the trunk and shoulder postures, hand pull forces, low back and shoulder muscle activities, and usability ratings. The biomechanical effects of the passive exoskeletons appeared to depend on the patient transfer methods. The participants preferred using the FLx ErgoSkeleton exoskeleton compared to the V22 ErgoSkeleton and Laevo V2.5 exoskeletons due to its simple design, easiness of use and minimal effort to learn the device.

4.1. Effects of passive exoskeletons and patient transfer methods on the low back demand

The RES muscle activities were significantly reduced by the FLx and V22 ErgoSkeletons (up to 40.4%RVC) compared to no exoskeleton condition, especially during the squat and stand pivot transfer method. This was linked to the trend of the right hand pull force (8.3N reduction compared to no exoskeleton condition). The result could be related to the hand effectors utilized in the V22 ErgoSkeleton. The hand effectors with the cables were designed to pull the external load; therefore, some amount of the external load acting on the hand could be transferred via the cables to the shoulders and the device itself (Picchiotti et al., 2019). Hand force has been one of the primary risk factors during patient handling, and associated with the spinal loads (Budarick et al., 2019; Wiggermann et al., 2020). These results along with previous findings suggest that the passive exoskeletons may have the potential to reduce the physical demands in the low back during patient transfer by directly reducing or transferring the hand forces to the shoulders and the device itself.

Although the greatest reduction of RES muscle activities was observed with the V22 ErgoSkeleton, the trunk angles were higher with this passive exoskeleton compared to no exoskeleton condition. For instance, the V22 ErgoSkeleton showed significantly higher peak trunk flexion (up to 9.7°) and right lateral flexion angles (up to 10.4°) relative to no exoskeleton condition. This indicates that the trunk angle differences found in this study may have a smaller contribution to reducing the RES muscle activity compared to the hand pull force. These greater trunk flexion angles may have been due to the fact that the participants had to bend their trunk more to securely position the hand effectors on the grasping points and properly activate the pulling cables of the V22 ErgoSkeleton. This is consistent with the previous study showing that increased trunk flexion was observed while wearing the V22 ErgoSkeleton during squatting lifting exertions (Picchiotti et al., 2019). In contrast, the FLx ErgoSkeleton did not show a practical difference of trunk angles compared to no exoskeleton, which was similar to the previous finding (Picchiotti et al., 2019). The FLx ErgoSkeleton was designed to limit a substantial amount of trunk flexion or twisting, which could lead to the results of the present study.

The effects of the passive exoskeletons on the ES muscle activities depended on the patient transfer methods. This could be related to the combination of the different body mechanics involved in the patient transfer methods and different support mechanisms produced in the passive exoskeletons. All three passive exoskeletons showed the greatest reduction in RES muscle activities, especially during the squat pivot transfer. The squat pivot transfer method exhibited greater trunk flexion and right lateral flexion angles than the other transfer methods. With the increased trunk flexion angles, more resistance or support torque could have been provided by passive exoskeletons; therefore, biomechanical benefits increased, which was consistent with the previous studies (Koopman et al., 2019; Madinei et al., 2020; Picchiotti et al., 2019).

The trunk lateral flexion on the right side (mean: 24.9°) was found much greater than the left side (mean: 6.4°). This could be related to the experimental setting in this study. The wheelchair was located at the right side relative to the hospital bed, which increased participants' trunk lateral flexion on the right side to transfer the patient. For the muscle activities of erector spinae, left erector spinae (mean: 160.1% RVC) showed higher muscle activities than the right side (mean: 153.0% RVC). Based on the biomechanical principles, the left-side erector spinae could be more active to counterbalance the torque around the spine. In addition, the left-side erector spine should be more stretched than the right-side, which could lead to greater passive muscle force on the left side. These side-specific results would depend on the location of the wheelchair relative to the hospital bed.

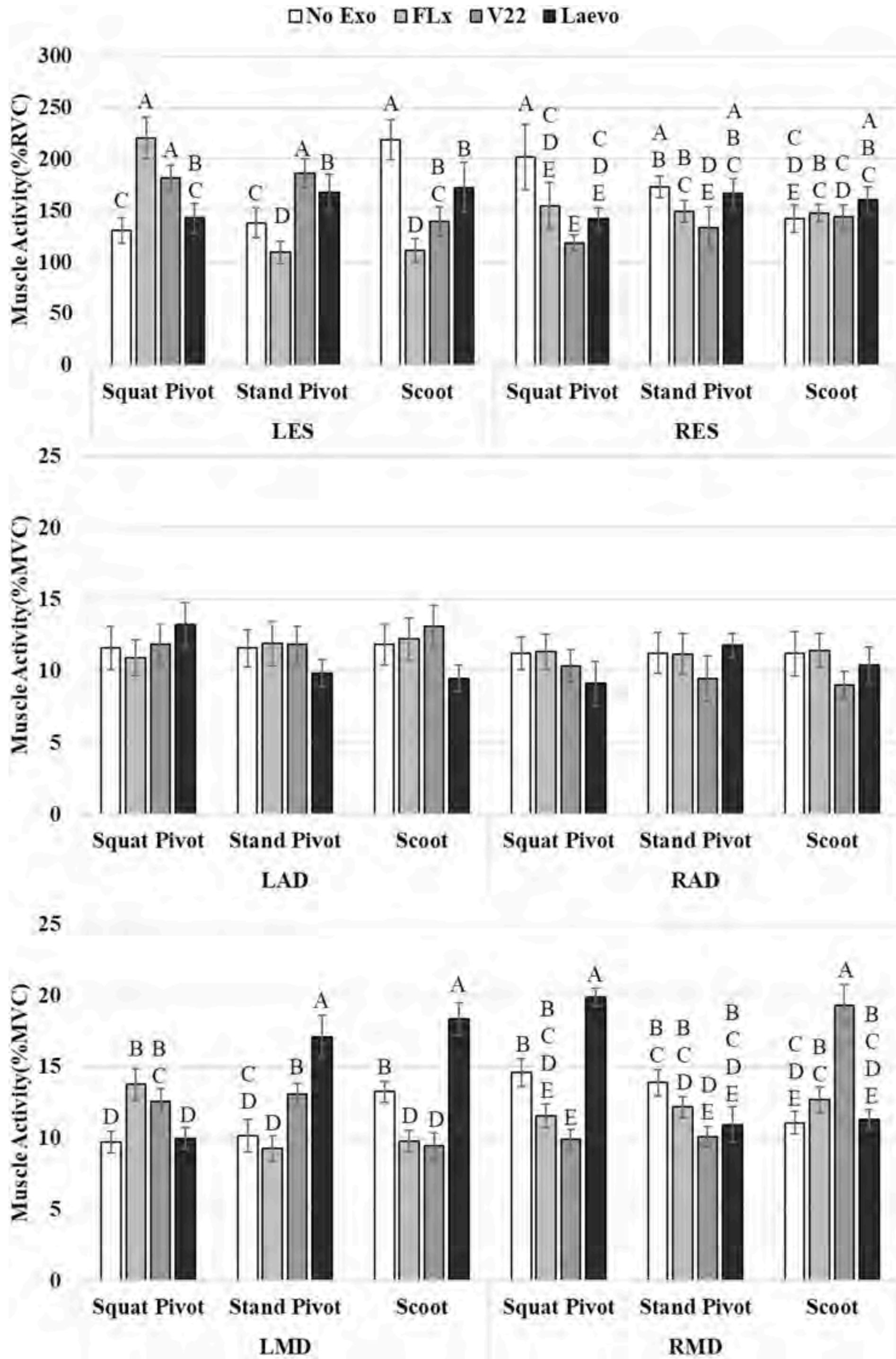

Fig. 6. Peak (90th percentile) normalized muscle activities of bilateral erector spinae (L/RES), anterior deltoid (L/RAD) and middle deltoid (L/RMD) by four different passive exoskeleton conditions (FLx ErgoSkeleton, V22 ErgoSkeleton, Laevo V2.5, and no Exo) and three different transfer methods (squat pivot, stand pivot, and scoot methods). Alphabet letters indicate a significant difference among the combination of the exoskeleton and patient transfer methods for each measure.

4.2. Effects of passive exoskeletons and patient transfer methods on the shoulder demand

Although the right AD muscle activities were significantly affected by passive exoskeletons, the difference was practically small (mean difference: up to 1.6%MVC). This was consistent with previous studies showing that back-support exoskeletons did not show any adverse effects on AD muscle activities during symmetric and asymmetric lifting tasks (Alemi et al., 2020; Madinei et al., 2020).

However, the Laevo V2.5 exoskeleton showed significantly higher left MD muscle activity (mean difference: by 4.1%MVC) compared to no exoskeleton. This was associated with a greater hand pull force (up to 11.2N) and greater left shoulder abduction angles (up to 5.1°). Moreover, when the Laevo V2.5 exoskeleton was used, the left MD muscle activities further increased with the stand pivot and scoot transfer method compared to the squat pivot method. The stand pivot and scoot transfer method often require either sustained or repeated trunk extension movement. Previous studies showed that inconsistent torque

Table 4
Mean (standard error) of 10-point usability ratings ranged from strongly disagree (0) to strongly agree (10) by three different passive exoskeleton conditions. Different alphabet letters (A and B) denote significant differences among passive exoskeleton groups using post-hoc tests.

Questions	FLx	V22	Laevo	*p*-value
1. I think that I would like to use this product frequently.	6.1 [B] (0.7)	3.4 [A] (0.7)	4.1 [AB] (0.8)	**0.01**
2. I found the product unnecessarily complex.	1.7 [A] (0.6)	5.0 [B] (0.8)	5.1 [B] (0.7)	**<0.001**
3. I thought the product was easy to use.	8.1 [B] (0.5)	6.0 [A] (0.6)	5.9 [A] (0.7)	**<0.001**
4. I think that I would need the support of a technical person to be able to use this product.	2.3 [A] (0.6)	4.0 [B] (0.8)	4.7 [B] (0.8)	**0.01**
5. I found the various functions in the product were well integrated.	7.2 (0.4)	5.5 (0.8)	6.3 (0.6)	0.13
6. I thought there was too much inconsistency in this product.	1.4 (0.6)	2.7 (0.7)	2.1 (0.6)	0.06
7. I imagine that most people would learn to use this product very quickly.	8.6 [B] (0.4)	7.1 [AB] (0.7)	6.8 [A] (0.7)	**0.01**
8. I found the product very awkward to use.	2.2 [A] (0.5)	6.9 [B] (0.8)	6.0 [B] (0.8)	**<0.001**
9. I felt very confident using the product.	8.2 [B] (0.4)	5.3 [A] (0.7)	5.8 [A] (0.6)	**<0.001**
10. I needed to learn a lot of things before I could get going with this product.	1.9 [A] (0.6)	3.4 [B] (0.8)	3.2 [B] (0.8)	**0.003**
Total System Usability Scale (SUS) scores	76.2 (2.9)	54.9 (4.6)	57.1 (4.8)	**0.002**

profiles (i.e., a hysteresis effect) of the Laevo V2.5 exoskeleton occurred during trunk extension movements (Koopman et al., 2019; Madinei et al., 2020). Due to inconsistent support from the Laevo V2.5 exoskeleton during trunk extension exertions (stand pivot and scoot), participants' postural demand of arms/shoulders may have increased to compensate for their movements.

4.3. Effects of passive exoskeletons on the usability (System Usability Scale: SUS)

The SUS scores showed that the FLx ErgoSkeleton exoskeleton had acceptable (e.g., good level) usability (SUS score: 76.2) whereas the other exoskeletons were within the unacceptable usability levels (SUS scores: 50–60). The participants preferred the FLx ErgoSkeleton exoskeleton mainly due to its simple design, minimal effort to learn, and ease of use. Both V22 ErgoSkeleton and Laevo V2.5 exoskeletons had lower usability scores because they had complex designs and were difficult to use, and therefore the participants did not feel confident to use the V22 ErgoSkeleton and Laevo V2.5 exoskeletons. This result was different from a previous study showing that the Laevo V2.5 exoskeleton showed an acceptable range of usability during simple sagittal plane lifting and lowering tasks (Huysamen et al., 2018b). The patient transfer activities involved complex asymmetric trunk motions, which could lead to lower usability scores than controlled sagittal lifting/lowering exertions performed in the previous study. In addition, the majority of the participants were female in this study. The load distributions on the chest support while using Laevo V2.5 could also increase female participants' discomfort, which has been reported in previous studies (Bosch et al., 2016; Hensel and Keil, 2019). This finding provides two important implications that 1) the effectiveness of passive exoskeletons may vary by tasks; 2) simple but effective design of passive exoskeletons requiring minimal effort to learn and use could be an important consideration for potential passive exoskeleton adoption for patient handling tasks.

4.4. Limitations

This study has some limitations that are noteworthy. First, only three types of passive back-support exoskeletons were evaluated in this study. Although we carefully selected three passive exoskeletons as a potential intervention to patient handling based on different support mechanisms involved in passive exoskeletons (Alemi et al., 2020; Picchiotti et al., 2019), the study results may not be generalized to other passive exoskeletons with a considerably different design. Second, only one simulated patient with BMI of 25.6 was used for the simulated transfer tasks in this study. Given the increasing number of obesity rates, the obese and extremely obese levels of patients could be also investigated to understand the feasibility and functional limit of back-support exoskeletons. Lastly, we evaluated the biomechanical effects of passive exoskeletons in a controlled laboratory setting. Our study results do not convey the feasibility and efficacy of passive exoskeletons in actual hospital settings. More rigorous field-based trials are essential to determine the feasibility, acceptability, and potential barriers of back-support exoskeletons for patient handling tasks.

5. Conclusion

Three passive back-support exoskeletons were tested and they showed significantly different effects on the trunk postures (flexion and lateral flexion), shoulder postures (flexion and abduction), hand pull forces, low back (erector spinae) and shoulder (middle deltoid) muscle activities during simulated patient transfer tasks between a wheelchair and a bed. Moreover, the biomechanical effects of passive exoskeletons on the trunk postures and ES and MD muscle activities depended on the patient transfer method (squat pivot, stand pivot, and scoot). The usability measures indicate that simple design, easy-to-use, and easy-to-learn may be important factors that can facilitate the adoption of back-support exoskeletons in healthcare settings.

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.

Table 1
Effect sizes (Cohen's d) of trunk and shoulder postures, bilateral hand pull forces, and normalized muscle activities of three passive exoskeletons relative to no exoskeleton condition.

	Measure	No Exoskeleton-FLx	No Exoskeleton –V22	No Exoskeleton – Laevo
Joint angle	Trunk flexion	0.36	0.98	0.64
	Trunk left lateral flexion	0.08	0.12	0.34
	Trunk right lateral flexion	0.26	0.94	0.27
	Left shoulder flexion	0.20	0.24	0.17
	Right shoulder flexion	0.20	0.35	0.26
	Left shoulder abduction	0.13	0.13	0.42
	Right shoulder abduction	0.05	0.28	0.32
Force	Left hand pull force	−0.07	0.01	0.16
	Right hand pull force	−0.11	−0.21	0.27
EMG	Left erector spinae	−0.11	0.05	−0.01
	Right erector spinae	−0.14	−0.26	−0.11

(*continued on next page*)

Table 1 (*continued*)

Measure	No Exoskeleton-FLx	No Exoskeleton –V22	No Exoskeleton – Laevo
Left anterior deltoid	0.00	0.05	−0.08
Right anterior deltoid	0.01	−0.14	−0.07
Left middle deltoid	−0.01	0.08	0.45
Right middle deltoid	−0.12	−0.01	0.09

Table 2
Effect sizes (Cohen's d) of usability ratings among three passive exoskeletons.

Measure	FLx–V22	FLx–Laevo	V22 – Laevo
1. I think that I would like to use this product frequently.	0.86	0.61	−0.21
2. I found the product unnecessarily complex.	−1.05	−1.18	−0.03
3. I thought the product was easy to use.	0.85	0.83	0.03
4. I think that I would need the support of a technical person to be able to use this product.	−0.54	−0.74	−0.19
5. I found the various functions in the product were well integrated.	0.62	0.40	−0.26
6. I thought there was too much inconsistency in this product.	−0.47	−0.27	0.21
7. I imagine that most people would learn to use this product very quickly.	0.61	0.67	0.10
8. I found the product very awkward to use.	−1.61	−1.33	0.26
9. I felt very confident using the product.	1.16	1.06	−0.17
10. I needed to learn a lot of things before I could get going with this product.	−0.47	−0.41	0.06
Total SUS scores	1.24	1.08	−0.10

Acknowledgement

This research was supported by the National Institute for Occupational Safety and Health (NIOSH) Grant #T42/OH008672. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH. The authors would like to thank Charan Madasu at Northern Illinois University for supporting the data collection.

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