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Comparing the Effects of User Preference and Experience When Using Passive Low Back Exoskeletons on Physical and Cognitive Load While Performing Simulated Manufacturing Tasks

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Abstract

Low-back passive exoskeletons have been introduced in manufacturing settings as personal protective equipment (PPE) with the intent to prevent back injuries. However, the effects of user preference and experience on physical and cognitive demands are still unclear. This study aimed to (1) evaluate users' physical and cognitive responses to different passive low back exoskeletons while performing simulated manufacturing tasks and (2) compare users' performance with their preferred exoskeletons after training. Twenty-four participants performed simulated manufacturing tasks for the intended use of the exoskeleton (lifting) and unrelated use (walking and drilling) without an exoskeleton and with four commercially available exoskeletons. The data presented in this paper analyzed a subset of data from one simulated manufacturing task (lifting). Over 70% of the participants benefited from at least one exoskeleton when performing the lifting task. Thirteen (54%) of the participants chose an exoskeleton that decreased muscle activation in the erector spinae (up to 20%) and/or the gluteus maximus (up to 10%). The most common deciding factors when the participants ranked the exoskeletons included support, comfort, and range of motion. However, the participants had different criteria for selecting a preferred exoskeleton. The knowledge gained from this research might lead to improved exoskeleton design and the development of new training protocols that ensure the safety and well-being of users.

Keywords

exoskeleton, training, physical demands, cognitive demands, manufacturing

Introduction

An estimated 16 million people, 13% of the United States (U.S.) labor force, work in the manufacturing sector. Approximately 43% of manual laborers and maintenance/repair workers have experienced lower back musculoskeletal disorders (MSDs), often due to exposure to physical risk factors such as overexertion and repetitive motion. Work-related MSDs are associated with a median of 8 days away from work, 2 days more than other nonfatal injuries and diseases (CDC, 2010). Reducing the risk of MSDs can improve productivity, reduce medical and workers' compensation costs, and increase employee satisfaction. Exoskeletons have been introduced in some manufacturing plants as personal protective equipment (PPE) to reduce the likelihood of MSDs. However, PPE must fit and function properly to minimize risks, or it may introduce hazards. Three types of fit, static, dynamic, and cognitive, must be considered before implementing exoskeletons in an operational environment (Stirling et al., 2020). Static fit considers alignment between target users' anthropometric characteristics and the sizing of the exoskeletons. Dynamic fit focuses on the relative alignment and considers how the users and exoskeletons move and interact with each other in dynamic systems. Cognitive fit assesses users' information processing ability and ideally remains at the same level throughout tasks. Therefore, it is essential to consider individuals' experiences and preferences when selecting PPE.

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Although previous studies have demonstrated that exoskeletons can potentially reduce loads or stress, the effects of user preference and experience on physical and cognitive demands are still unclear. Exoskeletons must fit and function properly to reduce the risk of MSDs (Goldenhar & Sweeney, 1996). Lack of coordination between the human and the exoskeleton can increase physical and cognitive demands, exposing workers to new risk factors in the workplace (Fox et al., 2018). Zhu et al. (2021) found that increasing cognitive demand while wearing an exoskeleton may offset the mechanical advantages of exoskeletons and subsequently increase spinal loading. This may be due to the changes in muscle recruitment patterns and coactivity. This study aimed to (1) evaluate users' physical and cognitive responses to different passive low-back exoskeletons while performing simulated manufacturing tasks and (2) compare users' performances with their preferred exoskeletons after training.

Methods

Twenty-four subjects (12 males and 12 females, age 28.5 ± 4.0 years, height 170.0 ± 8.0 cm, and weight 70.4 ± 12.9 kg; mean ± standard deviation) participated in this study. Participants were eligible if they met all the following requirements: (1) age 19 to 64 years, (2) no history of physician-diagnosed MSDs, (3) no injuries for the past 6 months, (4) right-hand dominant, and (5) little to no experience with a passive low-back exoskeleton. The experiment was divided into three distinct experimental sessions.

In session 1, the participants wore four different exoskeletons: Apex (HeroWear), Paexo Back (Ottobock SE & Co.), Laevo Flex (Laevo BV), and the HAPO (Ergo Santé) while performing simulated manufacturing tasks (lifting, walking, and drilling tasks). The analyses presented here are a subset of data from one simulated manufacturing task (lifting). For the lifting task, participants were asked to lift a 10 kg weight to two different heights, 41 cm from the floor and the participant's elbow height, with five repetitions for each height. The participants always started performing the tasks without the exoskeletons, and the order of exoskeleton presentation was randomized. Electromyography (EMG) sensors (Cometa, Milan, Italy) were used to capture bilateral muscle activity of the following eight muscle groups when participants were performing the task: biceps brachii, triceps brachii, anterior deltoid, middle deltoid, erector spinae, middle trapezius, rectus abdominis, and gluteus maximus at 2,000 Hz. The gluteus maximus was included to investigate potential muscle activation shifts (Baltrusch et al., 2020). Preliminary results of the gluteus maximus (GM) and erector spinae (ES) are presented here. After performing the task with and without the exoskeletons, participants completed the NASA Task Load Index (TLX) to evaluate perceived cognitive load and a user experience survey to capture their experience. At the end of the study, the participants ranked the exoskeletons based on tasks and overall experiences. The highest-ranked exoskeleton was considered preferred and worn in the subsequent two sessions.

Participants returned within 7 to 9 days for session 2. In session 2, the participants performed the same tasks with their preferred exoskeleton up to four rounds to increase familiarity. Neither physical nor cognitive performances were recorded for the second session, and most participants completed the session within an hour.

One or 2 days after session 2, the participants completed session 3. In session 3, the participants wore their preferred exoskeletons and performed the same tasks. The NASA-TLX, the user experience survey, and EMG procedures were used to measure their cognitive and physical performance.

A mixed effects model was used to evaluate how the use of the exoskeletons affected muscle activation. Intraclass correlations (ICCs) from the model explained the variation among the participants. A participant-specific one-way ANOVA and Dunnett's test were performed to compare the performance when using the exoskeletons relative to the baseline condition (without exoskeleton). Performance before and after training was compared using a two-sample Wilcoxon test. The significance level was $p < .05$. Descriptive statistics and qualitative analyses were used to assess cognitive workload. The assessments of cognitive workload from the NASA-TLX and surveys were used to evaluate the alignment between preference and cognitive demands. Decreases in muscle activation were used to assess alignment between preference and physical demand.

Results

Male (Figure 1) and female (Figure 2) participants responded differently to exoskeletons at each level. In Figures 1 and 2, the horizontal lines represent the 95% confidence intervals for the percentage change compared to the no-exoskeleton conditions; the line crossing 0 indicates that the changes were not statistically significant. All four exoskeletons reduced female participants' muscle activation in the erector spinae and gluteus maximus when lifting at both levels. However, exoskeletons did not significantly reduce muscle activation in the erector spinae when male participants were performing lifting tasks at the high level, even though over 60% of male participants reported feeling some level of support while performing lifting tasks at a high level, based on user experience feedback. ICCs for both sexes and levels were relatively high, which indicated high variances among the random factor (participants). This might be because each participant responded to exoskeletons differently. Therefore, participant-specific analysis was performed. More than 70% of participants (17 out of 24, 7 males, 10 females) experienced decreased muscle activations in the erector spinae and/or gluteus maximus with at least one exoskeleton. No participants indicated extra stress or distraction from the exoskeletons while performing the task in the NASA TLX or user experience survey. Overall, female participants exhibited a

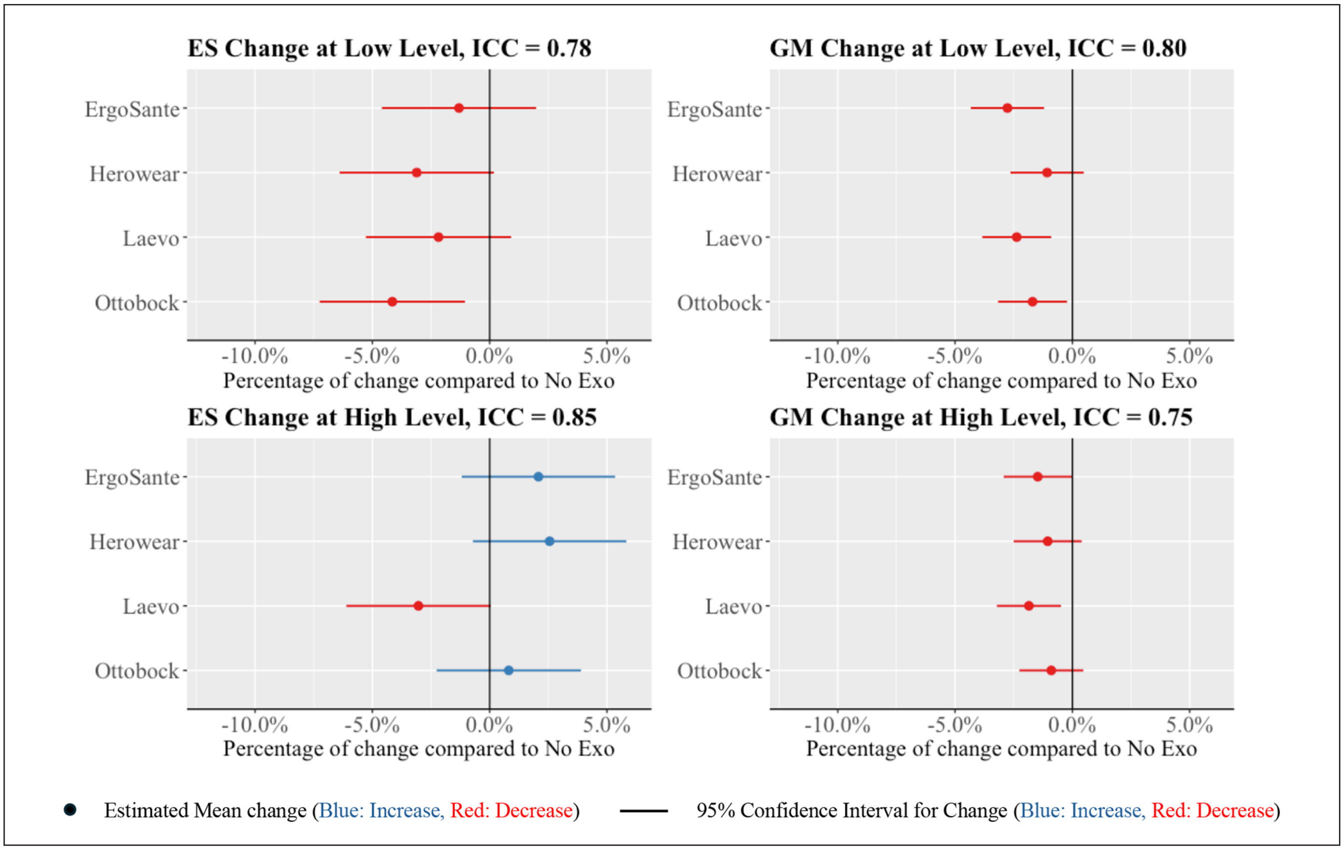

Figure 1. Relationship between fixed factor (exoskeleton) and male participants' muscle activation.

greater reduction in muscle activation in erector spinae and gluteus maximus in the exoskeletons compared to the male participants.

At the end of session 1, all participants agreed they felt supported during lifting tasks while using the exoskeletons. However, four participants did not agree that the exoskeletons would benefit them in the long term. Participants chose a preferred exoskeleton based on the ease of use, which is a combination of their perceived support, comfort, and fit, but not necessarily in any particular order. Based on changes in muscle activation and self-reported cognitive workload, 40% (9 out of 24) of participants' performances and preferences did not align. Some participants exhibited a muscle activation increase and/or decrease while wearing the non-preferred exoskeleton(s). However, this is not unexpected since support was not the only deciding factor for some participants.

After the training session (session 2) and evaluation (session 3), approximately half of the participants exhibited a decrease in the erector spinae (~50%) and/or gluteus maximus (~35%) activity, while others did not significantly benefit from the familiarity session. Whether female or male participants benefited more from the familiarization session was inconclusive. All participants felt more confident performing tasks with their preferred exoskeletons, and a decrease in NASA-TLX-derived cognitive workload was observed in 83% (20 out of 24) of participants. However, some participants appeared to benefit more from the training than others. For female participants who experienced significant benefits, activation reductions in erector spinae ranged from 6.95% to 25.51%, and activation reductions in gluteus maximus ranged from 1.75% to 7.60%. For male participants who experienced benefits, activation reductions in erector spinae ranged from 3.05% to 21.32%, and activation reductions in gluteus maximus ranged from 1.85% to 3.86%.

Discussion

Participants responded to each exoskeleton differently during session 1. Some participants benefited from the exoskeletons in terms of muscle activation (i.e., reduction in erector spinae and gluteus maximus), while some participants did not experience a statistically significant muscle activation benefit. Also, we did not observe loading redistributed from the erector spinae to the gluteus maximus. Nearly all participants felt some support with at least one exoskeleton and agreed that exoskeletons could help reduce back injuries in the long term. This result aligns with previous studies (Goršič et al., 2021; Yandell et al., 2021). Users' perceptions of the exoskeletons were mostly positive, even though some might be skeptical.

Figure 2. Relationship between fixed factor (exoskeleton) and female participants' muscle activation.

Female participants benefited more from the exoskeletons than male participants at both low and high height levels. This was anticipated, since a previous study suggested that the benefits of exoskeletons varied among participants and might not be obvious when the load was relatively light. Participants exhibited a greater activation decrease when the loading weight-to-body weight ratio was at 20%; this ratio was lower in our study (Alemi et al., 2019; Goršič et al., 2021). The loading weight, 10 kg, to body weight ratios were higher for female participants than male participants in our study. Based on our observations and informal conversations during the session, more female participants considered the task more physically demanding and required longer breaks than males, which could indicate that the 10 kg loading was relatively heavy for female participants. This might explain why exoskeletons benefited female participants more than male participants. No participants reported significant stress or distraction while performing the lifting tasks. More than half of the participants selected exoskeletons that benefited them the most, and participants usually had their own criteria when selecting their most preferred exoskeleton. The most common deciding factors included support, comfort, and range of motion; however, participants might prioritize one factor over the other.

After an hour of training, participants gradually adapted to their preferred exoskeletons. Half of the participants showed reduced muscle activation in the erector spinae and/or gluteus maximus. Nearly all participants felt more comfortable wearing exoskeletons and performing lifting tasks. However, half of the participants did not benefit significantly from the training, similar to Jakobsen et al.'s (2025) finding that muscle activation changes were insignificant after regular usage. Goršič et al. (2021) reported that participants with low physical activity levels tended to have difficulty with adaptation. Results suggested that more extended training periods may be necessary for users to achieve full adaptation.

There are limitations to this study. Even though we aimed to recruit a diverse population from the community, most participants were young adults in college. The experiment was conducted in a controlled lab environment, and the participants performed the tasks at their own pace. The results of this study may not be representative of workers in the manufacturing sector. This was a short-term study; some participants may have benefited from longer adaptation to the exoskeletons.

In future studies, it may be beneficial to give participants options to adjust exoskeleton settings, such as support levels and lift different loadings, to further understand the benefits of exoskeletons and users' preferences.

Conclusion

Over 70% of participants benefited from at least one exoskeleton when performing the lifting task. More than half of the participants chose an exoskeleton that benefited them the most physically. The most common deciding factors when the participants ranked the exoskeletons include support, comfort, and range of motion. However, participants had different criteria for selecting a preferred exoskeleton. Due to fitting issues, only two female participants could wear all four exoskeletons, which highlights the need to consider female anthropometry in the design of exoskeletons, especially since the number of female workers in the manufacturing sector has increased and will likely continue increasing. After training, participants gradually adapted to the exoskeletons. However, additional training may be necessary for the user to fully achieve adaptation.

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