

The Effects of Passive and Active Back Support Exoskeletons on Endurance, Perceived Exertion, and Back Discomfort During Fatigue-Induced Repetitive Lifting

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Abstract

Back-support exoskeletons (BSEs) show promise for mitigating physical strain in industrial settings, yet their effectiveness during fatigue-inducing tasks remains underexplored. This study evaluated the effects of powered and unpowered BSEs on endurance, perceived exertion, and back discomfort during repetitive lifting. Sixteen participants lifted a box (15% body mass) at ~8 lifts/min until exhaustion under three conditions: no exoskeleton, unpowered, and powered. Endurance time (i.e., time-to-fatigue), number of lifting cycles, perceived exertion (RPE), and back discomfort (RPD) were recorded. The powered BSE significantly increased time-to-fatigue ($p = .03$) and number of lifting cycles ($p = .03$) compared to control. RPE increased over time across all conditions ($p < .001$) but was significantly lower with powered versus control ($p = .015$). The unpowered device showed a non-significant trend toward reduced RPE. Neither device significantly alleviated back-discomfort. These findings suggest powered exoskeletons may better regulate fatigue during repetitive lifting; however, further research should explore long-term biomechanics effects and user adaptation.

Keywords

back-support exoskeleton, fatigue, repetitive lifting, endurance

Introduction

The mechanical load on the low back significantly contributes to occupational low back pain (LBP), primarily due to over-exertion, repetitive movements, and sustained trunk postures (Coenen et al., 2013). Low-back injuries also arise from cumulative muscle fatigue from dynamic lifting and prolonged bending positions (Dolan & Adams, 1998). Back-support exoskeletons (BSEs) are wearable devices that provide mechanical support to the trunk, reducing trunk extensor activity and spinal loads. Consequently, BSEs are emerging as a potential intervention to mitigate LBP risk in industrial settings (de Looze et al., 2016). However, most existing research has primarily assessed BSEs efficacy under unfatigued conditions, limiting our understanding of their impact during fatiguing tasks. Hence, this study assessed how fatigue is affected by BSEs-use, during repetitive lifting.

without a BSE (Bosch et al., 2016; Poon et al., 2019). Some studies have explored the effects of BSEs during repetitive lifting (Kozinc et al., 2021; Rodzak et al., 2024), but findings are inconclusive, and no study has compared powered versus unpowered BSEs under repetitive lifting conditions. During repetitive lifting, muscle fatigue may impair neuromuscular control of spinal stability (Srinivasan & Mathiassen, 2012), potentially increasing spinal forces. Further, as muscle fatigue progresses, individuals may adapt their working strategies to compensate for fatigue (Bernardo et al., 2018; Kazemi et al., 2022). While BSEs may reduce lower back strain, their capacity to mitigate fatigue-related discomfort and improve endurance remains unclear. When individuals are fatigued, exoskeleton-use may result in unpredictable consequences and adaptation effects, which may exacerbate their side effects and affect perceived exertion and comfort.

Background

Till date, the investigation of fatigue associated with BSE-use has been limited to a few studies exploring whether endurance is affected in static forward bending with and

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Conversely, exoskeletons may assist users in mitigating fatigue and delaying fatigue-induced impairments, which may hold performance-related significance. Hence, this study aimed to assess the effects of BSE-use on endurance time, perceived exertion, and back discomfort in repetitive lifting. We selected two BSEs significantly different in weight, human-exoskeleton interface, support mechanism, and assistance levels: (1) Apex (HeroWear, USA), a soft lightweight exosuit, and (2) Apogee, a powered, rigid device (German Bionic, Germany). We hypothesized that both BSEs would extend lifting endurance and delay fatigue compared to unassisted lifting, with the powered BSE providing greater endurance due to its active supportive torque mechanism. Further, both devices would similarly reduce exertion, as differences in assistance mechanisms and usability may balance their overall impact.

Approach

Sixteen healthy adults (10M, 6F) with mean (SD) age 29(8)years, stature of 173.4(5.8)cm, and body mass of 68.2(9.4)kg were recruited from the university community. Participants completed repetitive lifting across three randomized lab sessions: control (no exoskeleton), a powered BSE, and an unpowered BSE. The unpowered BSE used in this study was Apex, which weighs 1.6kg and is designed to provide support through two elastic bands that store and release energy to assist movement. In contrast, the powered BSE was the Apogee, a rigid device weighing 7.3kg, equipped with two electrical motors and a sensing mechanism that detects the user's movements and provides support as needed. For each BSE, participants completed a familiarization session prior to experimental data collection. The powered device assistance was set at 50%, and for the unpowered BSE, strong-strength (i.e., mid-level, s1500) elastic bands were used. Participants symmetrically lifted and lowered a box with 15% of their body mass, at ~8 lifts/min, between waist and ground level. The activity continued until: (i) task failure, or (ii) reported exhaustion (18 out of 20 for perceived exertion), or (iii) completion of 20 min of lifting. At the end of each minute, participants reported ratings of perceived exertion (RPEs) on a Borg 6 to 20 scale (Kuijt-Evers et al., 2007), and ratings of perceived discomfort (RPD) in the lower back, using the Borg CR-10 scale (Borg, 1998), as subjective outcomes. Total time to fatigue (i.e., the total time participants were able to perform the lifting task before meeting one of three termination criteria) and lifting cycles were used as objective endurance indicators. For subjective outcomes, data were divided into 1/3rd segments marking the beginning, middle, and end phases of lifting to represent the trends over time. Mixed-factor ANOVA models were used to examine the main and interaction effects of *BSE* (control, powered BSE, and unpowered BSE) and *Sex* on endurance time and lifting cycles. The main and interaction effects of *Time*, *BSE*, and *Sex* were examined on RPE and

back RPD, with post hoc Fisher's LSD tests for significant effects.

Outcome

Participants completed 47.4 (SD 30.4) trials on average, in the control condition, with a mean (SD) time to fatigue of 343.1 (225.7)s. The main effect of *BSE* was significant on both endurance metrics (time to fatigue: $p=.03$, lifting cycles: $p=.035$). Post hoc tests indicated that the powered BSE significantly increased the time to fatigue ($p=.03$, 30.8%) and the number of lifting cycles ($p=.03$, 29.1%), compared to the control. The change in time to fatigue and lifting cycles with the passive BSE was not statistically significant. Both RPE and back RPD significantly increased throughout the lifting trial ($p<.001$). *BSE* had a significant main effect on perceived exertion ($p=.03$) but not on perceived lower back discomfort. Post-hoc comparisons revealed that RPE was significantly lower in the powered BSE condition compared to the control condition ($p=.02$, 6.7%), and not significantly different between control and passive BSE conditions. Further, RPE was not significantly lower with unpowered BSE ($p=.06$, 4.6%) than in the control condition.

Conclusion

This study is one of the first to directly compare the effects of powered and unpowered back-support exoskeletons on endurance and subjective perception during fatiguing repetitive lifting. Findings showed that the powered BSE significantly improved endurance, increasing time to fatigue and lifting cycles compared to the control. The unpowered BSE, while lighter and more flexible, did not yield significant endurance benefits. This suggests that powered device provides more effective mechanical assistance in regulating fatigue and sustaining physical effort. Prior research on lifting endurance presents mixed results, with endurance improvements of 30% to 75% (Rodzak et al., 2024; Tan et al., 2019), while others found no significant effect (Kozinc et al., 2021; So et al., 2022). These variations highlight the influence of task, exoskeleton designs, and user characteristics on BSE effectiveness. Regarding subjective outcomes, the powered BSE led to a significant reduction in RPE, whereas Apex-use showed no statistically significant change from the control. However, neither exoskeleton alleviated lower back discomfort, emphasizing that BSEs may reduce overall exertion but not necessarily localized discomfort, which requires additional ergonomic considerations. The greater efficacy of powered BSE may be due to differences in support mechanisms and torque outputs, leading to varying contributions to spinal load reduction. For unpowered device, the peak external moment was estimated at 23 ± 5 Nm for s1500 elastic stiffness level (Zelik et al., 2022), while no published data is available on powered device's supportive torque. However, GermanBionic (2024) reports that its

electric torque generators provide up to 36 kg of lifting support per movement. Future research should explore the long-term effects of BSEs on spinal loading, body kinematics, muscle activity, and exoskeleton-user interaction. Overall, our findings support the potential of active BSEs like Apogee in physically demanding industries where fatigue management is crucial for productivity and safety.

Declaration of Conflicting Interests

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