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Article

Evaluating the Efficacy of a Passive Exoskeleton for Enhancing Ergonomics in Manufacturing

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Featured Application: This study explores the integration of an occupational passive back-support exoskeleton in manufacturing, demonstrating its potential to reduce physical discomfort and physical exertion and enhance ergonomic practices. It highlights the role of the exoskeleton as a proactive tool for improving occupational health and safety in industrial settings.

Abstract: Manual material handling (MMH) significantly impacts worker health and productivity, often leading to musculoskeletal disorders (MSDs) primarily in the lower back. As a novel assistive technology, exoskeletons may serve as ergonomic tools to mitigate these work-related MSDs. It is essential to examine exoskeletons from the users' perspectives before their widespread implementation in occupational settings. This study investigates the effectiveness of a passive back-support exoskeleton (BExo) in reducing perceived physical exertion and improving ergonomic safety in a manufacturing context. Twenty-two college students were recruited to perform MMH tasks in a controlled lab environment, both with and without the BExo, followed by completing a survey questionnaire on various aspects of the BExo. Using ANOVA, the study analyzed biomechanical exertion across various body parts and tasks. The findings indicate that the BExo substantially alleviated discomfort and physical exertion in the low back, shoulders and knees, thereby enhancing an ergonomic posture and reducing fatigue. These results underscore the potential of passive exoskeletons to boost workers' safety and efficiency, providing valuable insights for future ergonomic strategies in industrial settings.

Keywords: manual material handling; manufacturing ergonomics; passive back-support exoskeleton; occupational health and safety; musculoskeletal disorder prevention; user acceptance; ergonomic interventions

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1. Introduction

Manual material handling (MMH) is a critical component of manufacturing operations and includes the physical manipulation of objects through tasks such as lifting, carrying, and assembling [1]. These activities are prevalent across diverse manufacturing sectors, including logistics, warehouse management, and assembly lines. The importance of MMH in manufacturing ergonomics is profound, as it significantly influences worker health, safety, and productivity [2].

Occupational injuries and incidents impact employees' lives and create significant financial challenges for workers, businesses, insurance companies, and healthcare systems [3]. Inadequate material handling practices are a primary source of workplace injuries and musculoskeletal disorders (MSDs), particularly those affecting the lower back, which are pervasive in manufacturing environments. An approximate 27.8% of injuries in the workplace within the industrial sector are attributed to MSDs [4]. MSDs, especially back-related issues caused by excessive bio-mechanical strain, have substantial economic and social ramifications, affecting personal health and placing a strain on healthcare systems [5]. In addition, completing MMH occupational tasks in confined environments, such as most settings involving MMH, affects workers' posture, time to finish tasks, and overall performance [6].

Assessment and management of occupational risks is important in lowering the incidence of workplace injuries [7]. Addressing the inherent risks and challenges in MMH tasks is essential for ensuring worker safety and sustaining productivity. Traditional methods, such as reviewing workers' compensation claims, have typically reflected a reactive stance to worker safety. However, a shift towards a proactive approach is utilizing predictive ergonomics to analyze worker–environment interactions. This could significantly mitigate the incidence of injuries. In this context, the adoption of assistive technologies like exoskeletons is pivotal. The advent of exoskeleton technology, particularly, devices offering lower-back support, has introduced an era of engineered assistance for workers engaged in physically intensive tasks. These devices are designed to reduce injury risk and physical strain, therefore improving workplace safety and efficiency [8,9].

In the pursuit of competitive advantage, manufacturing industries are increasingly adopting advanced technologies to create a dynamic work environment with high productivity [10]. One of these emerging technologies is the use of wearable assistive devices to boost workers' productivity and health as a crucial factor in maintaining industrial competitiveness. By enhancing occupational ergonomics, these emerging technologies contribute to meeting modern market demands and the well-being and efficiency of the workforce. In the manufacturing sector, where MMH and other physically demanding tasks are commonplace, the incorporation of wearable assistive technologies such as occupational exoskeletons can significantly alleviate the burden on workers. By offering biomechanical support and reducing fatigue, exoskeletons play a crucial role in promoting occupational health and ergonomics, which makes them a valuable asset in industries where manual labor is prevalent. Exoskeleton technology is rapidly becoming more prevalent, holding great promise for elevating the quality of workers' lives [11]. Using exoskeletons for MMH tasks is particularly beneficial, as those tasks are usually associated with non-ergonomic postures that lead to physical discomfort and injuries in the long term [12]. An exoskeleton system represents a common form of interaction between humans and machines [13] and can be powered, passive, and hybrid. Powered exoskeletons are still mostly restricted to laboratory research due to their higher costs and greater complexity. In contrast, passive exoskeletons are growing in popularity for integration as assistive ergonomics tools into practical industry applications due to their being more affordable and user-friendly [14,15].

Passive exoskeletons are innovative devices, engineered to reduce the risk of injury and alleviate the physical strain associated with such tasks, thereby enhancing workplace safety and productivity [16]. The passive exoskeleton offers a viable substitute for its active counterpart by eliminating the need for batteries or any external power supply as well as relying on systems of springs and pulleys instead of motors to assist with movement. Its design, which often incorporates a belt or a buckle for attachment, ensures it is both light and user-friendly, which makes it convenient to don and doff and enhances mobility and comfort for the user [17]. Besides reducing physical strain, the exoskeleton may also lighten the cognitive load in tasks requiring prolonged posture, potentially improving balance and mental performance [18].

Exoskeletons represent an innovative method for preventing workplace injuries, yet their extensive adoption remains limited [19]. The full adoption of passive exoskeletons as assistive technologies is hindered by a lack of clarity on users' evaluation of their effects and risks [20,21]. Studies indicate that exoskeletons customized for individual needs may be more effective than generic models [22,23]. However, thorough evaluations, weighing their advantages and disadvantages, are still needed to guide developers, ergonomists, and users. A detailed analysis of how these exoskeletons can be used for performance improvement across various work tasks is also lacking. Thus, there is a need for research to uncover the full potential and limitations of passive exoskeletons, specially through user-centric simulations that mirror typical manual labor tasks [24].

The impact of this technology is especially notable in the development of occupational passive lower back-supporting exoskeletons (BExos), which are tailored to assist workers who are frequently involved in physically demanding activities. The advancement of technology has significantly increased the accessibility and practicality of exoskeletons in various workplace settings. This accessibility has encouraged more companies to explore exoskeletons as a tool for improving both worker safety and productivity [25]. Integrating assistive technology into manufacturing environments is vital for optimizing human performance, safety, and well-being. Aligning these technologies with human factors and ergonomics enables targeted design modifications, fostering user acceptance and trust [25–27]. Tailoring technology to ergonomic principles allows for specific design enhancements, creating a more user-friendly interface. By incorporating human factors and ergonomics, the design aligns with the natural capabilities and limitations of the human body, reducing the risk of injuries and fatigue.

Research shows that exoskeletons are promising in enhancing manufacturing ergonomics by offering mechanical support that contributes to reducing strain on muscles and joints during MMH tasks [28,29]. Exoskeletons designed for back support could be beneficial in various contexts, given their ability to lower the activation level of back muscles. This reduction could decrease the likelihood of MSDs in tasks that involve frequent lifting or maintaining awkward and static positions [29,30].

Considering repetitive lifting tasks, a study on the biomechanical analysis of BExos, using a simulation of lifting showed that the use of an exoskeleton plays a significant role in reducing lumbar spine stress and lowering metabolic energy expenditure during symmetric lifting activities, highlighting its potential utility in diverse work environments where repetitive lifting is a requirement [28]. Another study highlighted that passive exoskeletons support users by supplying some of the torque needed for physical tasks, such as lifting or holding a bent posture. As a result, these devices have the potential to lessen the effort demanded from the spinal muscles, reduce spinal strain, and enhance task performance [20]. A study by Lazzaroni, et al. [5] showed a lessened compressive load on the spinal disc as a result of wearing a BExo, showing its potential in reducing the likelihood of incurring back-related MSDs. Considering the walking task, research findings indicate that utilizing an exoskeleton can lead to a reduction in the energy expenditure associated with walking. This suggests that exoskeletons have the potential to enhance walking efficiency by lowering the metabolic demands on the body [31].

A systematic analysis of factors influencing the acceptance of industrial exoskeletons [32] revealed the necessity of addressing user expectations, comfort, safety, and task compatibility to improve user experiences and adoption rates. A study on the impact of using a passive trunk exoskeleton among employees suffering from low-back pain demonstrated a notable improvement in self-efficacy, with a 7% increase among users, suggesting that the exoskeleton aided physical task performance and also boosted users' confidence in managing their condition. This study also identified critical concerns regarding the design and social perception of the exoskeleton, including its comfort, ease of use, and the stigma associated with wearing such devices in the workplace [33]. Another study [34] on the impact of exoskeletons on healthy individuals performing repetitive tasks revealed that a passive trunk exoskeleton can alleviate back discomfort during static tasks but restricts movement in activities requiring extensive trunk or hip flexion, such as walking. It indicated that while that exoskeleton aids in specific repetitive tasks, it impedes versatility in more dynamic environments. The discomfort experienced does not directly impact the short-term performance. Furthermore, research on the interaction of patients with lower back pain with a passive trunk exoskeleton showed that they experienced reduced discomfort and were more willing to use the exoskeleton daily. However, those without lower back pain were less inclined to use the device, highlighting limitations in acceptance among pain-free individuals [35,36].

Despite the growing body of research on passive exoskeletons in occupational settings, a major obstacle to their broadened utilization in industrial settings is the limited or incomplete understanding of their impact and potential risks. Previous research has shown that customizable exoskeletons, tailored to individual user needs, are expected to outperform standardized, one-size-fits-all models in terms of effectiveness [37]. Additionally, there is a deficiency in comprehensive evaluations that discuss the pros and cons of these devices, which is crucial for informing developers, ergonomics specialists, consumers, and workers [20,21]. Moreover, there is an absence of detailed studies on the performance of passive exoskeletons in varying work tasks [17]. Therefore, it is essential to conduct targeted research to explore both the challenges and the strengths of these exoskeletons, particularly from the perspective of end users engaged in simulated tasks that replicate common job assignments such as manual material handling.

The goal of this study was to address this gap by providing a comprehensive analysis of users' interactions with a passive back-supporting occupational exoskeleton. The study focuses on the advantages and difficulties encountered when users wear a back-support exoskeleton during tasks that involve the manual handling of materials, set within simulations of actual industrial conditions. In addition, the research offers a statistical comparison of the participants' reported physical exertion and the biomechanical effort they perceive while engaging in these tasks.

The structure of the rest of the paper is as follows: Section 2 details the materials and methods; Section 3 presents the results and a discussion of the findings; and Section 4, reporting a summary of the findings, a discussion of the study limitations, and future directions of research on assistive technologies, concludes this paper.

2. Methods

This section elaborates on the methodology and procedures used in the study. We designed a set of MMH tasks to be completed by the participants across two sessions: one with the use of an exoskeleton, and one without. Each participant was confirmed to be in good health, without any physical discomfort, medical conditions, or musculoskeletal disorders. All study procedures in this research adhered to the Declaration of Helsinki and received approval from the Institutional Review Board and the Office of Research Compliance and Integrity of Santa Clara University (No: 23-11-2076). In addition, prior to their participation in the study, informed consent was collected from all individuals.

2.1. Participants

This study involved 22 college students who volunteered as participants and explored the interaction between users and a passive back-supporting exoskeleton during manual material handling tasks. The participant group consisted of 12 females and 10 males, accounting for 54.55% and 45.45% of the sample, respectively. The average age of the participants was approximately 20.5 years, with a standard deviation of 4.48 years and a median age of 19 years. The participants' average weight was around 66.334 kg (146.26 pounds), with a standard deviation of 11.45 kg (25.25 pounds) and a median of 65.49 kg (144.40 pounds). No participant had a current or historical musculoskeletal disorder.

2.2. Experiment, Apparatus, and Tasks

We utilized the Ottobock BackX (Figure 1), a passive back-support exoskeleton designed for industrial applications, to perform simulated manual material handling (MMH) tasks. It was selected for its relevance and availability in our laboratory settings and based on its suitability for our study objectives. According to the device guidelines, this BExo is designed to alleviate gravity-induced forces on the lower back and reduces exertion during tasks involving stooping, lifting, and reaching by providing supportive force to user's chest and thighs. We followed the guidelines to adjust the exoskeleton based on each participant's physical characteristics, and all procedures of donning and doffing the exoskeleton were strictly adhered to during the experiments. Prior to the start of the experiment, the participants received an orientation session to become acquainted with the study protocol and equipment. They were provided with a consent form which detailed the study's scope and allowed them ample time to read and consent to their participation. All participants voluntarily agreed to participate and completed the consent forms before beginning the tasks. They were informed that they could withdraw from the study at any time without any consequences. However, all participants completed the tasks as planned. Upon concluding the experimental tasks, the participants were asked to fill out a survey to gather their feedback on the experience.

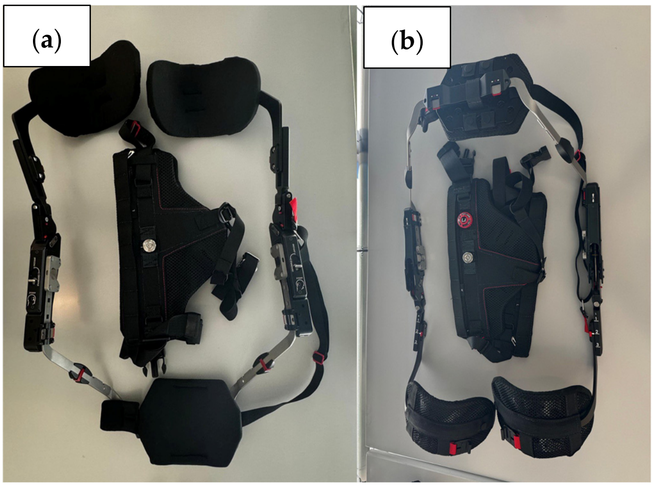

Figure 1. BExo used in the study; (**a**) back of the exoskeleton; (**b**) front of the exoskeleton.

The study involved the participants performing these tasks both with and without the exoskeleton support. The experiment comprised several distinct activities (Table 1). Breaks of an average of 3–5 min were provided throughout the session to prevent fatigue and ensure the participants' well-being. Initially, each participant performed a sequence that included walking for two minutes and then carrying and lifting a 7 kg (15.6 pound) box. These tasks were completed without the aid of the exoskeleton. The walking task consisted in the participants walking in the lab an 8 ft distance, back and forth, at their preferred walking speed. The carrying task involved moving the box between two points that were 2.6 m (8 ft) apart within the laboratory setting. Each task of carrying and lifting the box was repeated in two sets of three repetitions. The height at which the box was to be placed during the lifting tasks was fixed at 90 cm (2 ft). The scenarios and task execution are shown below in Figure 2 (photos published with participants' consent).

Table 1. Task specifications in the study.

Task	Repetitions	Duration	Specifications
Walking	2 Trials (one with; one without BExo)	2 min	Walk in the lab
Carrying a Box	2 Trials; 2 sets of 3 (one with; one without BExo)	Distance of 2.6 m (8 ft)	Box weight: 7 kg (15.6 lbs.)
Lifting a Box	2 Trails; 2 sets of 3 (one with; one without BExo)	At comfort pace	Box height placement: 90 cm (2 ft)

Figure 2. Procedure setup and task performance in the lab; (**a**) front and back view of the BExo; (**b**) tasks completed by the participants.

2.3. Survey Components and Analysis

We used two types of assessment for testing the impact of the exoskeleton on perceived physical exertion (using the Borg scale) and the interaction between the users and the exoskeleton (using a detailed survey).

2.3.1. Borg Scale

We used the Borg scale of 0–10 in this study, with "0" representing no perceived physical exertion (PPE), and "10" representing maximum PPE by the participant. The Borg CR10 scale is designed to rate muscle exertion and pain, which is particularly relevant in studies focusing on muscle fatigue and its effects on postural control. It provides a clear and direct measure of muscle exertion, which is central to understanding the impact of muscle fatigue on postural stability [38]. The Borg CR10 scale is validated for assessing perceived fatigue during work-related material handling tasks and can effectively discriminate between different levels of task difficulty. The applicability across various types of work and exertion levels has made it a broadly useful tool in occupational health studies to evaluate and understand work-related fatigue [39] and in studies with a specific focus on evaluating the ergonomic efficacy of exoskeletons in various occupational settings [8,9,29,39–41].

During the experimental trials, the participants evaluated their perceived discomfort and physical exertion using the Borg CR10 scale, where a score of 0 signifies no physical exertion, and a score of 10 represents the highest level of physical exertion experienced by the participants while performing the tasks [42]. The participants rated their discomfort in each body part, including neck, shoulders, upper body, chest, wrists, lower body, knees, ankles, feet, and elbows. The Borg scale is a reliable method for assessing user perception in experiments involving various tasks. This subjective evaluation provides direct insights into individual interactions with the exoskeleton and the intensity of physical effort. Lower ratings on the Borg scale after using the exoskeleton indicated its effectiveness in reducing strain and workload.

2.3.2. Survey

In addition to the Borg scale, the participants completed a detailed survey assessing several dimensions of the exoskeleton's usability and impact. We used a validated survey questionnaire used in a study on user perception of exoskeletons in various tasks [43]. The complete questionnaire used in the study is shown in Appendix A, Table A1. The survey included sections on ease of use, practical utility, user attitudes, trust, and overall experience. Each aspect was rated on a scale from 0 to 10. The purpose of this detailed survey was to provide a comprehensive assessment of the exoskeleton from multiple perspectives, ensuring a thorough understanding of its usability and impact and areas for improvement. The detailed feedback from the participants offers valuable insights for further development and optimization of exoskeleton technologies in occupational settings.

Ease of use: The participants rated cognitive effort, movement freedom, physical effort, and overall ease of use. This comprehensive evaluation covered mental demand, autonomy of movement, physical exertion, and user-friendliness.

Usability: The participants assessed posture improvement, fatigue level, perceived inefficiency, movement constraint, and overall helpfulness. These evaluations provide a holistic view of the exoskeleton's impact on physical alignment, user fatigue, and task efficiency.

Attitudes and trust: The participants rated the exoskeleton's trustworthiness, ergonomic impact, general sentiment, comfort, and perceived innovation. Understanding these attitudes helps gauge user confidence in and acceptance of the technology.

Additional feedback: The participants were also asked to provide their ratings on usage likelihood, perceived power augmentation, training requirements, and impact on autonomy. These ratings offer insights into practical considerations and user expectations of the exoskeleton.

The survey results were analyzed using descriptive statistical methods to quantify and interpret the intensity of perceived discomfort and physical exertion and the overall effectiveness of the exoskeleton while completing manual material handling tasks. The analysis aimed to provide critical insights for ergonomic improvements and enhance occupational health and safety.

2.4. Statistical Analysis

The survey results were initially analyzed using descriptive statistical methods to quantify perceived physical exertion (PPE) and effectiveness of the exoskeleton. Further analysis included both one-way and two-way Analysis of Variance (ANOVA) to examine the effects of various factors on PPE. ANOVA is an inferential statistical method that was used to assess differences among groups and conditions, providing a robust understanding of the exoskeleton's impact on worker ergonomics.

One-way ANOVA is used to determine whether there are any statistically significant differences between the means of three or more independent (unrelated) groups. The judgment criteria for the effectiveness of a factor on an output is the F-ratio, which is used to test the hypothesis of equal means. A significant F-ratio suggests that at least one group mean significantly differs from the others.

Two-way ANOVA is used to investigate the interaction effects between two independent variables on a dependent variable. It extends one-way ANOVA by adding another factor and the interaction term. The mean square for the interaction is used to find the F-ratio for the interaction. A significant F-ratio for the interaction indicates that the effects of one factor depend on the level of the other factor.

ANOVA results are interpreted using the F-ratio and its corresponding p-values. A significant p-value (typically <0.05) suggests that the null hypothesis of equal means, as a results of a factor effect, can be rejected, indicating statistically significant differences between groups of interaction effects. Post-hoc tests such as Tukey's HSD are used following significant ANOVA results to pinpoint where the difference lies among group means.

In this study, the factors were "task", with the three levels of walking, lifting a box, and carrying a box, and "support" that referred to the participants' wearing or not the BExo as a support, and therefore, had the two levels of exo and no exo. The other factor considered was the effect of the BExo on reducing PPE on various body parts; we considered ten body parts, i.e., neck, shoulder, upper back, chest, wrist, lower back, knee, ankle, feet, elbow (10 levels). The total factor combination for preparing data for ANOVA analysis was Task (3 levels) $\times$ Support (2 levels) $\times$ Body part (10 levels) leading to 60 total variations. The output to be analyzed for the ANOVA models was PPE, which represented the sum of perceived physical exertion per combination for all participants. This comprehensive approach allowed for detailed understanding and analysis of the effects of different factors like task, support, and body part on perceived physical exertion.

3. Results and Discussion

This section presents the study's results and explores the potential applications of the insights gained from using the BExo as an ergonomic tool for improving the occupational safety and health of workers performing heavy tasks, such as manual material handling. We conducted statistical analyses, including ANOVA and Tukey's HSD test for mean comparison, to evaluate the total perceived physical exertion experienced by the participants during various tasks performed with and without the back-supporting exoskeleton. Additionally, we analyzed the responses to the Borg scale questionnaire, reporting the average score out of 10 per attribute, to provide further insights into user interactions with this assistive device.

3.1. Overall Impact of the BExo

The one-way ANOVA (as in Table 2) for exoskeleton support showed a significant reduction in overall perceived physical exertion when the back-supporting exoskeleton was used, with an F-ratio of 8.07 (p-value of 0.0062, statistically significant at $\alpha = 0.05$). This indicates that the differences in PPE with and without the exoskeleton were unlikely to be due to chance. The mean difference in the PPE scores between exoskeleton and no exoskeleton was 7.25, with a 95% confidence interval from 2.09 to 12.41, confirming significant differences. Therefore, there was a significant reduction in PPE when the tasks were performed with the exoskeleton, demonstrating its effectiveness in alleviating physical strain across various tasks. This highlights the potential of exoskeletons as an indispensable ergonomic tool in high-exertion settings such as manufacturing. The average PPE across all experiments is shown in Figure 3.

Table 2. ANOVA of PPE for exoskeleton support.

Source	DF	Sum of Square	Mean Square	F-Ratio *
Support	1	889.3500	889.350	8.0678
Error	58	6393.6333	110.235	
C. Total	59	7282.9833		

* Corresponding p-value is 0.0062 at $\alpha = 0.05$ level.

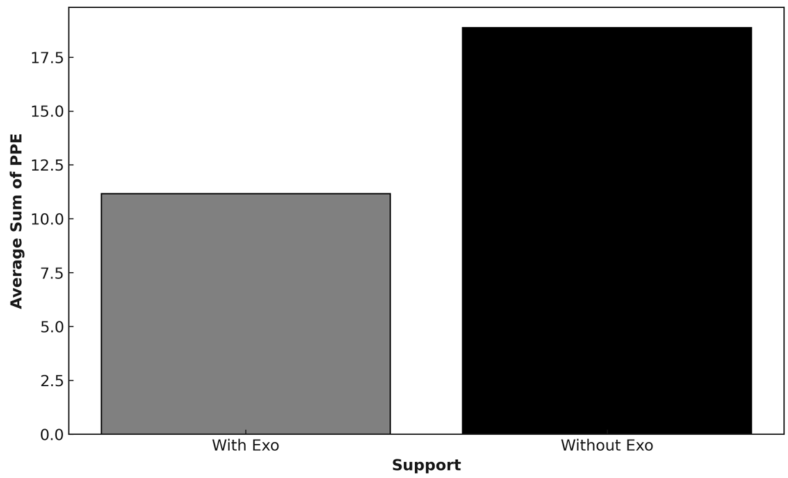

Figure 3. Participants' average PPE per support type.

3.2. BExo Impact on Body Parts

The comparison for the average sum of PPE with and without the use of an exoskeleton across different body parts is shown in Figure 4. The BExo significantly reduced the perceived physical exertion for several body parts. For the lower back, the reduction was substantial, with a decrease of 22.67 points, indicating a major alleviation of exertion. The knee showed a notable reduction of 9.33 points, and the shoulder a significant drop of

10 points. The upper back experienced a reduction of 9 points, while the ankle and wrist showed decreases of 6.66 and 5.33 points, respectively. The feet and elbow also benefited from the exoskeleton, with reductions of 4 and 3.67 points, respectively.

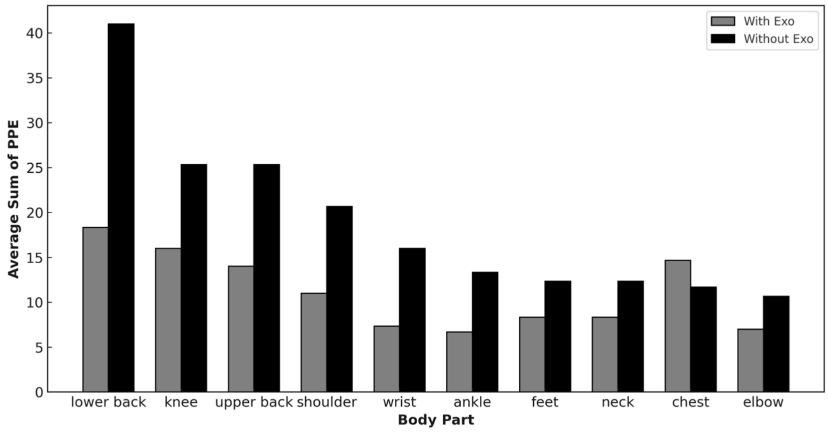

Figure 4. Participants' average sum of PPE with and without BExo per body part.

In contrast, the chest experienced a slight increase in PPE with the exoskeleton, with a rise of 3 points, suggesting that the exoskeleton might add some load to this area. The neck showed a minimal reduction in PPE, with a decrease of only 1.34 points, indicating that the exoskeleton's impact on the neck was not as pronounced. Overall, the exoskeleton appeared to be effective in reducing physical exertion in most body parts, particularly in the lower back, knee, and shoulder, while having less significant or slightly adverse effects on others like the chest and neck.

3.3. BExo Impact on PPE in Different Tasks

The analysis of perceived physical exertion across different tasks, such as walking, lifting, and carrying a box, revealed significant variations, as shown by the ANOVA results with an F-ratio of 9.44 and a p-value of 0.0003 (Table 3). This indicates that the type of task substantially affects the level of physical exertion experienced by individuals, emphasizing the importance of task characteristics in evaluating the effectiveness of exoskeleton usage. The significant differences across tasks suggest that exoskeletons may provide varying degrees of support depending on the specific activities performed.

Table 3. ANOVA of PPE by task.

Source	DF	Sum of Square	Mean Square	F-Ratio *
Task	2	1812.1333	906.067	9.4402
Error	57	5470.8500	95.980	
C. Total	59	7282.9833		

* Corresponding p-value is 0.0003 at $\alpha = 0.05$ level.

Tukey's HSD test was performed to compare the PPE scores across different tasks (walking, carrying a box, and lifting a box) with and without exoskeleton support. For the walking task, the mean difference in the PPE scores between the exoskeleton and no exoskeleton conditions was 3.8 (p-value of 0.0553), indicating no statistically significant difference (95% CI: −0.07 to 7.67). For the lifting task, the test showed a significant mean difference of 8.15 in the PPE scores between using or not the BExo, with a p-value of 0.0420 (95% CI: 0.31 to 15.99), confirming that the exoskeleton significantly reduces physical exertion in lifting tasks. For the carrying task, the mean difference in the PPE scores was 6.55, with a p-value of 0.0814, suggesting no statistically significant difference (95% CI: −0.78 to 13.88).

These results highlight the effectiveness of the exoskeleton in significantly reducing physical exertion during lifting tasks, while its impact on walking and carrying tasks is less pronounced. These results are visually confirmed in Figure 5 and provide compelling argument for the targeted use of exoskeletons in particularly strenuous tasks. This could potentially guide ergonomic interventions more effectively in workplace settings.

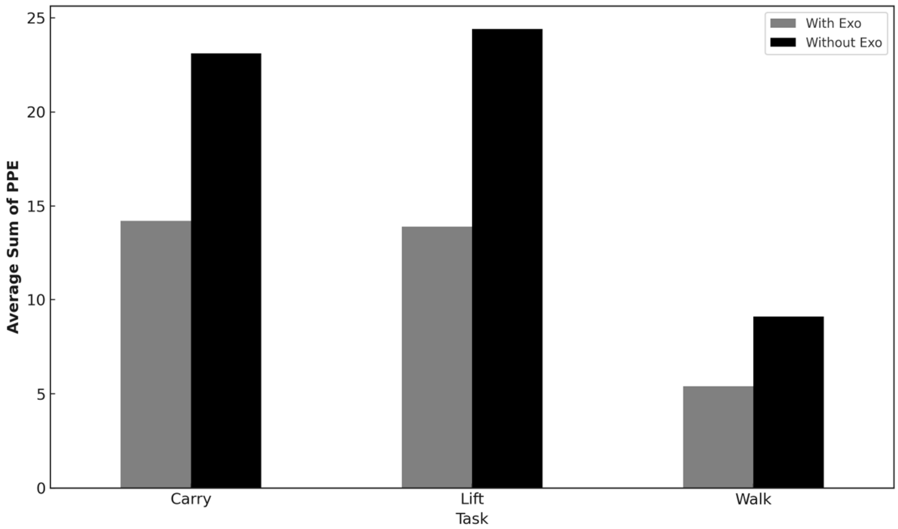

Figure 5. Effect of BExo support on PPE for different tasks.

3.3.1. Lifting a Box

As shown in Figure 6, the most impacted body parts benefiting from the use of an exoskeleton during the task of lifting a box were the lower back, knee, and shoulder. The lower back, in particular, showed a significant reduction in perceived physical exertion (PPE) when using the exoskeleton, with the PPE scores dropping from around 60 to 20. The knee also exhibited a notable decrease, with the PPE scores decreasing from approximately 35 to 15. Similarly, the shoulder benefited substantially from the exoskeleton support, with the PPE scores reduced from around 30 to 15. These findings highlight the effectiveness of exoskeletons in alleviating physical strain on the lower back, knees, and shoulders during lifting tasks, potentially reducing the risk of occupational injuries and enhancing the ergonomic support in high-exertion activities.

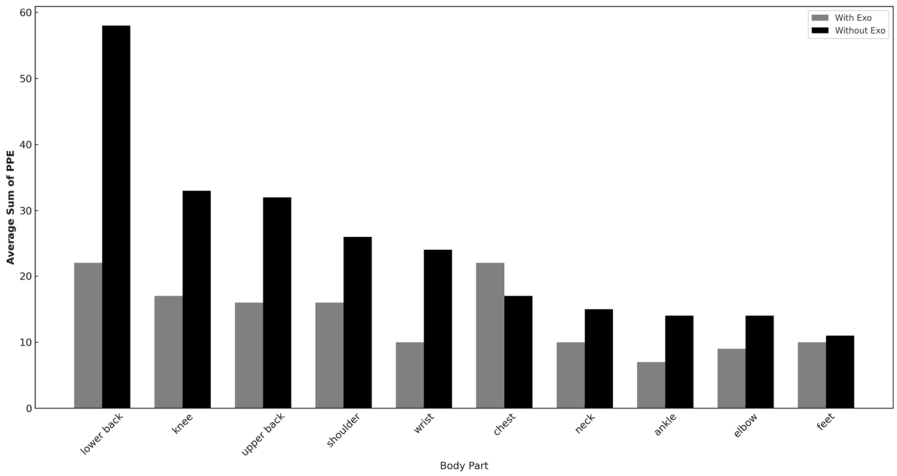

Figure 6. Participants' average sum of PPE per body part for lifting a box.

3.3.2. Carrying a Box

Looking at the effect of the BExo on PPE in the task where the participants carried the box (Figure 7), the lower back exhibited the highest PPE score without the exoskeleton, at approximately 55, which was substantially reduced to around 25 with the exoskeleton, demonstrating the BExo effectiveness in alleviating lower back strain. Similarly, the shoulders showed a high PPE score of about 45 without the exoskeleton, which decreased to approximately 20 with its use, while the neck showed a reduction from around 35 to 15, highlighting the exoskeleton's benefits for these body parts. The upper back had a PPE score of about 30 without the exoskeleton, reduced to around 10 with it, and the arms showed a decrease from about 25 to 10. This highlights that the body parts experiencing the highest exertion without exoskeleton support benefited the most from its use. This evidence validates the exoskeleton's role in significantly reducing physical exertion, particularly for the lower back, shoulders, and neck, during carrying tasks, emphasizing its potential as a valuable ergonomic tool in high-exertion activities.

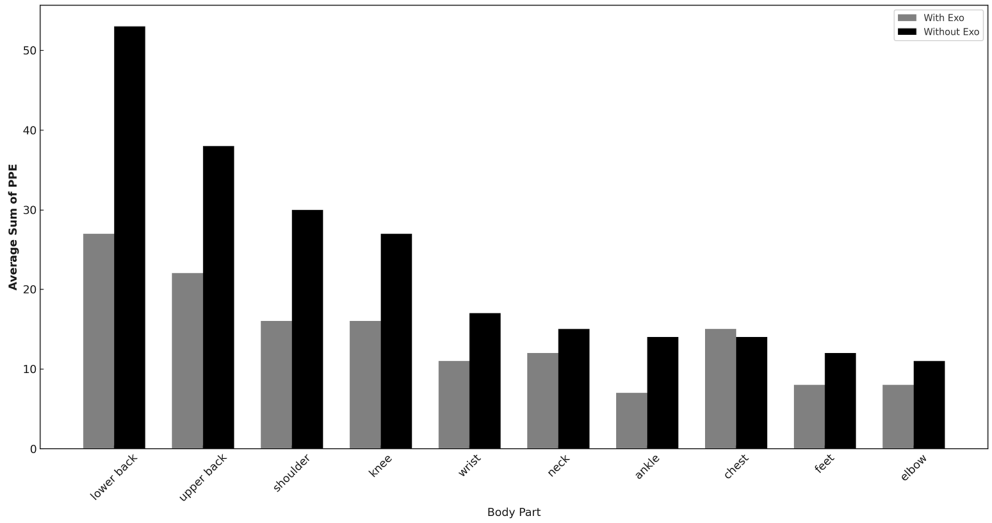

Figure 7. PPE per body part in relation to support for carrying a box.

3.3.3. Walking

The average perceived physical exertion per body part for the task of walking, comparing conditions with and without the exoskeleton, is shown in Figure 8. The knees exhibited the highest PPE score without the exoskeleton, at approximately 16, which was reduced to around 14 with the exoskeleton, demonstrating the exoskeleton effectiveness in alleviating knee strain. The feet showed a PPE score of about 15 without the exoskeleton, which decreased to approximately 10 with its use. Similarly, the ankles reported a PPE score of around 14 without the exoskeleton, which decreased to 8 with its use.

The lower back showed a PPE score of about 13 without the exoskeleton, reduced to around 6 with it. The elbows experienced a reduction in PPE from approximately 12 to 6. Other body parts, such as the neck, shoulders, upper back, and chest, also experienced reductions in PPE, though to a lesser extent. The neck showed a decrease from around 10 to 5, the shoulders from 9 to 4, the upper back from 8 to 5, and the chest from 7 to 4. These reductions underscore that the body parts experiencing the highest exertion without exoskeleton support benefited the most from its use. This evidence validates the exoskeleton's role in significantly reducing physical exertion, particularly for the knees, feet, and lower back, during walking tasks, emphasizing its potential as a valuable ergonomic tool in high-exertion activities.

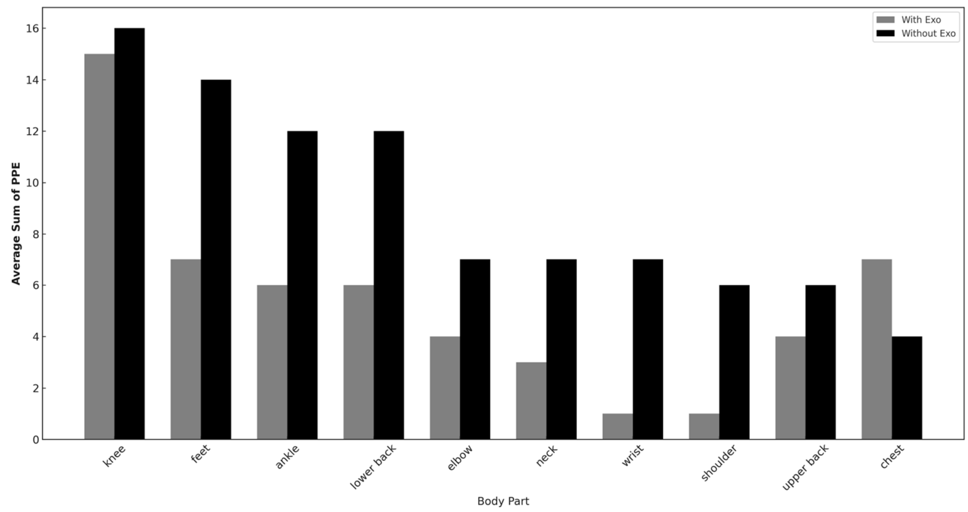

Figure 8. Participants' average sum of PPE per body part when walking with and without the exoskeleton.

3.4. Interaction Effect Analysis Using ANOVA

An ANOVA model was developed to investigate the effects of task, support, and body part, as well as their two-way interactions, on PPE. This analysis (Table 4) confirmed the previous results regarding the significant effects of all main factors and adds new insights into their interactions. The interaction between task and support demonstrated an F-ratio of 3.95, suggesting that the impact of support varied depending on the task performed. The task and body part interaction, with an F-ratio of 4.22, indicated that the exertion felt differed by body part depending on the specific task, emphasizing the role of task specificity on physical exertion. Additionally, the interaction between support and body part, with an F-ratio of 4.21, implies that the effectiveness of exoskeleton support varied across different body parts.

Table 4. Two-way ANOVA for the effects of task, support, body part on PPE.

Source	DF	Sum of Square	F Ratio	*p*-Value
Task	2	1812.1333	56.64	<0.0001 *
Support	1	889.35000	55.59	<0.0001 *
Body part	9	2344.4833	16.28	<0.0001 *
Task × Support	2	126.4000	3.95	<0.0378 *
Task × Body part	18	1216.866	4.22	<0.0046 *
Support × Body part	9	605.816	4.21	<0.0019 *

* Corresponding *p*-value is less than $\alpha = 0.05$, showing statistical significance.

These results collectively underscore the complex dynamics between task types, support mechanisms, and body part engagement, which are crucial for designing ergonomic interventions and optimizing task allocation in work settings to minimize physical strain and enhance performance efficiency.

Parameter Estimate from the Two-Way ANOVA Model

The detailed parameter estimates for each factor, their levels, and interactions resulting from the two-way ANOVA model are shown in Appendix B. The results with statistical significance are summarized in Table 5. The task-related effects showed that both Task C (carrying) and Task L (lifting) increased exertion significantly compared to the baseline exertion of walking, with lifting being slightly more demanding than carrying. The support from the exoskeleton (Support [Ex]) significantly reduced the perceived exertion by 3.8500 units, indicating its effectiveness in alleviating physical strain. Regarding the body parts, the lower back and knee reported higher exertion levels than other body parts, with the lower back showing the most significant increase. Conversely, the exertion levels for the ankle, elbow, feet, and neck were significantly lower, which might reflect less strain or different kinds of movements involving these parts during the tasks. The interaction effects also highlight interesting dynamics between support and body parts. Specifically, the exoskeleton provided additional benefits when interacting with the chest area, reducing exertion further by 5.3500 units. In addition, its interaction with the lower back was even more noteworthy, reducing exertion by 7.4833 units, indicating a targeted effectiveness at this common part of strain. Task-specific interactions further revealed that carrying a box increased exertion in both the lower and the upper back significantly. Similarly, lifting a box also elevated the exertion in the lower back. These findings underscore the complex interplay between task type, ergonomic support, and anatomical impacts, suggesting that exoskeleton design and task adjustments should be considerate of specific body part vulnerabilities and task demands to optimize worker health and productivity. The full results with all variables and interactions are included in Appendix B, Table A2.

Table 5. Results from the two-way ANOVA model (all statistically significant).

Term	Estimate	Std Error	t-Ratio	*p*-Value
Intercept	15.0167	0.5163	29.0800	<0.0001
Task [C]	3.6333	0.7302	4.9800	<0.0001
Task [L]	4.1333	0.7302	5.6600	<0.0001
Support [Ex]	−3.8500	0.5163	−7.4600	<0.0001
Body Part [ankle]	−5.0167	1.5490	−3.2400	0.0046
Body Part [elbow]	−6.1833	1.5490	−3.9900	0.0009
Body Part [feet]	−4.6833	1.5490	−3.0200	0.0073
Body Part [knee]	5.6500	1.5490	3.6500	0.0018
Body Part [lower back]	14.6500	1.5490	9.4600	<0.0001
Body Part [neck]	−4.6833	1.5490	−3.0200	0.0073
Body Part [upper back]	4.6500	1.5490	3.0000	0.0077
Support [Ex] × Body Part [chest]	5.3500	1.5490	3.4500	0.0028
Support [Ex] × Body Part [lower back]	−7.4833	1.5490	−4.8300	0.0001
Task [C] × Body Part [lower back]	6.7000	2.1906	3.0600	0.0068
Task [C] × Body Part [upper back]	6.7000	2.1906	3.0600	0.0068
Task [L] × Body Part [lower back]	6.2000	2.1906	2.8300	0.0111

3.5. Analysis of the Survey

The scoring of each attribute regarding users' interaction with the BExo is shown in Table 6. The results were sorted based on the mean score in each category from the highest to the lowest score. The survey results were analyzed to provide a comprehensive assessment of the exoskeleton's impact on user experience, usability, and overall effectiveness. Each survey component was evaluated based on the feedback from the participants, with scores ranging from 0 to 10. These survey results provide valuable insights into the potential of exoskeletons to enhance workplace safety and reduce the risk of injuries. The high scores in safety, trust, and ergonomic assistance underscore their benefits. However, the moderate scores in empowerment and willingness to reuse suggest room for improving the exoskeleton design and functionality. Addressing the feelings of constraint and intimidation can further enhance user experience and acceptance.

Table 6. Comparing descriptive statistics in BExo evaluation (sorted by mean score) *.

Category	Min	Median	Mean	Max	Std Deviation
Safe with BExo	1	7	6.91	10	1.93
Trust in BExo	1	7	6.59	9	2.02
Importance of BExo	1	8	6.45	10	2.94
Easy to Use	1	7	6.32	10	2.48
Like BExo	1	6.5	6.23	10	2.54
Ergonomic Assistance	2	5.5	5.95	10	2.4
Comfort	1	6.5	5.86	9	2.4
Posture Improvement	2	5.5	5.55	9	1.74
Helpfulness	1	6	5.41	9	2.28
Freeness	2	4.5	5.09	9	1.93
Empowerment	0	5	4.82	10	2.28
Intention to Reuse	1	5	4.77	10	2.72
Initiating BExo Use	1	1	4.73	10	4.19
Physical Effort	0	3	3.27	7	2
Constraint	0	3	3.09	8	1.85
Tiredness	0	2.5	2.64	6	1.43
Loss of Autonomy	0	2.5	2.45	5	1.84
Cognitive Effort	0	2	2.41	6	1.99
Long Training Need	0	1.5	2.41	8	2.22
Time Wasted	0	2	1.86	5	1.46

* Detailed scores per participants are reported in Appendix C, Table A3.

Certain attributes with mean and median values greater than 5, including helpfulness, ease of use, feeling safe wearing the BExo, trust in the BExo, and posture improvement, showed positive user perceptions. These metrics recorded mean values of 5.41, 6.32, 6.91, 6.59, and 5.55, and medians of 6.00, 7.00, 7.00, 7.00, and 5.50, respectively. The high scores in these categories indicate that the users generally found the exoskeleton beneficial in enhancing their posture, straightforward to operate, and instilling a sense of safety and reliability. Such feedback is crucial, highlighting the exoskeleton's utility in improving worker safety and efficiency, while also suggesting a robust trust and comfort level among users.

Attributes with mean and median values less than 5, such as perceived tiredness, perceived time wasted, perceiving the exoskeleton as a constraint, cognitive effort, level of freeness, and perceived physical effort, indicate areas needing enhancement. The respective mean values for these metrics were 2.64, 1.86, 3.09, 2.41, 5.09, and 3.27, with medians of 2.50, 2.00, 3.00, 2.00, 4.50, and 3.00. These findings suggest that the exoskeleton did not significantly increase tiredness or the cognitive burden, which is indicative of its beneficial ergonomic design. However, the moderate scores for perceived constraint and physical effort point to some discomfort and physical exertion and restricted movement. Additionally, the middling score for freeness suggests that the users experienced a degree of movement limitation, which could affect task performance and overall satisfaction.

3.5.1. Ease of Use

The participants rated cognitive effort, movement freedom, physical effort, and overall ease of use. The cognitive effort required to use the exoskeleton was rated at 2.42 out of 10, suggesting that the mental demand of operating the device is relatively low. Movement freedom, or freeness, scored 5.09 out of 10, indicating a moderate level of autonomy in movement while using the exoskeleton. The physical effort required to operate the exoskeleton was rated 3.27 out of 10, reflecting that the physical exertion needed was manageable but could be improved. Overall, the exoskeleton's ease of use was rated 6.32 out of 10, suggesting that while the device is generally user-friendly, there are opportunities to further reduce the cognitive and physical effort required to use it effectively.

3.5.2. Usability

Usability was assessed through several dimensions, including posture improvement, fatigue level, perceived inefficiency, movement constraint, and overall helpfulness. The exoskeleton received a posture improvement rating of 5.55 out of 10, highlighting its effectiveness in enhancing physical alignment. The participants reported a fatigue level (tiredness) of 2.64 out of 10, indicating that the exoskeleton helped to significantly reduce fatigue during use. Perceived inefficiency, or time wasted, was rated very low at 1.86 out of 10, suggesting that the exoskeleton did not significantly hinder productivity. However, movement constraint received a score of 3.09 out of 10, indicating that some users felt restricted in their movements while using the device. Overall, the helpfulness of the exoskeleton was rated 5.41 out of 10, reflecting a positive impact on task efficiency but also highlighting areas for improvement in reducing movement constraints.

3.5.3. Attitude and Trust

The participants provided ratings on various aspects of their attitudes towards the exoskeleton, including trustworthiness, ergonomic impact, general sentiment, comfort, and perceived innovation. Trustworthiness received a high rating of 6.59 out of 10, showing that the users felt confident about the device's reliability and functionality. The ergonomic impact, measured as ergonomic assistance, was rated 6.0 out of 10, indicating that the exoskeleton provided significant support in reducing physical strain. General sentiment, or how much the participants liked the exoskeleton, was rated 6.23 out of 10, reflecting a generally positive attitude towards the device. Comfort received a score of 5.86 out of 10, suggesting that while the exoskeleton is relatively comfortable, there is room for enhancement. Perceived innovation was rated 5.09 out of 10, indicating a moderate recognition of the exoskeleton's technological advancement.

3.5.4. Additional Feedback

The participants were also asked to provide their ratings on usage likelihood, perceived power augmentation, training requirements, and impact on autonomy. Usage likelihood, or the intention to reuse the exoskeleton, was rated 4.44 out of 10, suggesting that while the overall experience was positive, there is room to increase the willingness to reuse the device. Perceived power augmentation, or empowerment, received a rating of 4.82 out of 10, indicating that the exoskeleton moderately enhanced the user's sense of strength and capability. The training requirements were rated very low at 2.41 out of 10, reflecting that minimal training was needed to use the exoskeleton effectively. Impact on autonomy, measured as loss of autonomy, was also rated low at 2.45 out of 10, suggesting that the exoskeleton did not significantly hinder the user's sense of control and independence.

Overall, the feedback suggests that while the exoskeleton had a positive impact on reducing physical exertion and supporting safer lifting practices, further refinement in its design could improve flexibility, comfort, and broader utility in various manual handling tasks. These insights are crucial for the ongoing development and optimization of exoskeletal devices in occupational settings.

4. Conclusions

This study conclusively demonstrated the efficacy of a passive back-supporting exoskeleton (BExo) in reducing physical exertion and enhancing ergonomic posture during manual material handling tasks in manufacturing settings. Our findings show that the exoskeleton significantly decreased discomfort and physical exertion in critical areas such as the back, shoulders, and knees, which are often prone to injury in industrial environments. By enhancing ergonomic postures, the exoskeleton alleviates immediate physical strain and contributes to the long-term prevention of musculoskeletal disorders, a leading cause of workplace injuries. The ANOVA results revealed that the exoskeleton significantly reduced the perceived physical exertion across various tasks and body parts. Notably, significant reductions were observed in the lower back, shoulders, and knees, underscoring the device's effectiveness in mitigating physical strain. These findings were further corroborated by the survey results, which indicated that the users experienced improved posture and reduced fatigue. Our results corroborate existing research on the effectiveness of exoskeletons in reducing physical strain in specific body regions, based on experimental studies involving healthy individuals [8,9,18,19,29,34,43,44].

Despite these positive outcomes, the survey also highlighted areas for improvement, particularly in reducing feelings of constraint and improving overall comfort. The participants expressed generally positive attitudes towards the exoskeleton, rating its trustworthiness, ergonomic impact, and overall helpfulness highly. However, moderate scores for perceived empowerment and willingness to reuse suggest that further refinement is needed to enhance user experience and acceptance. Addressing these issues, particularly, the feelings of constraint and the physical effort required to use the device, could significantly improve its usability and effectiveness. Our results agree with previous studies that identified critical concerns regarding the design and social perception of the exoskeleton, including its comfort and ease of use and the stigma associated with wearing such devices in the workplace [33,45].

The study was limited by its sample size and demographic, which primarily involved young, healthy college students. This demographic may not fully represent the diverse workforce in manufacturing settings. Additionally, the analysis had many levels, increasing the likelihood of statistical errors. While the findings provide valuable insights, caution should be exercised in generalizing the results to a broader population due to these limitations. Future research should aim to include a larger and more diverse sample to enhance the robustness and generalizability of the findings.

Furthermore, the study relied solely on survey methods and did not use biophysical measures like electromyography (EMG), which means it was not confirmed whether the exoskeleton was optimally adjusted according to users' body specifics. This limitation underscores the need to incorporate more precise, physiological assessments in future studies. Additionally, the laboratory environment does not entirely mimic the complexities and variations of real-world manufacturing scenarios, potentially affecting the generalizability of the results. These factors highlight the importance of conducting further research involving more diverse populations and real-world settings to validate and expand upon these findings.

Future research should focus on larger, more diverse populations and include field studies to assess the practical applications of exoskeletons in actual work environments. It is crucial to also explore the long-term effects of exoskeleton use on worker health and productivity, including potential negative outcomes such as dependency or over-reliance on the technology. Since several passive exoskeletons are available on the market, and only one type was tested in this trial, future studies should consider testing a range of exoskeletons to determine the best fits for various tasks and user needs. Additionally, addressing the gender-specific differences observed could involve ergonomic adjustments and personalized fitting sessions to ensure that the technology is equally beneficial and accessible to all users.

The impact of the exoskeleton on perceived physical exertion during manual material handling tasks, in this study, was evaluated using college students who lacked extensive experience in such tasks. This participant selection is acknowledged as a limitation that may influence the applicability of the results to a professional workforce, who might perceive and interact with the exoskeleton support differently due to their familiarity with the physical demands and their developed handling techniques. However, studying individuals without manual material handling experience also offers valuable insights into the utility of the exoskeleton for novice workers and its potential for easing the learning curve in physically demanding roles. Future research should aim to compare the responses of both experienced and inexperienced workers to more fully understand the benefits and limitations of the exoskeletal technology across different user groups, thereby facilitating the design of more adaptable and universally effective exoskeleton systems.

Given these insights, the deployment of passive exoskeletons in manufacturing could lead to considerable improvements in worker safety, comfort, and productivity. However, to fully realize these benefits, ongoing refinement of the design, personalized training programs, and adaptation to user feedback are essential. This study lays a strong foundation for future research and developments in this field, aiming to tailor ergonomic solutions that meet diverse industrial needs while promoting a safer and more efficient workforce.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are only partially available on request from the corresponding author due to the privacy protocols as in the IRB approval documents.

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Conflicts of Interest: The authors declare no conflicts of interest. The exoskeleton used in this study was chosen for its relevance and availability in our laboratory settings. The authors confirm there are no operational or financial ties with Ottobock, and the BackX was selected independently based on its suitability for our study objectives.

Appendix A

Table A1. Post-experiment survey of user assessment of the BExo [41].

Category	Question	0 =	10 =
Usability	I think the exoskeleton improves my posture.	No improvement	Extreme improvement
	I feel less tired when using the exoskeleton for this task.	Not tired at all	Extremely tired
	I think the exoskeleton makes me waste time.	No time wasted at all	Waste too much time
	I think the exoskeleton is a constraint.	No constraint at all	Strong constraint
	The exoskeleton was helpful during the postures.	Not helpful at all	Extremely helpful
Ease of use	I think using the exoskeleton requires some cognitive effort.	No effort at all	A lot of effort
	I don't feel free in my movement when I am wearing the exoskeleton.	Not free at all	Extremely free
	I think using the exoskeleton requires some physical effort.	0: no effort at all; 10: a lot of effort	0: no effort at all; 10: a lot of effort
	I think the exoskeleton is easy to use.	Extremely difficult to use	Extremely easy

Table A1. *Cont.*

Category	Question	0 =	10 =
Attitude and Trust	I am not scared by the exoskeleton.	Extremely scared	Not scared at all
	I think using the exoskeleton is an important technology innovation.	Extremely unimportant innovation	Extremely important innovation
	I don't like this exoskeleton.	Don't like it at all	Extremely like it
	I feel uncomfortable when I use the exoskeleton.	Extremely uncomfortable	Extremely comfortable
	Wearing the exoskeleton makes me feel safe during the movements.	Not safe at all	Extremely safe
	In your opinion, to what extent do you believe that the exoskeleton can assist you in performing movements in an ergonomic manner? *	Not helpful at all	Extremely helpful
	I trust the exoskeleton to assist in my movements.	No trust at all	Extremely trustworthy
Additional Thoughts	I think I am losing my autonomy when I am wearing the exoskeleton.	No loss of autonomy	Total loss of autonomy
	I think you need a long training to use the exoskeleton.	No training required	Extremely long training required
	Wearing the exoskeleton makes me feel powerful.	Not powerful at all	Extremely powerful
	I would prefer to use the exoskeleton if I had to do the task again.	Not likely to use it	Extremely likely to use it.

* In this context, "performing movements in an ergonomic manner" means doing actions in a way that prioritizes your comfort, efficiency, and safety.

Appendix B

Table A2. Results from the two-way ANOVA model.

Term	Estimate	Std Error	t-Ratio	*p*-Value
Intercept	15.0167	0.5163	29.0800	<0.0001
Task [C]	3.6333	0.7302	4.9800	<0.0001
Task [L]	4.1333	0.7302	5.6600	<0.0001
Support [Ex]	−3.8500	0.5163	−7.4600	<0.0001
Body Part [ankle]	−5.0167	1.5490	−3.2400	0.0046
Body Part [chest]	−1.8500	1.5490	−1.1900	0.2479
Body Part [elbow]	−6.1833	1.5490	−3.9900	0.0009
Body Part [feet]	−4.6833	1.5490	−3.0200	0.0073
Body Part [knee]	5.6500	1.5490	3.6500	0.0018
Body Part [lower back]	14.6500	1.5490	9.4600	<0.0001
Body Part [neck]	−4.6833	1.5490	−3.0200	0.0073
Body Part [shoulder]	0.8167	1.5490	0.5300	0.6045
Body Part [upper back]	4.6500	1.5490	3.0000	0.0077
Task [C] × Support [Ex]	−0.6000	0.7302	−0.8200	0.4220
Task [L] × Support [Ex]	−1.4000	0.7302	−1.9200	0.0712
Support [Ex] × Body Part [ankle]	0.5167	1.5490	0.3300	0.7426
Support [Ex] × Body Part [chest]	5.3500	1.5490	3.4500	0.0028
Support [Ex] × Body Part [elbow]	2.0167	1.5490	1.3000	0.2094

Table A2. *Cont.*

Term	Estimate	Std Error	t-Ratio	*p*-Value
Support [Ex] × Body Part [feet]	1.8500	1.5490	1.1900	0.2479
Support [Ex] × Body Part [knee]	−0.8167	1.5490	−0.5300	0.6045
Support [Ex] × Body Part [lower back]	−7.4833	1.5490	−4.8300	0.0001
Support [Ex] × Body Part [neck]	1.8500	1.5490	1.1900	0.2479
Support [Ex] × Body Part [shoulder]	−0.9833	1.5490	−0.6300	0.5335
Support [Ex] × Body Part [upper back]	−1.8167	1.5490	−1.1700	0.2562
Task [C] × Body Part [ankle]	−3.1333	2.1906	−1.4300	0.1698
Task [C] × Body Part [chest]	−2.3000	2.1906	−1.0500	0.3076
Task [C] × Body Part [elbow]	−2.9667	2.1906	−1.3500	0.1924
Task [C] × Body Part [feet]	−3.9667	2.1906	−1.8100	0.0869
Task [C] × Body Part [knee]	−2.8000	2.1906	−1.2800	0.2174
Task [C] × Body Part [lower back]	6.7000	2.1906	3.0600	0.0068
Task [C] × Body Part [neck]	−0.4667	2.1906	−0.2100	0.8337
Task [C] × Body Part [shoulder]	3.5333	2.1906	1.6100	0.1242
Task [C] × Body Part [upper back]	6.7000	2.1906	3.0600	0.0068
Task [L] × Body Part [ankle]	−3.6333	2.1906	−1.6600	0.1145
Task [L] × Body Part [chest]	2.2000	2.1906	1.0000	0.3286
Task [L] × Body Part [elbow]	−1.4667	2.1906	−0.6700	0.5117
Task [L] × Body Part [feet]	−3.9667	2.1906	−1.8100	0.0869
Task [L] × Body Part [knee]	0.2000	2.1906	0.0900	0.9283
Task [L] × Body Part [lower back]	6.2000	2.1906	2.8300	0.0111
Task [L] × Body Part [neck]	−1.9667	2.1906	−0.9000	0.3812
Task [L] × Body Part [shoulder]	1.0333	2.1906	0.4700	0.6428
Task [L] × Body Part [upper back]	0.2000	2.1906	0.0900	0.9283

Appendix C

Table A3. Participants' detailed scores.

ID	Posture Improvement	Tiredness	Time Waste	Constraint	Helpfulness	Cognitive Effort	Freeness	Physical Effort	Ease of Use	Scared
P1 *	8.00	2.00	0.00	1.00	8.00	2.00	7.00	1.00	8.00	1.00
P2	7.00	1.00	0.00	0.00	3.00	0.00	5.00	1.00	1.00	1.00
P3	6.00	2.00	2.00	2.00	7.00	1.00	3.00	1.00	8.00	9.00
P4	7.00	5.00	2.00	4.00	7.00	5.00	3.00	4.00	7.00	9.00
P5	4.00	3.00	4.00	4.00	3.00	2.00	4.00	2.00	6.00	1.00
P6	5.00	2.00	3.00	3.00	6.00	3.00	4.00	4.00	1.00	1.00
P7	4.00	2.00	2.00	2.00	5.00	2.00	6.00	4.00	6.00	9.00
P8	5.00	2.00	0.00	1.00	5.00	1.00	8.00	3.00	7.00	1.00
P9	2.00	3.00	3.00	5.00	4.00	0.00	5.00	3.00	5.00	1.00
P10	2.00	4.00	3.00	4.00	2.00	5.00	6.00	5.00	7.00	9.00
P11	5.00	5.00	5.00	4.00	4.00	6.00	4.00	6.00	6.00	1.00
P12	4.00	3.00	3.00	5.00	2.00	4.00	3.00	5.00	6.00	9.00
P13	5.00	2.00	3.00	3.00	6.00	2.00	4.00	1.00	5.00	1.00

Table A3. *Cont.*

ID	Posture Improvement	Tiredness	Time Waste	Constraint	Helpfulness	Cognitive Effort	Freeness	Physical Effort	Ease of Use	Scared
P14	6.00	1.00	2.00	4.00	6.00	1.00	6.00	3.00	7.00	1.00
P15	5.00	2.00	1.00	1.00	4.00	1.00	2.00	2.00	8.00	1.00
P16	6.00	3.00	3.00	5.00	8.00	4.00	4.00	7.00	1.00	1.00
P17	7.00	6.00	2.00	2.00	8.00	6.00	6.00	6.00	8.00	9.00
P18	5.00	3.00	2.00	3.00	6.00	1.00	6.00	3.00	8.00	1.00
P19	7.00	3.00	0.00	2.00	7.00	1.00	4.00	4.00	7.00	10.00
P20	7.00	0.00	0.00	1.00	9.00	0.00	9.00	0.00	10.00	10.00
P21	9.00	1.00	1.00	8.00	8.00	1.00	9.00	1.00	9.00	9.00
P22	6.00	3.00	0.00	4.00	1.00	5.00	4.00	6.00	8.00	9.00
P1	1.00	1.00	1.00	1.00	9.00	1.00	0.00	0.00	6.00	1.00
P2	8.00	1.00	7.00	8.00	4.00	4.00	5.00	1.00	6.00	1.00
P3	7.00	7.00	8.00	7.00	7.00	8.00	2.00	6.00	6.00	7.00
P4	1.00	8.00	8.00	8.00	7.00	8.00	5.00	4.00	8.00	7.00
P5	8.00	4.00	3.00	7.00	4.00	5.00	3.00	5.00	3.00	3.00
P6	8.00	5.00	4.00	7.00	6.00	8.00	4.00	4.00	4.00	1.00
P7	7.00	8.00	4.00	7.00	5.00	7.00	3.00	2.00	3.00	4.00
P8	8.00	8.00	7.00	9.00	5.00	7.00	1.00	1.00	6.00	4.00
P9	8.00	5.00	4.00	4.00	3.00	4.00	0.00	3.00	5.00	2.00
P10	6.00	5.00	4.00	8.00	3.00	7.00	4.00	1.00	2.00	7.00
P11	1.00	5.00	8.00	7.00	4.00	5.00	5.00	8.00	0.00	4.00
P12	8.00	5.00	3.00	5.00	2.00	4.00	4.00	6.00	3.00	2.00
P13	8.00	5.00	4.00	7.00	8.00	8.00	0.00	3.00	4.00	7.00
P14	1.00	9.00	7.00	8.00	6.00	8.00	2.00	1.00	7.00	7.00
P15	9.00	9.00	8.00	6.00	5.00	6.00	1.00	1.00	5.00	6.00
P16	8.00	8.00	6.00	8.00	8.00	8.00	5.00	2.00	3.00	7.00
P17	8.00	8.00	4.00	7.00	9.00	8.00	3.00	2.00	5.00	1.00
P18	5.00	6.00	9.00	5.00	3.00	7.00	4.00	1.00	3.00	3.00
P19	9.00	9.00	9.00	9.00	9.00	9.00	1.00	0.00	7.00	8.00
P20	10.00	10.00	9.00	10.00	10.00	9.00	0.00	0.00	10.00	10.00
P21	9.00	8.00	8.00	8.00	9.00	8.00	1.00	1.00	7.00	7.00
P22	4.00	3.00	4.00	6.00	5.00	6.00	1.00	1.00	3.00	6.00

* P represent Participant.

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