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Sustainable Workforce Health: Exoskeleton Effects on Posture and Performance in Repetitive Lifting for Labor-Intensive Industries and Construction

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Abstract

Work-related musculoskeletal disorders (WMSDs) are among the most frequently reported injuries among industrial workers, primarily due to prolonged exposure to awkward postures. While ergonomists emphasize process and equipment redesign, exoskeletons offer a promising supplementary solution for improving workplace ergonomics. However, the effectiveness of different exoskeleton designs remains understudied. This study employs an experimental approach to evaluate the impact of two passive exoskeletons—(A) HAPO SD and (B) BSKO—on posture and task performance during repetitive lifting activities. Postural assessment was conducted using an AI-driven software that analyzes posture based on the Rapid Upper Limb Assessment (RULA) method. The findings indicate that both exoskeletons influenced posture and performance, albeit with varying effectiveness. Exo A demonstrated more consistent benefits by shifting postures toward moderate-risk categories (RULA scores of 3 to 4) while enabling participants to complete more repetitions and sustain longer task durations compared to both the no-exoskeleton condition and the BSKO exoskeleton. However, statistical analyses did not confirm significant differences in posture improvements between exoskeleton and no-exoskeleton conditions, underscoring the importance of ergonomic training and safe lifting techniques as primary interventions. These findings contribute to the growing body of research on exoskeleton applications in workplace ergonomics, emphasizing the need for careful exoskeleton selection to optimize worker augmentation and mitigate fatigue.

Keywords

Artificial Intelligence, Ergonomics, Exoskeletons.

1 Introduction

1.1 Background

Work related musculoskeletal disorders (WMSDs) are one of the main leading causes of workers' disabilities, and absences among industrial workers in the United States (US) (Merlino *et al.* 2003). Punnett and Wegman (2004) stated “MSDs are the single largest category of work-related illness, representing a third or more of all registered occupational diseases in the United States, the Nordic

countries, and Japan". Moreover, in Europe, the European Agency for Safety and Health at Work (2019) reported that 60% of employees' complaints are WMSDs. Among these significant numbers, the most frequent reporting are in the areas of agriculture, water supply, construction, and manufacturing, reporting 60%, 53%, 52%, and 46%, respectively. The high risk of developing WMSDs in these sectors are often attributed to the nature of the activities conducted that expose workers to various ergonomic risk factors (Al-Khiami *et al.* 2024a). A study by Kim *et al.* (2019) defined construction activities as complex, repetitive, dynamic, and often conducted in non-optimal postures. Additionally, manufacturing and agricultural industries were also found to share similar characteristics (Kumaraveloo and Lunner Kolstrup 2018, Zahari *et al.* 2023).

The physically demanding activities in the aforementioned industries contribute to several risk factors that increase the likelihood of developing WMSDs. These risk factors include repetitive movements, vibration, awkward postures, heavy lifting, and manual material handling (da Costa and Vieira 2010, Rahman and Sakamoto 2024). Sarkar *et al.* (2016) asserted that awkward postures are generally associated with the development of WMSDs. These postures are typically measured in terms of the angulation of each body segment from the neutral position. The greater the angulation, the higher the risk of developing WMSDs. Neutral postures, in this context, refer to a position where the worker stands straight with their arms down at their sides.

The United Nations Sustainable Development Goals (SDGs), introduced in 2015, provide a global framework for addressing critical challenges. Among these, SDG 3 (Good Health and Well-being) and SDG 8 (Decent Work and Economic Growth) are particularly relevant to workplace safety and health (Das *et al.* 2024). Several efforts towards mitigating WMSDs include prevention through design that include assessing and redesigning tools, equipment, and processes to eliminate risks that may contribute to injuries (Nath *et al.* 2017).

1.2 Industrial Exoskeletons

While ergonomic practices form one part of the solution, a holistic approach to the problem includes the potential integration of industrial exoskeletons, an aspect often overlooked (Moore *et al.* 2021). Okpala *et al.* (2019) define exoskeletons as "*mechanisms designed to be wrapped around the limbs of an operator, thereby allowing the replication or enhancement of forces at body segments*".

Howard *et al.* (2020) assert that exoskeletons can help workers improve their overall productivity by augmenting the human musculoskeletal system, thus reducing muscle contractions. Certain types of exoskeletons can redirect stress from activities to other parts of the body less prone to musculoskeletal disorders. Additionally, back exoskeletons, essential for lifting activities, potentially improve posture by maintaining neutral positions, reduce muscle activity, thus delaying muscle fatigue and enhancing overall endurance.

Several studies have evaluated the effectiveness of exoskeletons in various settings. Kakhki *et al.* (2024) investigated back exoskeletons during manual handling activities in a simulated environment. Their survey study found that participants perceived improved posture and reduced fatigue. A similar study conducted both on-site and controlled laboratory experiments on railway workers wearing back exoskeletons. Workers were observed with and without exoskeletons. The study demonstrated that the exoskeletons helped workers maintain natural working postures and better postural alignment during tasks. It was also observed that the workers' tendency towards non-ergonomic practices was reduced (Di Natali *et al.* 2024). Madinei *et al.* (2020) assessed two different types of back exoskeletons during symmetric and asymmetric repetitive lifting. The study utilized electromyography (EMG) to measure muscle activity, inertial measurement units (IMUs) for motion analysis, and collected subjective feedback. The results showed that exoskeleton usage reduced peak trunk extensor muscle activity by

9 – 20%. However, the IMU data revealed that the use of exoskeletons did not significantly alter the lifting postures of participants (Madinei *et al.* 2020).

While several studies have developed computer vision techniques to assess postures in real-time settings (Li *et al.* 2020, Lin *et al.* 2022) and proved their accuracy, to the best of the author's knowledge, limited studies have utilized non-intrusive computer vision to assess posture improvement during repetitive lifting tasks utilizing back exoskeletons.

1.3 Research Question

Exoskeletons can be designed in various ways, each offering different types of support and potentially varying effects on the user. According to Al-Khiami *et al.* (2024b) more than 132 exoskeleton models are available worldwide. This diversity in design means that findings from studies on single exoskeleton type cannot necessarily be generalized to all exoskeleton varieties. Despite these promising findings in individual studies, there remains a gap in understanding how different exoskeleton designs compare in terms of their effectiveness for improving posture and task performance during repetitive lifting tasks, ultimately contributing to SDG3 and SDG8. This study aims to address these gaps by comparing two exoskeleton designs. The following research questions guide this investigation: (1) How do different exoskeleton designs affect postural risk during repetitive lifting tasks? (2) What is the impact of exoskeleton use on task performance metrics (3) How do the effects of exoskeletons on posture and performance vary across different body segments, particularly the neck and trunk?

2 Research Methodology

2.1 Experimental Design

This research was designed as a controlled experimental pilot study to investigate the effects of different exoskeleton designs on posture and performance during repetitive lifting tasks. The pilot study approach was chosen to establish and validate experimental protocols, test measurement methodologies, and generate preliminary data to inform future large-scale studies. The design incorporated repeated measures across multiple sessions over 18 days, allowing for systematic comparison of different exoskeleton conditions while controlling for learning effects and fatigue.

2.2 Experimental Setup

The experiment evaluated two commercially available back exoskeletons with distinct support mechanisms:

(A) HAPO SD (Ergosante, France) utilizes a spring-based system to reduce back muscle strain. The device transfers load from the upper trunk to the thighs through springs, which provide support during bending motions and assist the user in returning to an upright position. A stabilizing lumbar belt complements the spring mechanism to promote proper posture throughout activities (Ergosante 2023).

(B) BSKO (Exoskeleton, Denmark) employs an elastic band system for back support. During bending movements, the elastic bands stretch and store potential energy. This energy is then released during the lifting motion, providing assistive force to complement the user's back muscles and reduce muscular load during lifting and bending tasks (Exoskeleton 2024, Orthexo 2024).

Hereafter, HAPO SD and BSKO will be referred to as Exo A and Exo B, respectively.

2.2.1 Experimental protocol

The study employed a single participant who was experienced in proper lifting techniques and familiar with exoskeleton use. The participant performed repetitive lifts of a 24 kg kettlebell until subjective failure. Each repetition consisted of four phases: bending to grasp the kettlebell, returning to neutral stance, lowering to release the load, and resuming neutral stance.

The experiment was structured into six trials conducted over an 18-day period, with three-day rest intervals between trials to ensure full recovery. Each trial consisted of four sets, with each set performed under one of three conditions: Exo A, Exo B, or No Exo. To mitigate fatigue effects, the sequence of conditions was randomized across trials. Between sets, specific rest periods were implemented: 10 minutes between the first and second sets, and 15 minutes between both the second and third sets and the third and fourth sets, allowing for higher levels of recovery for the latter sets. Figure 1 summarizes the experimental structure and sequence of conditions in each trial.

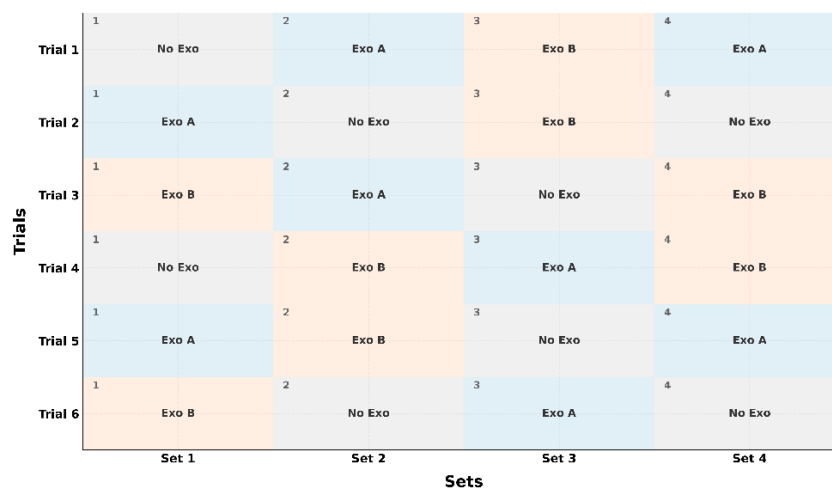


Figure 1. Experimental structure and set sequence

2.2.2 Posture Analysis

A video-based posture analysis was conducted in this study. All the sets were recorded using an iPhone 12 Pro stabilized using a tripod. The phone was positioned to capture the side view of the participant. The recorded videos were then processed and analyzed using LEA (Lifting Ergonomics Assessment), a specialized software developed by Ergosanté (2024). This application employs artificial intelligence and computer vision algorithms to automatically detect and track the upper body in a recorded video. Specifically, LEA measures the angular positions of the neck, arms, forearms, and trunk throughout the lifting motion. The software then generates a detailed report, providing quantitative biomechanical data and risk scores based on the Rapid Upper Limb Assessment (RULA) method (McAtamney and Nigel Corlett 1993).

RULA is a widely recognized ergonomic assessment tool designed to evaluate the risk of upper extremity disorders in workplace tasks (McAtamney and Nigel Corlett 1993). By utilizing this automated analysis approach, an objectively quantified postural parameters and assessment of potential ergonomic risks associated with the lifting task can be made.

First, the report provides “Angulations”. These are basically measurements of angulations formed by each body segment between their reference position (person standing straight, with arms down, in neutral posture). Measuring both flexions and tilt, the application provides a percentage duration of which the participant specific body part is within an angle class. The larger the angle formed, the higher

the likelihood of the conducted activity to result in WMSDs. The LEA application converts the measured angulations into RULA scores following the methodology of McAtamney and Nigel Corlett (1993). The scoring system is as follows: (1) Neck, trunk, and shoulder scores range from 1 to 6, categorized as 1-2, 3-4, and 5-6. (2) Elbow scores are 1, 2, or 3. These scores correspond to action levels: Action level 1 (scores 1-2): The posture is considered acceptable (coded green). Action level 2 (scores 3-4): The posture requires further analysis and investigation (coded orange). Action level 3 (scores 5-6): Changes to the posture are required (coded red). Figure 2 illustrates the participant in neutral and lifting positions, as analyzed by the LEA application.

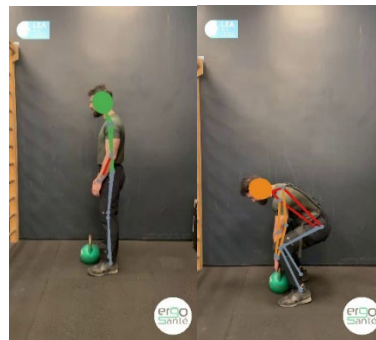


Figure 2. LEA posture analysis

The study's data maintains validity and reliability through several key features. The systematic data collection over 18 days using the LEA application provides consistent, unbiased measurements of posture. The randomized testing sequence and controlled rest periods eliminates order effects and standardizes fatigue management. Most importantly, the consistent patterns in performance metrics (repetition counts and duration) across multiple trials demonstrate measurement reliability.

3 Results and Discussion

The following section illustrates the results extracted from the reports generated by LEA. This includes the RULA reports scores for neck, trunk, left and right shoulders, and elbows. Since the task involves repetitive lifting and the exoskeleton's main purpose is to support the back, all results reported from shoulders and elbows are excluded.

3.1 RULA Results

Table 1 shows the duration percentage the participant exposed to score 1-2, 3-4, or 5-6.

Table 1. Participant scores in neck and trunk as duration percentage

Trial No.	Condition	Neck			Trunk		
		1-2	3-4	5-6	1-2	3-4	5-6
Trial 1	No Exo	27	72	1	15	85	0
	Exo A	6	93	0	0	100	0
	Exo B	7	87	6	21	79	0
	Exo A	1	94	5	4	96	0
Trial 2	Exo A	1	98	1	1	99	0
	No Exo	2	96	2	3	97	0
	Exo B	2	97	1	4	96	0
	No Exo	0	95	5	20	80	0
Trial 3	Exo B	3	97	0	1	99	0
	Exo A	1	97	2	2	98	0

	No Exo	1	97	2	26	74	0
	Exo B	2	98	0	1	99	0
Trial 4	No Exo	1	97	1	1	99	0
	Exo B	1	91	8	1	99	0
	Exo A	0	98	2	1	99	0
	Exo B	2	98	0	0	100	0
Trial 5	Exo A	0	100	0	0	100	0
	Exo B	0	99	1	0	100	0
	No Exo	0	99	1	1	99	0
	Exo A	0	100	0	0	100	0
Trial 6	Exo B	1	99	0	1	99	0
	No Exo	0	100	0	1	99	0
	Exo A	1	99	0	0	100	0
	No Exo	0	99	1	1	99	0
Average		2.46	95.83	1.63	4.38	95.63	0.0

3.1.1 Neck Posture Analysis

The neck posture data reveals a nuanced picture of the participant's movement patterns. A mere 2.46% average duration across all trials and sets achieved a RULA score of 1-2, indicative of neutral postures. This low percentage aligns with the expectation that neutral neck positions are challenging to maintain during active work tasks. The predominant score range of 3-4, accounting for 95.83% of the duration, suggests a consistent engagement in the task with moderate postural stress. While this score range does not indicate severe risk, it underscores the need for attention to neck posture during repetitive lifting activities. As for the small proportion (1.63%) scoring in the 5-6 range, requiring action level 3, indicates moments of higher risk that, while infrequent, warrant consideration in overall task design and ergonomic interventions.

3.1.2 Trunk Posture Analysis

The trunk posture data presents a somewhat different profile. A slightly higher percentage (4.38%) of duration in the 1-2 score range suggests more frequent instances of neutral or near-neutral trunk postures compared to the neck. Notably, the absence of any duration in the 5-6 score range is a positive finding, indicating that extreme trunk postures were avoided throughout the trials.

The predominance of scores in the 3-4 range (95.63%) aligns with the neck data, confirming consistent engagement in physical activity. This distribution suggests that the lifting task induces moderate postural stress on the trunk.

The similar distributions of scores between neck and trunk (both showing a strong predominance in the 3-4 range) suggest a coordinated movement pattern where both body segments are similarly engaged throughout the task. However, the slightly higher percentage of 1-2 scores in the trunk (4.38% vs 2.46% for the neck) might indicate that maintaining neutral trunk postures is somewhat easier than maintaining neutral neck postures during this specific lifting task. This can be attributed to the use of the back exoskeletons. The absence of 5-6 scores for the trunk across all conditions is particularly noteworthy. This consistency across conditions suggests that the basic biomechanics of the lifting task, rather than the presence of exoskeletons, may be the primary determinant in avoiding extreme trunk postures. The analysis of average durations for each degree (as shown in Table 2) is crucial in understanding whether the instances of improved posture (scores 1-2) are attributable to exoskeleton use or other factors such as task familiarity or individual movement strategies.

Table 2. Average percentage of duration in neck and trunk per RULA score

Body part							
Neck				Trunk			
RULA Score	No Exo	Exo A	Exo B	Degree	No Exo	Exo A	Exo B
1 to 2	3.88	1.25	2.25	1 to 2	8.50	1.00	3.63
3 to 4	94.38	97.38	95.75	3 to 4	91.50	99.00	96.38
5 to 6	1.63	1.25	2.00	5 to 6	0.00	0.00	0.00

For neck postures, it is observed that the use of exoskeletons appears to influence the distribution of RULA scores, albeit in a somewhat unexpected manner. The percentage of time spent in the posture range (RULA score 1-2) decreased from 3.88% in the No Exo condition to 1.25% with Exo A and 2.25% with Exo B. This suggests that the exoskeletons might be slightly constraining the ability to achieve or maintain optimal neck postures. Conversely, the mid-range scores (3-4) increased from 94.38% in the No Exo condition to 97.38% with Exo A and 95.75% with Exo B. This shift indicates that while the exoskeletons may reduce the frequency of optimal postures, they also seem to provide some stabilization, keeping the neck in a moderate risk range for a larger percentage of time. Interestingly, the highest risk postures (scores 5-6) showed mixed results. Exo A slightly reduced the time in this range (from 1.63% to 1.25%), while Exo B saw a small increase (to 2.00%). These changes, while small. Both Exo A and Exo B support mainly the back and do not interfere with the neck. Therefore, the neck posture can be attributed to the user's experience in repetitive lifting tasks.

As for the trunk posture, the data presents a more pronounced effect of exoskeleton use. In the No Exo condition, 8.50% of the time was spent in the optimal posture range (scores 1-2). This dramatically decreased to 1.00% with Exo A and 3.63% with Exo B. While this might initially seem concerning, it should be interpreted in conjunction with the other score ranges.

The mid-range scores (3-4) for trunk postures increased from 91.50% in the No Exo condition to 99.00% with Exo A and 96.38% with Exo B. This substantial increase suggests that both exoskeletons are effective at keeping the trunk in a moderate risk range, potentially preventing more extreme postures. Notably, there were no instances of high-risk trunk postures (scores 5-6) in any condition. This is a positive finding, indicating that the lifting task, with or without exoskeletons, did not induce extreme trunk postures. The absence of high-risk trunk postures across all conditions is noteworthy and suggests that the basic task design and training may be effective in preventing extreme trunk flexion or rotation, regardless of exoskeleton use. It also shows that users who are well familiar with proper lifting techniques might not necessarily benefit from posture improvements when using exoskeletons.

While the exoskeletons appear to reduce the time spent in optimal postures, the increased time in the moderate risk range (3-4) may be beneficial in a repetitive lifting task. It could indicate more consistent, controlled movements that might reduce fatigue over time, even if they do not achieve the lowest possible RULA scores.

3.1.3 Significance test

To confirm whether using Exo A, Exo B, or no Exo has a significant difference on the posture of the participant, a Kruskal-Wallis H-test, a non-parametric test suitable for comparing three or more independent groups is conducted (Ostertagová *et al.* 2014). Table 3 shows the findings.

Table 3. Kruskal-Wallis H-test Results Comparing RULA Score Distributions Across Exoskeleton Conditions

Body Part	RULA Score Range	H-statistics	p-value	significance
Neck	1-2	3.42	0.18	NS
	3-4	0.66	0.72	NS

	5-6	0.98	0.61	NS
Trunk	1-2	4.61	0.10	NS
	3-4	4.61	0.10	NS

The Kruskal-Wallis H-test results across the different exoskeleton conditions show no statistically significant differences (NS) at the $p < 0.05$ level. However, it's crucial to note that this lack of statistical significance does not necessarily imply that the conditions are similar or that exoskeletons have no effect. Rather, it indicates that with the current sample size and study design, we cannot statistically prove that the conditions are different.

3.2 Set Duration and Repetition Count

Even though the RULA score difference did not prove statistically significant in the postural risks across different exoskeleton conditions, it is imperative to investigate how these postural patterns might be influenced by the intensity and duration of the lifting task. To explore this relationship, the repetition count and duration of each set, along with the observed postural data is explored. Table 4 presents the repetition count and duration for each set across the three conditions (No Exo, Exo A, and Exo B).

Table 4. Average repetition count and duration across all sets for different exoskeleton conditions.

Condition	Repetition Count	Duration (s)
No Exo	23.5	92.4
Exo A	31.9	119.2
Exo B	26.8	100.2

Table 4 illustrates notable differences in both repetition count and set duration across the three conditions. Without an exoskeleton, the user completed an average of 23.5 repetitions over 92.4 seconds, equating to 0.25 repetitions per second. In contrast, Exo A was found to be the most effective and facilitated 31.9 repetitions over 119.2 seconds, while Exo B allowed for 26.8 repetitions in 100.2 seconds. An average increase of 8.4 repetitions and 3.3 repetitions for Exo A and Exo B, respectively. Interestingly, both exoskeleton conditions resulted in a slightly increased pace of 0.27 repetitions per second. These findings suggest that the use of either exoskeleton (Exo A or Exo B) enhanced the overall endurance of the participants, potentially delaying the onset of subjective fatigue and increasing the sustained work rate. The increased repetition count and longer set duration with exoskeletons indicate that participants were able to maintain the lifting task for extended periods compared to the no-exoskeleton conditions.

Exo A's superior performance can be attributed to several key design elements. The spring-based mechanism appears to provide more consistent support compared to the elastic band system used in Exo B, particularly during the transition between bending and lifting phases. Additionally, Exo A's load transfer system, which redirects force from the upper trunk to the thighs, may offer more effective weight distribution. The inclusion of a lumbar-stabilizing belt in Exo A's design likely contributed to better postural control during lifting tasks. These design features collectively resulted in higher repetition counts and longer task durations compared to both Exo B and no-exoskeleton conditions.

In relation to posture, the results indicate that even with extended activity durations, extreme postures (score 5-6) were not reached. This means that utilizing exoskeletons, while it did not result in a RULA score of 1-2, it also did not disrupt the posture of the user, shifting it towards extreme RULA scores (5-6) at any time throughout the duration of the activity.

4 Conclusion

This pilot experimental study investigated the effects of different back exoskeleton designs on posture and performance during repetitive lifting. Analysis of 24 recorded trials using the LEA application revealed that both exoskeleton designs influenced posture and task performance, with Exo A demonstrating superior benefits. The spring-based mechanism and lumbar stabilization features of Exo A appeared to provide more consistent support compared to Exo B's elastic band system, resulting in higher repetition counts and longer task durations. Though statistical analysis showed no significant differences in postures across conditions, important design considerations emerged. The effectiveness of Exo A's load transfer system and stabilizing features suggests that optimal exoskeleton design should focus on providing consistent support throughout the lifting motion while incorporating features that enhance postural stability. Additionally, the findings indicate that exoskeletons may be more effective at reducing muscle fatigue than improving posture for users already trained in proper lifting techniques.

These findings have significant implications for exoskeleton implementation. First, employers should prioritize ergonomic training and proper lifting techniques as foundational elements, with exoskeletons serving as supplementary support rather than replacements for safety training. Second, the varying effectiveness of different designs highlights the importance of user testing before investment decisions. However, this study's limitations, including its single-participant design and focus on specific exoskeleton features, suggest the need for broader investigation.

Future research should explore exoskeleton effectiveness across diverse user populations and industrial settings, utilizing diverse designs, particularly examining how different design elements perform for users with varying levels of lifting experience. Additionally, investigating temporal patterns in posture changes could provide insights into how specific exoskeleton features influence movement strategies and fatigue development.

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