Understanding the Impact of an Active Exoskeleton System on Vigilance Level of Workers During Common Repetitive Construction Tasks

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Abstract

The adoption of active exoskeleton systems in the construction industry shows potential for reducing work-related musculoskeletal disorders (WMSDs) by providing physical support to workers during labor-intensive tasks. However, concerns about the potential impact of exoskeletons on workers' vigilance and attention to hazards have not been fully explored. This study examines the effect of active exoskeletons on the vigilance levels of construction workers during common construction tasks. A high-fidelity, immersive virtual reality (VR) environment was developed to realistically simulate material handling tasks and collect eye-tracking data. Eighteen participants completed tasks under two conditions: with and without the use of an active back-support exoskeleton. Eye-tracking metrics, including fixation count and fixation duration on predefined Areas of Interest (AOI) of hazards in the simulated environment, were collected from the participants and analyzed to assess vigilance levels. The results showed no statistically significant difference in vigilance levels between participants, regardless of whether they used the exoskeleton. These findings suggest that the use of active exoskeletons does not negatively affect workers' vigilance or their ability to identify hazards. This study provides an empirical basis for supporting the wider adoption of active exoskeletons on construction sites.

Keywords –

Active Exoskeleton; Vigilance; Psychological Assessment; WMSDs

1 Introduction

The construction industry often requires workers to engage in repetitive, physically demanding tasks while maintaining uncomfortable postures for extended periods [1,2]. This biomechanical stress on the musculoskeletal system increases the likelihood of developing Work-Related Musculoskeletal Disorders (WMSDs) [3,4]. Data from the U.S. Bureau of Labor and Statistics reveals that WMSDs constitute approximately 37% of non-fatal injuries and illnesses among construction workers [5]. Furthermore, studies indicate that the construction industry faces annual workers' compensation costs exceeding $400 million due to WMSDs [6].

Prominent safety organizations like NIOSH and OSHA have advocated proper ergonomic practices to reduce WMSDs in construction [7]. However, the industry continues to be characterized by physically demanding tasks involving repetitive movements and awkward postures. The primary challenge stems from the dynamic and diverse nature of construction work, which resists the application of standardized ergonomic practices across all tasks and sites.

Exoskeletons, also known as wearable robotic systems, are gaining recognition as vital tools in the construction industry for mitigating WMSD risks. These devices are designed to assist workers by providing support during heavy lifting, distributing weight more evenly, and promoting proper posture, thus benefiting various construction tasks. Exoskeletons are generally categorized into two types: active and passive. Active exoskeletons are equipped with actuators, such as electric motors, hydraulics, or pneumatics, which actively amplify the wearer's physical strength [8]. On the other hand, passive exoskeletons do not have actuators; they rely on materials like springs or dampers to store energy from human movement and release it when needed to support the wearer [8]. While passive exoskeletons are often preferred due to their lower cost and ease of use, active exoskeletons offer greater potential for broader adoption in construction due to their capacity to provide more substantial physical assistance. However, as active exoskeletons become more prevalent in construction, new challenges and considerations are likely to arise.

Although powered exoskeletons offer considerable potential to mitigate WMSDs in construction, their widespread adoption remains hampered by a limited understanding of their broader impacts on workers' psychophysiological state. While much of the current research focuses on understanding the physiological impact of exoskeletons [9–14]—such as muscular fatigue, metabolic cost and ergonomic risks, the psychological dimensions are often overlooked. The current body of knowledge fails to provide a comprehensive understanding of the psychological impacts of exoskeletons which may lead to decreased productivity and safety risks for workers wearing exoskeletons. The deployment of an exoskeleton on a job site may cause additional distractions, negatively impacting their vigilance (situational awareness) [15–18]. Wearing a powered exoskeleton may introduce new distractions for workers, such as the need to adjust the device, manage its operation, or adapt to the altered physical sensation it brings. These distractions can take attention away from the task at hand, reducing vigilance and potentially increasing the likelihood of accidents. For instance, if a worker is overly focused on the functioning of the exoskeleton—such as ensuring it is aligned correctly or adjusting to the support it provides—they may be less attentive to their immediate environment, including hazards or moving equipment. Wearing a powered exoskeleton may introduce new distractions for workers, such as the need to adjust the device, manage its operation, or adapt to the altered physical sensation it brings. These distractions can take attention away from the task at hand, reducing vigilance and potentially increasing the likelihood of accidents [19]. For instance, if a worker is overly focused on the functioning of the exoskeleton—such as ensuring it is aligned correctly or adjusting to the support it provides—they may be less attentive to their immediate environment, including hazards or moving equipment.

To that end, this research aims to investigate how active exoskeleton systems affect the vigilance levels of construction workers during routine tasks. To achieve this, a high-fidelity, immersive virtual reality (VR) environment was created to replicate common construction activities. This simulated environment served as a virtual testbed for gathering eye-tracking data, which was then analyzed to determine the impact of active exoskeleton use on workers' vigilance. The insights gained from this study contribute to understanding the psychological implications of implementing powered exoskeletons on construction sites, particularly regarding how they influence attention and focus during tasks.

2 Vigilance for Worker Safety in Technology-driven Construction Sector

In the construction industry, the integration of emerging technologies such as robotics heightens the need for psychophysiological well-being. Such technologies bring new complexities and learning curves, which can impact workers' psychophysiological well-being [20,21]. Ensuring psychophysiological well-being is essential for the construction workers in adapting to technology-driven workplaces, embracing innovation, and maintaining safe, productive work environment. The introduction of advanced technologies in construction can significantly alter cognitive demands on workers. As construction sites become more technologically advanced, maintaining vigilance about potential hazards is also increasingly and equally important [22]. Workers need to be continuously aware of both safety hazards and new risks introduced by technology. This involves staying vigilant to the operational aspects of technology, understanding its limitation, and being prepared for unexpected scenarios that might arise from technological integration. When safety hazards go unrecognized, workers are prone to engaging in unsafe behaviors, facing unexpected exposure to hazards, and potentially suffering severe injuries. Conversely, identifying safety hazards enables workers to evade such exposures, implement proper safety protocols, and prevent injuries at the workplace. Distracting technology can hinder the performance of construction tasks, impairing workers' ability to detect and address hazards effectively. Such technology not only affects their productivity but also compromises overall safety at the construction site.

3 Impact of Active Exoskeleton on Vigilance Level of Workers

While active exoskeletons in the workplace show great promise, they also introduce a range of new safety and usability concerns, from physical issues to psychological implications. The deployment of an exoskeleton on a job site can inevitably cause additional distractions, negatively impacting their vigilance (situational awareness) [15–18]. The additional sensory inputs from the device, such as vibrations or sounds, can lead to sensory overload, potentially overwhelming a worker's ability to process critical environmental cues. Moreover, the cognitive load required to operate the exoskeleton may divert attention away from the surrounding environment, reducing overall awareness. In addition, there is also a risk of overconfidence and complacency as workers become accustomed to the enhanced physical capabilities provided by exoskeletons. This could lead to a decreased perception of risk and, consequently, reduced vigilance. The altered sense of body awareness (proprioception) caused by exoskeleton use may affect spatial judgment, potentially leading to misjudgments of physical space and increased risk of accidents. Additionally, the pressure to perform with new technology and anxiety about potential malfunctions can induce stress, further impacting a worker's ability to maintain optimal vigilance levels. Further, active exoskeletons may produce noise that interferes with important auditory cues in the workplace, and some designs might limit peripheral vision, potentially causing workers to miss visual warnings or approaching hazards.

4 Assessment of Active Exoskeletons on Workers' Vigilance Level

This research aims to explore how active exoskeleton systems influence the vigilance levels of construction workers during typical construction activities. Figure 1 outlines a two-phase research methodology.

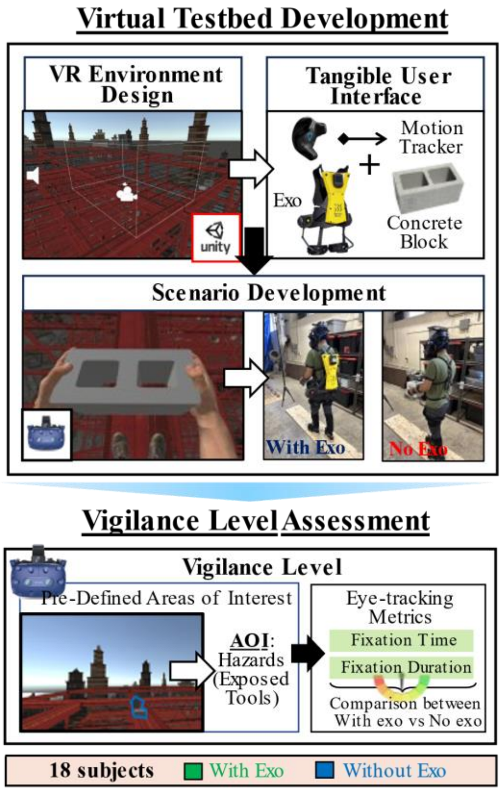

Figure 1. Research Methodology for Assessment of Active Exoskeleton on Workers' Vigilance Level

The study consists of two key phases: Virtual Testbed Development and the Assessment of Vigilance. In the first phase, an immersive and interactive virtual testbed was created to simulate realistic material handling tasks, under two conditions: with and without the use of an active exoskeleton. This environment allowed for the comparison of performance in both scenarios. In the second phase, workers' vigilance levels were assessed by analysing eye-tracking data collected from predefined areas of interest within the virtual environment, corresponding to both conditions. The following subsection will offer a detailed explanation of each step involved in these phases.

4.1 Virtual Testbed Development

In the first module of the proposed framework, a high-fidelity virtual testbed was developed to simulate typical construction tasks. This effort centered on designing a user-centered, simulated workspace to safely assess the impact of active exoskeletons on the vigilance level of workers during common construction tasks. The virtual job site was modeled using Building Information Modeling (BIM) software, specifically Autodesk Revit, and then imported into Unity, a game engine, to create a realistic construction environment, as seen in Figure 2-A. To enhance realism, the virtual space was populated with various elements, including construction machinery, automated systems like drones, personal protective equipment (PPE), and both static and dynamic virtual workers.

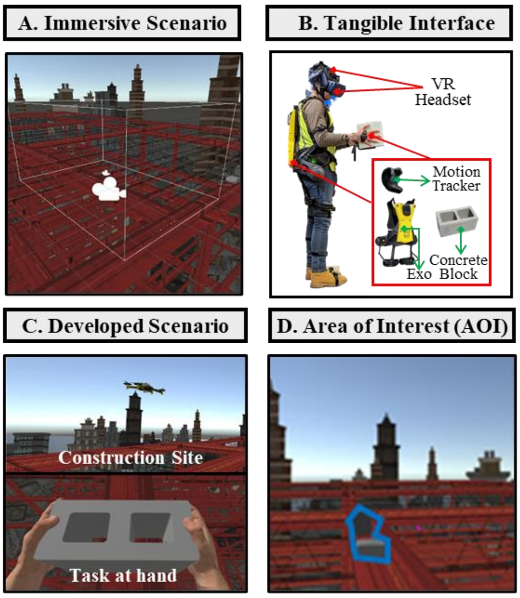

Figure 2. Development of the Virtual Testbed (A) Immersive Scenario Design; (B) Tangible User Interface; (C) Scenario of Material Handling Task at Height; (D) Area of Interest (AOI) in the virtual environment

A virtual representation of an active exoskeleton was integrated into the virtual environment as the primary tool for interaction. To make physical objects interactive in the immersive environment, a motion-tracking sensor was attached to each object, which was then rendered in the VR setting, as seen in Figure 2-B. The core task simulated in this environment involved material handling, where participants lifted and carried concrete blocks to a designated area, all while working at heights by walking on an iron beam (Figure 2-C). By incorporating the working at height scenario into the simulated material handling tasks, the authors could comprehensively evaluate how the use of powered exoskeletons might influence the vigilance.

To analyze the impact of active exoskeletons on vigilance level of construction workers during common construction tasks, two scenarios were developed: one where participants performed the material handling tasks without an exoskeleton, and another where they used the exoskeleton. In both scenarios, participants interacted with real concrete blocks and an actual powered exoskeleton, presented as physical objects within the virtual environment. The tasks involved picking up the blocks, walking a 4-meter distance along a narrow 40 cm-wide wooden plank, designed to simulate an iron beam at height, and placing the blocks in a specified location. The immersive VR experience, including consistent sounds and visual effects, was the same for all participants, ensuring uniform conditions across both scenarios and eliminating potential biases. In the simulated environment, an Area of Interest (AOI) of hazards was predefined, which represented possible distraction within the virtual environment. Figure 2-D shows the AOI in the simulated environment. The AOIs in the virtual environment were intentionally placed within participants' peripheral vision and along their natural line of sight during task performance. This design ensured that hazards appeared within the operational workspace, mimicking real-world conditions where workers must remain vigilant to dynamic and spatially distributed risks. The immersive VR setting simulated realistic construction scenarios, where hazards typically appear within the operational workspace rather than at extreme angles requiring extensive head rotation.

4.2 Vigilance Level Assessment

Eighteen participants took part in the material-handling task as part of the study. The average age of the participants was 25.2 ± 4 years, with a mean height of 179 ± 5.5 cm, body mass of 74 ± 6.5 kg, and a body mass index (BMI) of 23.1 ± 2.5 kg/m². Before the experiment, all participants were given detailed informed consent forms that outlined the study's purpose, the data collection process, confidentiality measures, and their rights as participants. Written informed consent was obtained from each participant, in accordance with the guidelines approved by the Institutional Review Board (IRB) at the University of Illinois Urbana-Champaign. The researchers ensured that none of the participants had any medical conditions that could interfere with their performance in the immersive virtual environment, ensuring the integrity of the experiment and the safety of all participants.

After agreeing to participate and signing the consent form, the participants were randomly assigned to one of two virtual scenarios: performing the material handling with exoskeleton or without exoskeleton (Figure 3-A). Each participant was equipped with an HMD VR headset (HTC Vive Pro Eye), which included Tobii Pro eye-tracking technology, along with motion tracking sensors (Vive Trackers and Leap Motion), as seen in Figure 3-B. Once the VR system was properly set up, participants were instructed to carry out the material handling task at height within the immersive testbed. The task involved lifting, carrying, and lowering a 10-pound concrete block to replicate typical construction activities. To simulate real-world conditions, participants used an actual concrete block, which was integrated into the virtual environment via a tangible user interface. This setup allowed participants to experience a realistic material handling task at height, ensuring the task closely resembled those found on actual construction sites.

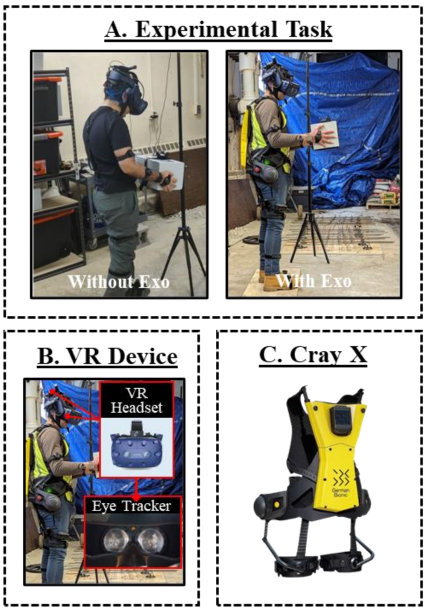

Figure 3. Vigilance Level Assessment Illustration (A) Experimental Task Setup (With and without active exoskeleton); (B) VR Device; and (C) Cray X exoskeleton

In addition, the actual active exoskeleton, Cray X, was integrated into the virtual testbed for the scenario involving material handling tasks with powered exoskeleton assistance. The study employed a crossover design, with participants randomly divided into two groups (nine participants in each group). In the first group, participants began by performing the material handling tasks without the use of the active exoskeleton. After completing this phase, they crossed over to the second phase, where they repeated the tasks using the Cray X exoskeleton. Conversely, the second group started by using the active exoskeleton and then performed the tasks without it. The Cray X, an active exoskeleton manufactured by German Bionic, weighs approximately 8 kg and was used to provide support during the material handling tasks, as seen in Figure 3-C. The Cray X active exoskeleton, used in this study, is designed to support back and lower body movements without restricting neck mobility. Since the exoskeleton primarily assists with lifting and carrying tasks, its weight distribution does not impose significant constraints on head movements. For both scenarios, participants performed the tasks for 5 minutes, with a 5 -minute break in between sessions. Throughout the experiments, the Tobii eye tracker, integrated with the HMD VR headset, collected data on participants' gaze points, focusing on predefined AOI within the virtual environment. This data was crucial for analyzing the participants' vigilance during the tasks. During the experiment, participants did not report significant discomfort or difficulty in rotating their heads to observe hazards.

The metrics used to assess participants' vigilance while performing tasks in the VR environment include Fixation Count, which measured the number of times participants looked at a predefined AOI; and Fixation Duration, which calculated the total time each participant spent fixating on the AOI. The fixation duration was calculated by subtracting the timestamp when the participant shifted their gaze away from the hazard AOI from the initial timestamp when they first looked at it. A fixation was only recorded if it lasted longer than 100 milliseconds. Both fixation count and fixation duration serve as indicators of vigilance, providing insights into how often and for how long participants were distracted by the hazards in the virtual environment.

To assess the impact of active exoskeleton systems on the vigilance levels of construction workers during typical tasks, the extracted eye-tracking metrics were analyzed statistically. The normality of the data was evaluated using the Shapiro-Wilk test. In this test, a non-significant p-value (generally greater than 0.05) suggests that the data does not significantly deviate from a normal distribution. However, the test yielded a p-value of less than 0.05, indicating that the data significantly deviated from normality. Given that the data did not meet the assumptions of normality, a non-parametric test, specifically the Mann-Whitney U test, was employed to examine the effect of the active exoskeleton on the vigilance levels of the construction workers.

5 Results and Discussion

Table 1 presents the results for the calculated fixation count and fixation duration on AOI during the experiment. When using the active exoskeleton, participants exhibited an average fixation count of 59.85 ± 21.3 and spent an average of 43.8 ± 26.65 seconds fixating on the AOI. This suggests that while performing the material handling tasks, participants shifted their attention away from the task to focus on potential hazards in the environment at least 60 times, for a total of approximately 44 seconds during the 10-minute session in the immersive environment. In contrast, when the tasks were performed without the active exoskeleton, the mean fixation count on AOI was slightly lower at 54.35 ± 16.8, with participants spending an average of 39.85 ± 21.25 seconds focusing on the hazards. These findings indicate that, regardless of whether the exoskeleton was used, participants allocated a significant portion of their attention to environmental hazards, but the exoskeleton may have influenced the frequency and duration of these attentional shifts. The fixation count was slightly higher when participants used the exoskeleton. This suggests that participants may have been more aware of their surroundings or potential hazards while wearing the device. However, the difference is relatively small, and the high standard deviations indicate considerable variability among participants. Similarly, participants spent slightly more time fixating on the hazards when wearing the active exoskeleton. This could indicate that the active exoskeleton might have influenced participants to be more cautious or attentive to potential hazards. Again, the high standard deviations suggest significant individual differences.

Table 1 Results of eye-tracking metrics for AOI

Metrics	With exo	Without exo
Fixation Count	59.85 ± 21.3	54.35 ± 16.8
Fixation Duration	43.8 ± 26.65	39.85 ± 21.25

To further evaluate the statistical significance of the differences observed between the two conditions (with and without the active exoskeleton), a Mann-Whitney U test was conducted at a significance level of 0.05. The results indicated that the p-values for both the fixation count, and fixation duration metrics were greater than 0.05. This suggests that the differences in attentional allocation between the two conditions, in terms of how frequently participants fixated on the AOI and how long they spent focusing on it, were not statistically significant.

In both conditions, participants demonstrated a high level of attention to potential hazards, with approximately 54-60 fixations on hazards during the 10-minute session. This suggests that participants maintained a good level of safety awareness regardless of exoskeleton use. While the exoskeleton condition showed slightly higher fixation counts and durations, the lack of statistical significance suggests that the device did not dramatically alter participants' visual attention patterns. The results indicate that the active exoskeleton doesn't significantly affect the vigilance level of construction workers during common construction tasks.

The slight increase in fixation counts and duration when using the exoskeleton could reflect a reallocation of cognitive resources, as suggested by Wickens' Multiple Resource Theory (MRT) [23,24]. According to MRT, cognitive resources are distributed across multiple modalities (visual, auditory) and processing stages (perception, cognition). The exoskeleton introduced additional sensory inputs, such as vibrations and altered proprioception, which could have competed for cognitive resources typically dedicated to visual processing and hazard detection. However, the lack of statistically significant differences in fixation metrics suggests that the exoskeleton's cognitive demands did not exceed participants' available resources, allowing them to maintain vigilance effectively. From the perspective of Endsley's Situation Awareness Model [25], which emphasizes perception, comprehension, and projection of environmental elements, participants demonstrated consistent attention to predefined AOIs representing hazards. This indicates that they effectively maintained all three levels of situation awareness—perceiving, comprehending, and anticipating hazards—despite the exoskeleton's sensory inputs. The slight increase in fixation metrics when using the exoskeleton may reflect heightened caution or attentiveness, but the high standard deviations suggest significant individual differences in how participants adapted to the device.

Despite the insightful findings, this study has several limitations that could be explored in future research endeavors. Firstly, the duration of the study (10 minutes) limits the ability to capture potential long-term effects of exoskeleton use on vigilance levels. Future studies should investigate whether prolonged use of exoskeleton leads to different outcomes in terms of hazard awareness and visual attention. Secondly, the sample size in this study may not accurately represent the full range of the construction workforce, which varies in age, gender, physical fitness, and experience. To improve the relevance of the findings, future research should include a larger and more diverse group of participants. This would help ensure the results are applicable to a broader segment of the construction industry. While the block-handling tasks used in this study are representative of common material handling activities in construction, they may not fully capture the characteristics of other construction tasks with different physical and cognitive demands. Future research should investigate the impact of exoskeleton use on vigilance during a broader range of construction tasks, including those requiring fine motor skills, spatial awareness, or dynamic hazard detection. Likewise, incorporating tasks with varying levels of complexity and collaboration (e.g., working with robotic systems or coordinating with other workers) would provide a more comprehensive understanding of how exoskeletons influence vigilance across different construction scenarios

Additionally, while this study focused on active exoskeletons, future research could compare the effects of active and passive exoskeletons on vigilance levels. Passive exoskeletons, which rely on mechanical components like springs or dampers rather than powered actuators, may introduce different cognitive and ergonomic challenges. A comparative analysis could provide deeper insights into how different types of exoskeletons influence workers' attention and safety awareness, ultimately informing the development of guidelines for their safe and effective use in construction settings. The 10-minute task duration in this study was chosen to establish a controlled and manageable experimental framework for assessing the immediate effects of active exoskeleton use on vigilance levels. While this duration allowed us to minimize participant fatigue and ensure consistency across trials, it lacks in reflecting the conditions of real construction work shifts, where vigilance effects may be cumulative over time due to prolonged exposure to physically and mentally demanding tasks. Future studies should investigate the effects of exoskeleton use over longer durations to provide a more comprehensive understanding of how vigilance evolves during extended work periods.

6 Conclusion

This study evaluated the impact of active exoskeleton systems on the vigilance levels of construction workers during common construction tasks. Eighteen subjects were required to complete material handling tasks under two conditions (with and without using an active back-support exoskeleton) in immersive virtual environments. Using eye-tracking metrics—specifically fixation count and fixation duration on AOI representing potential hazards in the simulated virtual environment, the results demonstrated that while participants showed slightly higher fixation counts and longer fixation durations when using the active exoskeleton, these differences were not statistically significant, as confirmed by the Mann-Whitney U test. Participants consistently maintained a strong level of attention to hazards, with approximately 54-60 fixations during the 10-minute task sessions, regardless of whether they used the exoskeleton. This suggests that the active exoskeleton did not distract workers or negatively impact their vigilance levels. Although there was a small increase in the number and duration of fixations when participants used the exoskeleton, the lack of statistical significance indicates that the device did not substantially influence workers' vigilance. These findings provide important insights into the psychological effects of active exoskeletons, indicating that their use does not diminish workers' vigilance levels to potential safety risks on construction sites. The findings could help formulate standard guidelines for the adoption of active exoskeletons in construction sites. While this study was conducted with a relatively small sample size, future investigations could recruit a larger pool of subjects to further generalize results. Future studies should include a larger and more diverse group of participants to enhance the reliability of the results and provide more robust insights into the impact of exoskeletons on vigilance levels. Further research is necessary to examine long-term effects and ensure these devices support overall worker performance and safety. While the VR environment provided a controlled setting for studying vigilance, it cannot fully replicate the complexity of real-world construction sites, including factors such as site noise, terrain unevenness, unpredictable distractions, and multi-worker coordination. These variables could significantly affect vigilance levels in practice. Future studies could validate the findings in actual construction settings to provide a more comprehensive understanding of how exoskeletons impact vigilance in dynamic and unpredictable environments. While the VR environment provided a controlled setting for studying vigilance, it cannot fully replicate the complexity of real-world construction sites, including factors such as site noise, terrain unevenness, unpredictable distractions, and multi-worker coordination. These variables could significantly affect vigilance levels in practice. Even though the Mann-Whitney U test was appropriate for this study given the non-normal distribution of the data and the exploratory nature of the research, more sophisticated statistical methods, such as mixed-effects models, could provide deeper insights into the effects of exoskeleton use on vigilance levels.

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References

[1] Valero E, Sivanathan A, Bosché F, Abdel-Wahab M. Musculoskeletal disorders in construction: A review and a novel system for activity tracking with body area network. Appl Ergon 2016;54:120–30. https://doi.org/10.1016/J.APERGO.2015.11.020.

[2] Wang D, Asce SM, Dai F, Asce M, Ning X. Risk Assessment of Work-Related Musculoskeletal Disorders in Construction: State-of-the-Art Review. J Constr Eng Manag 2015;141:04015008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000979.

[3] Kazar G, Comu S. Exploring the relations between the physiological factors and the likelihood of accidents on construction sites. Engineering, Construction and Architectural Management 2021. https://doi.org/10.1108/ECAM-11-2020-0958/FULL/XML.

[4] Passmore D, Chae C, Borkovskaya V, Baker R, Yim JH. Severity of U.S. Construction Worker Injuries, 2015-2017. E3S Web of Conferences 2019;97:06038. https://doi.org/10.1051/E3SCONF/2019970603 8.

[5] Bureau of Labor Statistics. Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work. 2020. https://doi.org/https://data.bls.gov/PDQWeb/cs.

[6] OSHA Small Business | Safety Pays Program - Estimator | Occupational Safety and Health Administration n.d.

[7] Antwi-Afari MF, Li H, Edwards DJ, Pärn EA, Seo J, Wong AYL. Biomechanical analysis of risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers. Autom Constr 2017;83:41–7. https://doi.org/10.1016/j.autcon.2017.07.007.

[8] Shein Esther. Exoskeletons today. Commun ACM 2019;62:14–6. https://doi.org/10.1145/3303851.

[9] Ojha A, Gautam Y, Jebelli H, Akanmu A. Physiological impact of powered back-support exoskeletons in construction: Analyzing muscle fatigue, metabolic cost, ergonomic risks, and stability. Autom Constr 2024;168:105742. https://doi.org/10.1016/J.AUTCON.2024.10574 2.

[10] Shayesteh S, Ojha A, Liu Y, Jebelli H. Evaluating the Impact of Powered Back-Support Exoskeletons and Virtual Reality Interventions on Gait Stability of Construction Workers at

Heights. Computing in Civil Engineering 2023: Resilience, Safety, and Sustainability - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2023, American Society of Civil Engineers; 2024, p. 392–9. https://doi.org/10.1061/9780784485248.047.

[11] Ojha A, Guo H, Jebelli H, Martin A, Akanmu A. Assessing the Impact of Active Back Support Exoskeletons on Muscular Activity during Construction Tasks: Insights from Physiological Sensing. Computing in Civil Engineering 2023: Resilience, Safety, and Sustainability - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2023, American Society of Civil Engineers; 2024, p. 340–7. https://doi.org/10.1061/9780784485248.041.

[12] Shayesteh S, Ojha A, Gautam Y, Jebelli H, Akanmu A. Evaluating the Impact of Back-Support Exoskeletons on Construction Workers' Fall Risk. Computing in Civil Engineering 2024 - Selected Papers from the ASCE International Conference on Computing in Civil Engineering, 2024.

[13] Liu Y, Asce SM, Ojha A, Jebelli H, Asce AM, Candidate PD, et al. Vision-Based Ergonomic Risk Assessment of Back-Support Exoskeleton for Construction Workers in Material Handling Tasks. Computing in Civil Engineering 2023: Resilience, Safety, and Sustainability - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2023 2024:331–9. https://doi.org/10.1061/9780784485248.040.

[14] Ojha A, Gautam Y, Zhao X, Sharifironizi A, Jebelli H, Matin A. Understanding the Impact of an Exoskeleton System on Metabolic Cost of Workers During Common Repetitive Construction Tasks. Computing in Civil Engineering , Pittsburgh: ASCE; 2025.

[15] Kulyk O, Van Der Veer G, Van Dijk B. Situational Awareness Support to Enhance Teamwork in Collaborative Environments. Proceedings of the 15th European Conference on Cognitive Ergonomics the Ergonomics of Cool Interaction - ECCE '08 n.d. https://doi.org/10.1145/1473018.

[16] Kass SJ, Cole KS, Stanny CJ. Effects of distraction and experience on situation awareness and simulated driving. Transp Res Part F Traffic Psychol Behav 2007;10:321–9. https://doi.org/10.1016/J.TRF.2006.12.002.

[17] Weisberg RW, Reeves LM. Cognition from memory to creativity. Cognition from Memory to Creativity 2013;1:354.

[18] Liao PC, Sun X, Zhang D. A multimodal study to measure the cognitive demands of hazard recognition in construction workplaces. Saf Sci 2021;133:105010. https://doi.org/10.1016/j.ssci.2020.105010.

[19] Hancock PA, Billings DR, Schaefer KE. Can You Trust Your Robot?: Ergonomics in Design: The Quarterly of Human Factors Applications 2011;19:24–9. https://doi.org/10.1177/1064804611415045.

[20] Sgarbossa F, Grosse EH, Neumann WP, Battini D, Glock CH. Human factors in production and logistics systems of the future. Annu Rev Control 2020;49:295–305. https://doi.org/10.1016/J.ARCONTROL.2020.04.007.

[21] Zhao X, Jebelli H. A computational method for real-time roof defect segmentation in robotic inspection. Computer-Aided Civil and Infrastructure Engineering 2025. https://doi.org/10.1111/MICE.13471.

[22] Wang D, Chen J, Zhao D, Dai F, Zheng C, Wu X. Monitoring workers' attention and vigilance in construction activities through a wireless and wearable electroencephalography system. Autom Constr 2017;82:122–37. https://doi.org/10.1016/J.AUTCON.2017.02.001.

[23] Wickens CD. Multiple resources and performance prediction. Theor Issues Ergon Sci 2002;3:159–77. https://doi.org/10.1080/14639220210123806.

[24] Wickens CD. Multiple Resources and Mental Workload. Human Factors: The Journal of the Human Factors and Ergonomics Society 2008;50:449–55. https://doi.org/10.1518/001872008X288394.

[25] Endsley MicaR. Toward a theory of situation awareness in dynamic systems. Human Factors: The Journal of the Human Factors and Ergonomics Society 1995;37:32–64. https://doi.org/10.1518/001872095779049543.