Evaluating the Impact of Powered Back-Support Exoskeletons and Virtual Reality Interventions on Gait Stability of Construction Workers at Heights

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ABSTRACT

Due to the labor-intensive nature of construction tasks, workers are exposed to an increased risk of work-related musculoskeletal disorders (WMSDs). Recently, a wide range of wearable robots (i.e., exoskeletons) has emerged in construction to reduce the risk of WMSDs. Although there are promising prospects for wearable robots to minimize the physical demands on workers, there is limited knowledge about their fundamental impacts on workers. In particular, there is a lack of studies on the impact of wearable robots on workers' gait stability in dangerous situations, such as heights, which puts workers at high risk. To fill this gap, this study evaluated the impact of powered back-support exoskeletons on workers' gait stability at heights through kinematic analysis. The analysis revealed that working at height with a back-support exoskeleton does not diminish users' gait stability. The findings can shed light on the widespread adoption of back-support exoskeletons in construction.

INTRODUCTION

The hazardous nature of construction workplaces and repetitive and physically intensive activities performed in unusual postures have exposed construction workers to an increased risk of work-related musculoskeletal disorders (WMSDs) (Okpala et al. 2022). In this regard, WMSDs have been a leading cause of functional impairments, productivity loss, and lifelong disability for construction workers (Nath et al. 2017). WMSDs also account for about 37% of nonfatal injuries and illnesses experienced by construction workers (Bureau of Labor Statistics 2020). While safety and health organizations, such as the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH), have promoted general ergonomic principles to reduce the risk of WMSDs among construction workers, the high rate of WMSDs continues to be a major concern in this sector.

To reduce the risk of WMSDs among construction workers, a wide range of wearable robots (i.e., exoskeletons) are emerging as ergonomic solutions at job sites to provide workers with lift support, weight distribution, and posture correction (Kim et al. 2019). These exoskeletons can support workers' backs, legs, arms, shoulders, and even their entire body to reduce strain while increasing strength. Given the prevalence of back-related WMSDs in the construction sector

(Wang et al. 2017), particular attention has been directed toward the potential of back-support exoskeletons (BSEs) in mitigating such risks. BSEs can aid the workers by delivering assistive moments around the hip or lower spine to support the back muscles, reducing the physical demands on the workers' backs (Gonsalves et al. 2021). However, in some cases, it is argued that BSEs may trigger unforeseen health and safety challenges for construction workers.

While exoskeletons offer several advantages, they might also pose unanticipated safety and usability challenges for workers, ranging from physical burdens to psychological issues. In this context, depending on the type of load and movement strategy, exoskeletons can alter the worker's center of gravity and prevent the human body from recovering due to a loss of balance, thereby increasing the risk of falling (Park et al. 2022). This issue is especially critical for the construction industry, where workers must perform daily tasks on cluttered and dynamic job sites. Considering that falling from heights is the leading cause of fatalities at construction job sites, the negligent use of exoskeletons can decrease the stability of workers and increase their fall risk. Despite such risk factors, there is a lack of studies to understand the impact of exoskeletons on workers' gait stability while working at heights.

To fill this gap, this study aims to evaluate the impact of back-support exoskeletons on workers' gait stability at heights using kinematic analysis. To that end, an experiment is designed in an immersive environment where healthy subjects are asked to carry a heavy load with and without a back-support exoskeleton while their kinematic movements are captured using an inertial measurement unit (IMU) sensor. Accordingly, the gait stability of the subjects is analyzed while working on the ground level and at high elevations. The results showed that working at height with an exoskeleton does not diminish the gait stability of the subjects, suggesting its suitability for physically demanding tasks in such environments. The findings can shed light on the widespread adoption of back-support exoskeletons in construction.

APPLICATIONS OF EXOSKELETONS IN CONSTRUCTION

Exoskeletons are wearable robots designed to assist and augment the physical ability of a person. Generally, exoskeletons can be classified as 'active' or 'passive' devices (Lee et al. 2012). Active exoskeletons are powered through actuators (e.g., electric motors, pneumatic muscles, hydraulics) that actively augment power to support the human body. On the other hand, passive exoskeletons use materials, springs, or dampers to store and release energy during body movements (Antwi-Afari et al. 2021). While passive exoskeletons are associated with lower costs and fewer safety risks, active exoskeletons are typically favored in the construction industry due to their great potential to actively assist workers in handling demanding tasks. To date, several studies have investigated the functionality and user experience of passive BSEs in construction (Antwi-Afari et al. 2021; Cho et al. 2018; Golabchi et al. 2022; Gonsalves et al. 2021).

These BSEs minimized awkward posture and reduced lower back overexertion during labor-intensive tasks, such as material handling and rebar work. The collective results of these studies indicated the effectiveness and usability of BSEs for tasks that might result in WMSDs. As exoskeletons are becoming more accepted in the construction industry, evaluating their physical and psychological impacts on workers becomes more crucial. While previous studies improved our understanding of the risks and challenges of implementing BSEs in construction, objective evaluation of those impacts on construction workers remains a constraint. One reason for this limitation can be the lack of a testbed for safe and feasible experimentation to understand the associated risks of BSEs in construction work environments. This study proposes a kinematic analysis approach in an immersive environment to address this limitation.

GAIT STABILITY ASSESSMENT METHODS

Gait stability assessment methods are generally used to evaluate the ability of a person to maintain balance while walking. While these methods are commonly utilized in clinical settings to identify individuals at risk of falling, they can also be used to assess the fall risk of workers in hazardous work environments (Jebelli et al. 2014). In this regard, one widely employed method for gait stability assessment is the center of pressure (COP) analysis, which involves measuring the point where the total force applied to the ground by feet is centered (Mehdizadeh et al. 2021). Accordingly, researchers have performed COP analysis using various instruments, such as force plates and wearable devices (Antwi-Afari and Li 2018). In recent years, several studies have used IMU sensors for gait stability assessments due to the simplicity of use and the convenience of the users during gait, allowing for more natural data collection. For example, Jebelli et al. utilized IMU sensors attached to the right ankle of subjects to collect kinematic data and calculate of maximum Lyapunov exponent (Max LE) for the fall-risk assessment of construction workers (Jebelli et al. 2016b). In another study, researchers used a waist-worn IMU sensor to assess the risk of exposure to slip, trip, and fall hazards (Lee et al. 2022). Furthermore, Habibnezhad et al. used IMU sensors attached to key body points (feet and trunk) to measure the dynamic stability and fall risk of ironworkers working at virtual heights (Habibnezhad et al. 2021).

METHODOLOGY

This study uses kinematic analysis to evaluate the impact of back-support exoskeletons (BSEs) on workers' gait stability at heights. Accordingly, time-series data extracted from IMU sensors are analyzed to quantify the gait stability of workers during a material handling task. To implement a safe experimentation process, a virtual reality (VR)-based simulation is developed to create the sense of working at a high elevation for the subjects. Subsequently, a comparative experiment was conducted to explore the effects of height and the use of BSEs on subjects' gait stability. Figure 1 demonstrates an overview of the proposed methodology.

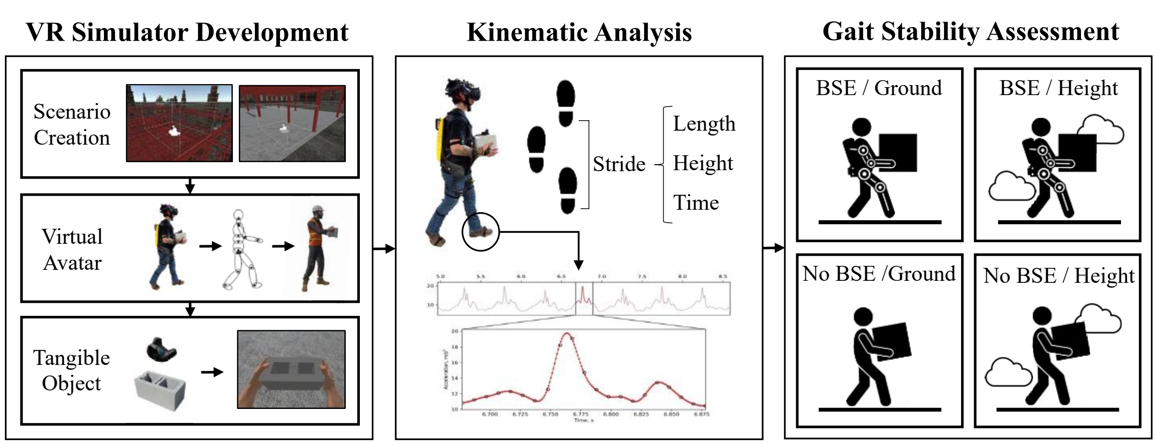

Figure 1. Overview of the proposed methodology.

Virtual Reality Simulator Development. In order to evaluate different aspects of working with exoskeletons in a safe and controlled environment, a high-fidelity simulation of a construction jobsite is created and rendered in VR using the Unity game engine. In the simulated environment, users can operate an actual BSE to carry heavy items while their surroundings represent an illusion of the actual workplace. In addition, a virtual full-body embodiment of the user is generated using an integrated tracking system that captures the actual body movements. The use of motion tracking sensors on the user's feet, lower back, and hands allows for accurate tracking of movements and coordination of the user's physical and virtual interactions in real-time.

Furthermore, each item that requires user interaction in the virtual environment is equipped with a motion tracking sensor to coordinate the position and orientation of the actual item in the space with the ones of the virtual object in the simulated environment. As such, users may freely touch, grip, and pick up virtual objects during task performance through provided visual and force feedback. The required computations were performed by implementing in-house scripts developed for the Unity game engine. This approach integrates the digital content with physical objects and equipment to further enhance the user's immersion and sense of presence in the immersive testbed, where the risks of implementing BSEs are evaluated. Accordingly, the material handling task on the ground level and at the virtual height is simulated for gait stability analysis.

Gait Stability Measurement. Recent developments in wearable technology have enabled the use of IMUs to assess a variety of gait parameters as an alternative to the relatively expensive clinical instruments (della Croce et al. 2018; Jebelli et al. 2016a). The gait characteristics can be extracted from the collected data by identifying the gait cycles for each subject. The gait cycle is the period after one foot strikes the ground and before the same foot contacts the ground again. In this study, the authors extracted spatiotemporal data from the IMU attached to the user's foot to compute the gait cycles using local minimums and maximums of the gait-stride displacements on the vertical axis. This process allowed for determining the stride length and height during each gait cycle. Additionally, the gait-stride time was calculated as an additional metric for evaluating gait stability.

Experimental Procedure. In order to evaluate the impact of BSE on workers' gait stability through the proposed measurement approach, the authors conducted a comparative experiment in an immersive environment. To that end, a material handling task was selected in which subjects were asked to walk in a straight line while carrying a load. Four different conditions were designed to determine the impact of BSE on gait stability metrics, namely: 1) material handling with BSE on the ground level, 2) material handling without BSE on the ground level, 3) material handling with BSE at height, and 4) material handling without BSE at height. These scenarios were designed to capture the differences between the gait stability metrics of the subjects under various conditions and elucidate the impact of high elevation and using an exoskeleton on construction workers' gait stability and fall risk.

Six healthy subjects between the ages of 22 and 28 (Mean = 25, SD = 2.97) were recruited for this study. None of the participants had any mental or physical disorder that could adversely affect their task performance. In addition, none of the participants had any prior experience working with exoskeletons for construction tasks. The subjects were equipped with a head-mounted display (i.e., HTC Vive Pro), motion-tracking sensors, and IMU sensors for task simulation and gait stability measurement. They were also provided with a BSE (i.e., Cray X, German Bionic) to accomplish the material handling task in specific scenarios. The selected exoskeleton featured actuators that could actively support the user's lower back with up to 30 kg (66 lb.) during the lifting and walking tasks.

Once the subjects were provided with information about the experimental procedure, they were randomly assigned to one of the conditions. Prior to the experiment, they were asked to walk in the immersive environment on the ground level to familiarize themselves with the simulation. IMU sensors were attached to different body parts of the subjects to collect time-series data at 125 Hz. Subsequently, subjects were instructed to hold a concrete brick and stand upright and still for 10 seconds for calibration purposes before walking. The subjects were then instructed to walk for 4 m (13 ft) in a straight line while carrying the load and return to the starting point. To replicate the feeling of walking on an iron beam during the material handling task at height, subjects were instructed to walk on a 40 cm (16 in) wide wooden plank superimposed on the virtual iron beam. Each subject performed this task in random order for all four experimental conditions while their kinematic movements were captured using IMU sensors. Figure 2 demonstrates the experimental procedure, including the equipment and designed scenarios.

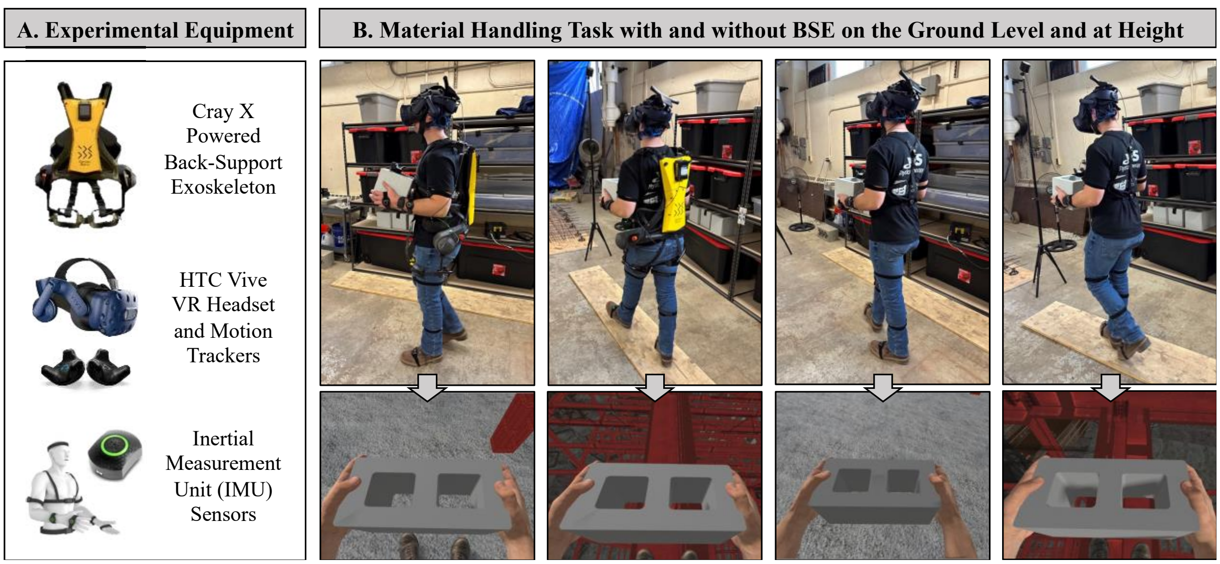

Figure 2. (A) The experimental equipment used in data collection, (B) subject performing the material handling task in the virtual environment, from left to right: with BSE on the ground, with BSE at height, without BSE on the ground, and without BSE at height.

RESULTS AND DISCUSSION

This study compared the gait parameters between different scenarios to explore the impact of using BSEs on construction workers' gait stability at height. Table 1 presents the average and standard deviation values for the gait stride length, height, and time across all the scenarios to provide an overview of the differences between the gait parameters. As seen in the table, walking at virtual height generally resulted in a shorter stride length and stride time on average compared to walking on the ground level. At the same elevation condition, however, using the BSE marginally increased the stride length and stride time on average. There is no meaningful difference in the stride height between different scenarios.

Table 1. Mean and standard deviation (SD) values of the gait parameters across different experimental conditions.

Condition	Stride Time (s) Mean ± SD	Stride Length (m) Mean ± SD	Stride Height (m) Mean ± SD
BSE-Ground	0.77 ± 0.22	0.59 ± 0.20	0.065 ± 0.011
BSE-Height	0.63 ± 0.11	0.38 ± 0.15	0.069 ± 0.018
No-BSE-Ground	0.81 ± 0.25	0.66 ± 0.16	0.072 ± 0.021
No-BSE-Height	0.69 ± 0.09	0.48 ± 0.12	0.063 ± 0.014

In addition, Table 2 presents the comparison results between each pair of experimental conditions. Since the obtained data did not follow a normal distribution, the authors employed the Wilcoxon signed-rank test, which is a nonparametric test. As seen in Table 2, the virtual elevation could influence subjects' gait-stride metrics. Specifically, when carrying a load at height with a BSE, the stride length was significantly decreased compared to carrying a load with a BSE on the ground level. Comparing the conditions of carrying a load without a BSE at height and on the ground, as well as carrying a load with a BSE at height and without a BSE on the ground, also led to a similar result. In addition, when carrying a load on a specific elevation level, there were no significant differences in gait-stride metrics between using a BSE and not using a BSE. These findings suggest that the use of a BSE at height may not impact the risk of falls and gait stability metrics.

Table 2. Reported Wilcoxon signed-rank test's p-values for the average of the gait parameters when comparing different experimental conditions.

Scenario	Stride Time	Stride Length	Stride Height
BSE-Ground vs. BSE-Height	0.313	0.031*	0.625
BSE-Ground vs. No-BSE-Ground	0.437	0.562	0.543
BSE-Ground vs. No-BSE-Height	0.438	0.094	0.411
BSE-Height vs. No-BSE-Ground	0.218	0.032*	0.296
BSE-Height vs. No-BSE-Height	0.625	0.219	0.336
No-BSE-Ground vs. No-BSE-Height	0.063	0.031*	0.225

* Significant at 0.05 level

The results of this study suggested that the use of a BSE did not significantly impact gait parameters in different scenarios. These findings indicate that the use of BSEs at height may not have a negative impact on workers' gait stability, providing new evidence to challenge the previous assumptions regarding the potential risks of employing exoskeletons in construction (Kim et al. 2019). Overall, these results provide insight into the potential benefits and limitations of using BSEs in construction operations at height and highlight the importance of evaluating the impact of emerging technologies on workers' safety and performance. Some of the limitations of the study also need to be addressed in future research. For example, this study only examined the immediate effects of using a BSE on gait stability metrics and did not consider the potential long-term effects or the impact of other relevant factors, such as physical fatigue or cognitive load, on workers' gait stability and fall risk. Further, this study only examined gait stability metrics on the fall risk and did not consider the impact of exoskeletons on other factors, such as worker productivity or overall job performance.

CONCLUSION

This paper investigated the impact of back-support exoskeletons (BSEs) on construction workers' gait stability at height using an immersive virtual reality simulator. Through a comparative experiment, the authors analyzed the gait-stride metrics of subjects during a material handling task on the ground level and at heigh, with and without a BSE. The results showed that the use of BSE does not diminish the gait stability of the users, both on the ground level and at height. As such, it can be argued that the use of BSE at height may not impact the risk of falls among construction workers. These findings can inform the development of safer construction practices, including the application of BSEs in hazardous work environments, and help reduce the risk of falls and pertinent injuries among construction workers. This study also highlights the potential of virtual reality-based simulations as a valuable tool for assessing the impact of emerging technologies on workers' safety and work performance.

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REFERENCES

Antwi-Afari, M. F., and Li, H. (2018). “Fall risk assessment of construction workers based on biomechanical gait stability parameters using wearable insole pressure system.” *Advanced Engineering Informatics*, Elsevier, 38, 683–694.

Antwi-Afari, M. F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H.-Y., and Wuni, I. Y. (2021). “Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers.” *Safety Science*, 142, 105382.

Bureau of Labor Statistics. (2020). “Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work.” <https://data.bls.gov/PDQWeb/cs.>(Jan. 2, 2023).

Cho, Y. K., Kim, K., Ma, S., and Ueda, J. (2018). “A Robotic Wearable Exoskeleton for Construction Worker's Safety and Health.” *Construction Research Congress 2018*, American Society of Civil Engineers, Reston, VA, 19–28.

della Croce, U., Cereatti, A., and Mancini, M. (2018). “Gait Parameters Estimated Using Inertial Measurement Units.” *Handbook of Human Motion*, Springer International Publishing, Cham, 245–265.

Golabchi, A., Miller, L., Rouhani, H., and Tavakoli, M. (2022). “Impact of Passive Back-Support Exoskeletons on Manual Material Handling Postures in Construction.” *39th International Symposium on Automation and Robotics in Construction (ISARC 2022)*.

Gonsalves, N. J., Ogunseiju, O. R., Akanmu, A. A., and Nnaji, C. A. (2021). “Assessment of a passive wearable robot for reducing low back disorders during rebar work.” *Journal of Information Technology in Construction*, 26, 936–952.

Habibnezhad, M., Shayesteh, S., Jebelli, H., Puckett, J., and Stentz, T. (2021). "Comparison of ironworker's fall risk assessment systems using an immersive biofeedback simulator." *Automation in Construction*, Elsevier B.V., 122, 103471.
Jebelli, H., Ahn, C. R., and Stentz, T. L. (2014). "The Validation of Gait-Stability Metrics to Assess Construction Workers' Fall Risk." *Computing in Civil and Building Engineering (2014)*, American Society of Civil Engineers, Reston, VA, 997–1004.
Jebelli, H., Ahn, C. R., and Stentz, T. L. (2016a). "Fall risk analysis of construction workers using inertial measurement units: Validating the usefulness of the postural stability metrics in construction." *Safety Science*, 84, 161–170.
Jebelli, H., Ahn, C. R., and Stentz, T. L. (2016b). "Comprehensive Fall-Risk Assessment of Construction Workers Using Inertial Measurement Units: Validation of the Gait-Stability Metric to Assess the Fall Risk of Iron Workers." *Journal of Computing in Civil Engineering*, 30(3), 04015034.
Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D. M., and Nussbaum, M. A. (2019). "Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions." *IISE Transactions on Occupational Ergonomics and Human Factors*, 7(3–4), 185–191.
Lee, H., Kim, W., Han, J., and Han, C. (2012). "The technical trend of the exoskeleton robot system for human power assistance." *International Journal of Precision Engineering and Manufacturing*, 13(8), 1491–1497.
Lee, H., Lee, G., Lee, S., and Ahn, C. R. (2022). "Assessing exposure to slip, trip, and fall hazards based on abnormal gait patterns predicted from confidence interval estimation." *Automation in Construction*, 139, 104253.
Mehdizadeh, S., van Ooteghem, K., Gulka, H., Nabavi, H., Faieghi, M., Taati, B., and Iaboni, A. (2021). "A systematic review of center of pressure measures to quantify gait changes in older adults." *Experimental Gerontology*, 143, 111170.
Nath, N. D., Akhavian, R., and Behzadan, A. H. (2017). "Ergonomic analysis of construction worker's body postures using wearable mobile sensors." *Applied Ergonomics*, 62, 107–117.
Okpala, I., Nnaji, C., Ogunseiju, O., and Akanmu, A. (2022). "Assessing the Role of Wearable Robotics in the Construction Industry: Potential Safety Benefits, Opportunities, and Implementation Barriers." *Automation and Robotics in the Architecture, Engineering, and Construction Industry*, Springer International Publishing, Cham, 165–180.
Park, J.-H., Kim, S., Nussbaum, M. A., and Srinivasan, D. (2022). "Effects of back-support exoskeleton use on gait performance and stability during level walking." *Gait & Posture*, 92, 181–190.
Wang, X., Dong, X. S., Choi, S. D., and Dement, J. (2017). "Work-related musculoskeletal disorders among construction workers in the United States from 1992 to 2014." *Occupational and Environmental Medicine*, 74(5), 374–380.