Enhancing Ergonomics and Posture with Wearable Robots for Construction Tasks: Evaluating the Impact of Virtual Reality-Based Exoskeleton Training Platforms

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ABSTRACT

The integration of wearable robotic exoskeletons in construction tasks presents a significant advancement in worker safety and efficiency. However, the effective use of these exoskeletons demands proper training to ensure ergonomic compliance and posture improvement. This study evaluates the impact of a Virtual Reality (VR)-based training platform on the proficiency in ergonomic awareness using exoskeletons for construction-related activities. A cohort of construction workers underwent the VR-based training program designed to simulate real-world construction scenarios while using exoskeletons. A mixed-methods approach was employed, combining quantitative assessments of posture and ergonomics with qualitative feedback from participants. Key metrics such as spinal alignment and joint stress were monitored through biomechanical analysis tools, both pre- and post-training. Questionnaires are designed for psychological and cognitive impacts of the VR training. Preliminary findings suggest that VR training significantly enhances the understanding and adoption of ergonomic principles among workers. Notably, there was a marked improvement in posture alignment and reduced musculoskeletal strain during task execution. Qualitative feedback highlighted the immersive nature of VR training, contributing to a quicker grasp of complex movements and better spatial awareness while equipped with the exoskeleton. The study underscores the potential of VR as a transformative tool for training in high-risk industries. The findings advocate for the integration of VR-based training in standard practice, paving the way for safer and more efficient work environments in the construction sector.

INTRODUCTION

The incorporation of wearable robotic exoskeletons into the construction industry represents a significant leap forward in enhancing worker safety and operational efficiency. These advanced devices are engineered to supplement human strength and endurance, presenting a groundbreaking solution to mitigate workplace injuries, particularly musculoskeletal disorders (MSDs) (Liu et al. 2024). However, the sophisticated nature of these exoskeletons necessitates specialized training to fully harness their ergonomic benefits and ensure their correct application in real-world scenarios.

Traditional training methodologies in the construction industry have predominantly focused on theoretical and hands-on approaches (Sacks et al. 2013), often limited by the constraints of the physical environment and the availability of resources. These methods may not adequately prepare workers for the intricacies and demands of operating exoskeletons within the challenging and varied environments of construction sites. This inadequacy creates a critical need for more effective, immersive, and adaptive training solutions.

Virtual Reality (VR) technology emerges as a transformative tool in addressing this need. VR provides an immersive and interactive platform where real-world scenarios can be simulated in a controlled, safe environment (Rokooei et al. 2023). This technology enables construction workers to experience and adapt to the use of exoskeletons in a variety of simulated work conditions, without the risks associated with on-site training. VR-based training can facilitate a deeper understanding of the exoskeletons' functionality, while simultaneously emphasizing critical aspects of workplace ergonomics and posture, which are essential in the prevention of work-related injuries.

The primary aim of this study is to assess the efficacy of a VR-based training program in improving the proficiency of construction workers in the use of wearable robotic exoskeletons. The research focuses on evaluating changes in ergonomic awareness and overall comfort in maneuvering these devices during typical construction tasks. The study also explores the potential psychological and cognitive impacts of VR training on participants, including their perception of safety, confidence in equipment handling, and overall job satisfaction. The anticipated findings from this study are expected to provide valuable insights into the long-term benefits of VR-based training, not only as a tool for skill enhancement but also as a means to foster a culture of safety and technological adaptability in high-risk work environments.

EXOSKELETONS IN THE CONSTRUCTION INDUSTRY

Exoskeleton technology has seen a rapid evolution over the past decade, transitioning from a concept primarily explored in science fiction to a practical tool in various industries, most notably in construction. These wearable robotic systems are designed to work in harmony with the user, augmenting their strength and reducing fatigue, especially in tasks involving heavy lifting and repetitive motions (Luckhaupt et al. 2019). In construction, exoskeletons have been applied in tasks like lifting heavy materials, providing support in overhead work, and assisting in tasks requiring sustained postures. The integration of exoskeletons into construction work has brought forth significant benefits, including reduced physical strain on workers, lower risk of work-related injuries, and increased overall efficiency on the job site. Despite these advantages, the adoption of exoskeleton technology presents challenges. One major hurdle is the need for specialized training to use these devices effectively and safely. Proper ergonomic practices are crucial, as improper use can lead to discomfort or even injury. Additionally, there is a need to address the psychological and physical adaptation of workers to this new technology, ensuring a smooth transition and acceptance.

Traditional training methods in the construction industry, which often rely on on-site instruction and demonstration, face limitations when applied to exoskeleton training. These methods may not adequately simulate the complex scenarios workers encounter or address the specific ergonomic challenges posed by exoskeleton use. There is a growing recognition that new, innovative training approaches are needed to bridge this gap and ensure that workers can fully leverage the benefits of this technology while maintaining safety and ergonomic integrity.

VIRTUAL REALITY AS A TRAINING MODALITY

Virtual Reality (VR) technology has emerged as a cutting-edge tool in various fields, known for its ability to create immersive, interactive environments (Wang et al. 2018). In the context of industrial training, VR provides a platform where realistic work scenarios can be simulated without the risks and constraints associated with physical training environments. This technology allows for a controlled, adaptable, and engaging training experience, making it a valuable tool for modern workforce training.

VR has become a pivotal tool in construction training. It has seen significant use in training for construction safety (Shayesteh et al. 2023). Moreover, VR has been utilized for training in the use of construction equipment and robotics operational tasks (Zhang and Pan 2021; Zhou 2015; Adami et al. 2021). The effective deployment of VR in construction, particularly in complex operations, demonstrates its significant potential for exoskeleton training within this sector. Specifically, in the domain of ergonomic training, VR also shows great promise. It enables the simulation of work tasks while providing immediate feedback on posture and body mechanics (Akdere et al. 2022). This is particularly relevant for exoskeleton training in construction, where maintaining proper posture is vital for preventing musculoskeletal disorders. VR can replicate various construction scenarios, allowing workers to practice and refine their movements and ergonomic practices in a safe, controlled setting.

POINT OF DEPARTURE.

This study aims to bridge the research gap in the combined use of exoskeleton technology and VR-based training in the construction industry. While existing research focuses on these aspects separately, this study concentrates on how VR can specifically enhance exoskeleton training, particularly concerning ergonomic and posture-related outcomes vital for worker safety and efficiency. The primary objective is to empirically evaluate the effectiveness of VR platforms in improving exoskeleton use in construction, with an emphasis on ergonomic improvements and reducing musculoskeletal injury risks. Additionally, the study explores VR training's broader impacts on worker engagement, learning retention, and safety awareness in advanced construction technologies.

DESIGN AND IMPLEMENTATION OF A VR-INTEGRATED ERGONOMIC TRAINING PLATFORM

Overview. This study developed a VR-based training platform aimed at enhancing ergonomic posture for construction workers using exoskeletons. The Meta Quest Pro (Meta 2022) VR headset was chosen for its advanced immersive technology. Additionally, Unity (Unity 2024) was selected as the development platform due to its robust features for creating interactive simulations. This training platform focuses on teaching workers correct ergonomic postures by displaying standard movement and allowing practice in a virtual environment, where their posture is continuously assessed for feedback demonstrated as Figure 1. The platform's efficacy was assessed through a structured experiment, concentrating on improving ergonomic practices among exoskeleton-using construction workers.

Ergonomic and Posture Assessment Methods. A comprehensive approach is employed to assess the posture of workers undergoing training. Initially, pose estimation of workers is conducted by analyzing video sequences captured by cameras placed laterally relative to the workers. This study leverages the MediaPipe framework (Lugaresi et al. 2019) for its real-time human pose tracking capabilities to output 33 human body key point positions. Initially, the input images I are transformed into a feature map F through a Convolutional Neural Network (CNN).

A Regional Proposal Network (RPN) then predicts body regions where a person is likely to be presented as $RPN(F) := [P_{bbox}, P_{score}]$ where P_{bbox} represents the bounding box coordinates and P_{score} represents the confidence scores indicating the presence of a human body within the proposed regions. Subsequently, within these identified regions, the module generates heatmaps $\boldsymbol{H} = \{H_0, H_1, \dots H_{32}\}$ corresponding to the 33 human body key points. The position of each key point P_k, is determined by locating the maximal value in the heatmap $H_k(i,j)$: $P_k = argmax_{i,j}(H_k(i,j))$, thereby pinpointing the location (i,j) of the k_{th} key point in image frame.

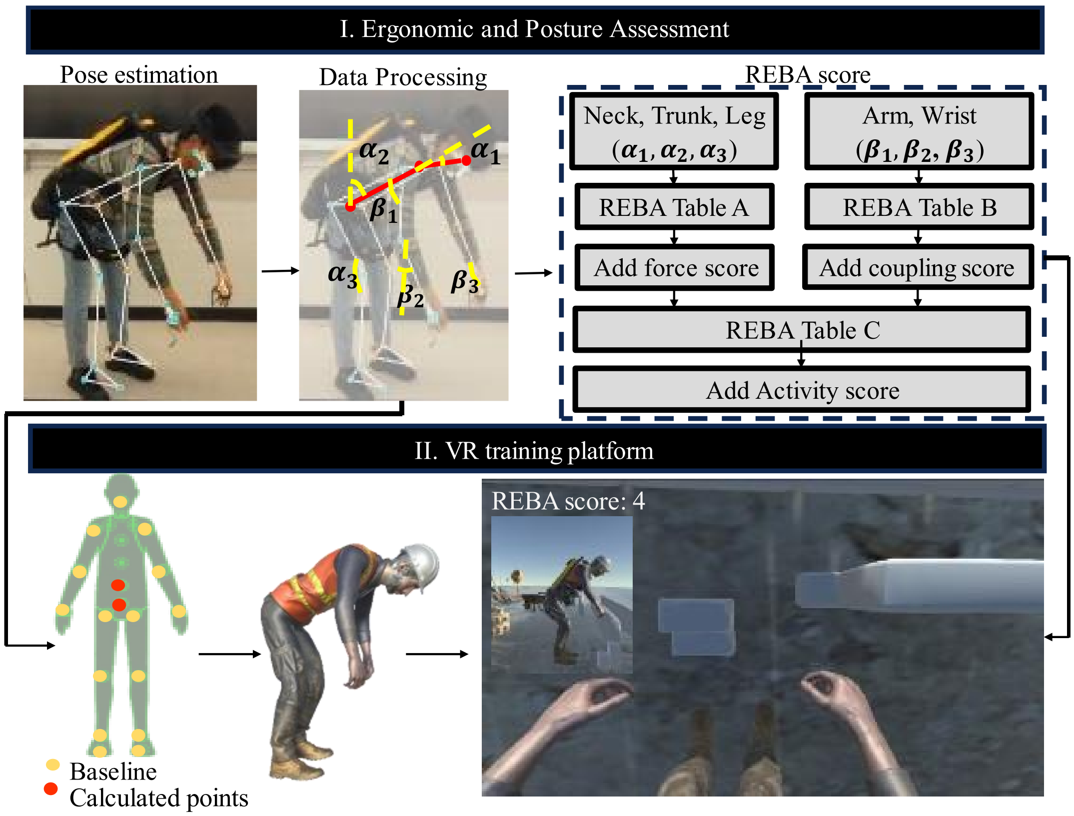

Figure 1. Overview of the proposed VR training platform design process

The positional data of key points are further processed to compute neck, trunk, and critical angular measurements within the human musculoskeletal structure. The neck is calculated as the connection between centroid of the ears and the centroid of the shoulders. The truck is derived from the connection between the centroid of the shoulders and the centroid of the hips. As an illustrative instance for angular measurement, the neck joint angle is deduced by employing key points corresponding to the anatomical landmarks of the centroid of the ears, the centroid of the shoulders, and the centroid of hips. Let the spatial coordinates of these key points be represented as A, B, and C respectively. The cervical joint angle β is then calculated utilizing the inverse cosine function in vector form $\beta = arccos(\frac{\overrightarrow{BA} \cdot \overrightarrow{CB}}{|\overrightarrow{BA}||\overrightarrow{CB}|})$.

Then, the pose is estimate with the Rapid Entire Body Assessment (REBA) (ErgoPlus 2024), an efficient ergonomic evaluation tool that systematically assesses biomechanical and MSD risks in various body regions, including Group A (the neck, trunk, legs) and Group B (arms, and wrists).

For Group A, each body region (neck, trunk, legs) is scored based on the deviation from neutral position, with additional consideration for rotation, side bending and load lifting. Group B's assessment of arms and wrists involves similar scrutiny, with scores adjusted for coupling. The scores from Groups A and B are then entered into the REBA table to determine a single score that reflects the overall risk of MSDs. This score guides ergonomic interventions, with higher scores indicating a greater need for changes in workstation design or work practices.

VR Training platform Design. The VR training platform consists of training and practice sessions. Initially, the training session displays avatar ergonomic movements performed with an exoskeleton. Subsequently, participants are instructed to manipulate the avatar to mimic the demonstrated ergonomic actions by completing specific tasks. During practicing, workers are provided with dual-view displays: a first-person perspective for task navigation and a third-person perspective for real-time postural observation. The primary interface is the first-person view, allowing workers to operate within an immersive construction environment and complete tasks. Unity's physics engine is utilized for simulating realistic interactions such as collisions and gravity effects. The third-person view, shown in a small window, provides a real-life camera perspective, offering an intuitive understanding of their posture. To accurately reflect the workers' actions onto the avatar, the Inverse Kinematics algorithm is employed to calculate the angles of interdependent joints given the corresponding known position from pose estimation. Users have the flexibility to switch between views as needed. Real-time REBA scores are also demonstrated as immediate feedback on their ergonomic practices.

VR Training Platform Evaluation. A case study was undertaken to evaluate the impact of VR training on ergonomic awareness in exoskeleton utilization. Ten healthy individuals participated, aged 25 to 30, with previous experience in VR but new to exoskeleton technology. They were asked to perform specific actions before and after the training with REBA score recorded during the tests. Quantitative analysis on REBA score distribution is delivered for both the whole body and separate body parts. The questionnaires further evaluated the psychological and cognitive impacts of VR training on participants, including their perception of safety, confidence in equipment handling, overall job satisfaction, willingness to adapt ergonomic innovations and the effectiveness of VR training featured five Likert scale items, with scoring ranging from 0 to 100%. A higher score indicated greater agreement with the statement.

ERGONOMIC TRAINING PLATFORM EVALUATION: CASE STUDY.

To validate the efficacy of the VR training platform, an experiment was conducted. For this specific case study, the back-support exoskeleton (Cray X) was chosen due to its pertinence in construction scenarios. The VR training was tailored to the exoskeleton's operational context, under the recording of a 1080p camera placed 2.5m laterally from the workers. Before and after the VR training, movement tests and evaluations were completed. Participants were instructed to traverse a distance of 2 meters towards a predetermined target, execute the lifting of a 20-pound object from ground level, and proceed forward while bearing the object (Figure 2). The study also included a detailed questionnaire, aimed at assessing the participants' psychological and cognitive responses regarding ergonomic performance while using the exoskeleton after the training.

RESULTS

In this study, we quantitatively and qualitatively evaluated the effectiveness of VR training on the ergonomic performance of participants using exoskeletons. The REBA scores were meticulously recorded in real-time during pre- and post-training tests across ten participants. Figure 3 illustrates the distribution of the overall REBA scores, alongside a detailed breakdown for assessed body parts. This categorization is systematically aligned with postures observed during three critical temporal phases: walking without load, heavy lifting, and walking while carrying load.

Figure 2. Subject in VR ergonomic training: (a) real world settings (b) view in VR.

Regarding the overall REBA scores, the pre-training tests indicated medium to high ergonomic risks during object handling. Contrastingly, post-training results exhibited a marked reduction in these risks, as evidenced by lower REBA scores. Additionally, the post-training score distribution was notably more concentrated, further underscoring the effectiveness of VR training on ergonomic practices.

The body part-specific REBA scores are also presented for evaluation (Figure 3). This analysis of pre-training body part breakdown scores not only revealed a notable lack of trust and coordination with the exoskeletons by the participants, but also provided a more detailed illustration of their specific ergonomic behaviors. For example, during the walking phase, several participants demonstrated unbalanced leg movements and unnatural twisting of the trunk. In the lifting phase, there was a prevalent tendency to engage in excessive trunk bending. Collectively, these behaviors contributed to elevated REBA scores, signaling potential safety risks. Post-training, a substantial decrease in these adverse behaviors was observed. This reduction not only signifies an improvement in ergonomic alignment but also highlights the efficacy of VR training in enhancing participants' proficiency with exoskeletons, especially in tasks involving heavy lifting. This improved ergonomic alignment demonstrates a substantial enhancement in participants' ability to handle heavy loads with the aid of exoskeletons, thus reinforcing the value of VR training in occupational settings.

The questionnaire feedback (Figure 4) reveals a positive shift in participants' ergonomic awareness post-VR training. This encompasses a heightened understanding of safe practices and confidence while engaging with exoskeletons. Participants reported an enhanced ability to integrate ergonomic principles into their workflow, indicating a successful transfer of VR training into practical application. The data further suggests that VR training surpasses traditional methods in teaching ergonomic concepts, as reflected in the high agreement scores.

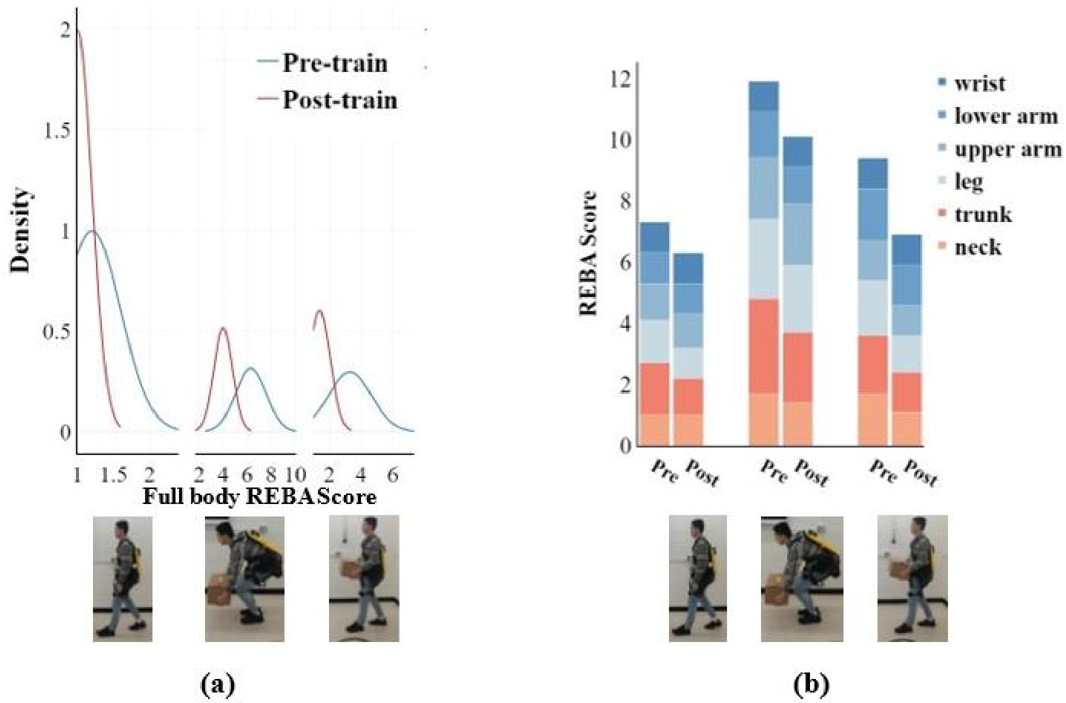

Figure 3. Ergonomic performance pre-training and post-training from REBA analysis during three temporal phases: Walking w/o Load, Heavy lifting, Walking w/ Load (a). Total REBA Score Distribution (b). Body Part Breakdown for Average REBA Score

What percentage do you rate your improvement or agreement with the following statements (0-100%)?
1. The VR training has increased my ergonomic awareness associated with exoskeleton use.
2. I am now confident that I can maintain ergonomic safety while performing tasks with exoskeleton due to the VR training.
3. The ergonomic principles learned through VR training have enhanced my work efficiency when using the exoskeleton.
4. I am willing to adapting ergonomic innovations in my workflow after the VR training.
5. The VR training has been more effective in helping me master ergonomic theoretical knowledge and its practical application compared to other training methods I have

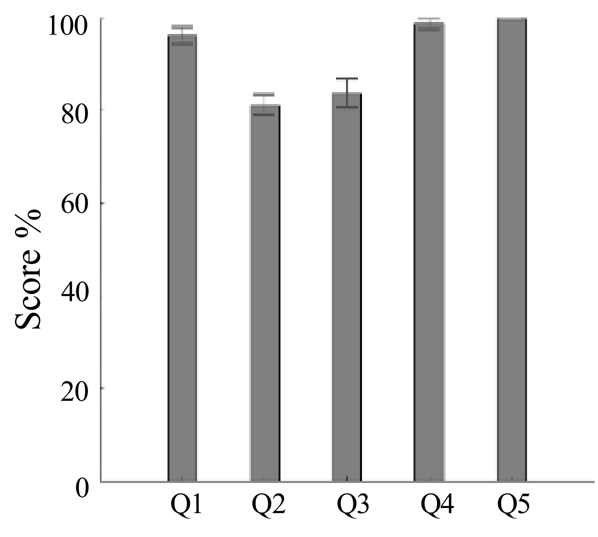

Figure 4. Questionnaire evaluation about ergonomic awareness after VR training

Overall, the increase in ergonomic awareness, as evidenced by the improved REBA scores and high questionnaire ratings, suggests that participants not only gained a better understanding of ergonomic principles but also were able to apply these principles effectively when using the exoskeleton. This comprehensive approach, integrating both practical skills and ergonomic knowledge, underscores the VR program's efficacy in fostering safer work practices among exoskeleton workers in construction.

CONCLUSION

The findings of this study provide compelling evidence on the efficacy of Virtual Reality (VR) training platforms in enhancing the proficiency of construction workers in using wearable robotic exoskeletons. Through an innovative approach that combines immersive VR environments with ergonomic and posture training, significant improvements were observed in how workers interact with and utilize exoskeletons in construction settings. Key outcomes of this research indicate that VR-based training notably improves ergonomic awareness and posture alignment among construction workers. This advancement is critical in reducing the risk of MSDs, which are prevalent in the construction industry. By simulating realistic work scenarios, VR training allows workers to practice and refine their movements in a safe, controlled environment, leading to better ergonomic practices and safer work habits. Moreover, the study contributes to the broader discourse on the integration of advanced technology in workforce training. The success of VR in this context demonstrates its potential as a versatile and effective tool for training in high-risk industries. It highlights the importance of adopting innovative training solutions that keep pace with technological advancements, ensuring that workers are adequately prepared to handle new equipment and work processes safely and efficiently. This research also opens avenues for further exploration into the long-term impacts of VR training, particularly in terms of skill retention, worker engagement, and overall job performance. The scalability of VR training platforms across different sectors within the construction industry presents another area for future investigation.

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