Evolving Construction Robotics Training: Embracing Virtual Reality for Effective Wearable Robot Use in Construction

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ABSTRACT

The construction industry is increasingly adopting wearable robots, such as exoskeletons, to mitigate ergonomic strain and injuries. This rise in exoskeleton use has sparked a surge in interest in effective training methods. To address this need, this research introduces a Virtual Reality (VR) platform specifically designed for exoskeleton training in construction. The platform aims to improve skill acquisition and promote workers' acceptance and adaptability. It provides a comprehensive, risk-free environment for immersive learning, allowing users to practice with exoskeletons on a simulated construction site equipped with a user-friendly user interface (UI) design. The training content, encompassing the introduction of exoskeletons, wear instructions, operational techniques, safety procedures, and maintenance protocols, is thoroughly determined and evaluated. The effectiveness of this VR platform was assessed through pre-tests and post-tests, comparing it with traditional lecture-based methods. Results show significant potential in enhancing workers' practical skills and knowledge. Additionally, the training platform's design was evaluated using questionnaires completed by training professionals, underscoring VR's role as a significant advancement in occupational safety and the operation of exoskeletons within the construction industry. The findings also highlight the recommendation of incorporating multisensory elements to further enrich the immersive training experience.

INTRODUCTION

Work-related musculoskeletal disorders (WMSDs), a prominent issue in occupational health, denote soft-tissue injuries affecting the body's muscles, nerves, tendons, joints and cartilage in the upper and lower limbs, neck, and lower back (OSHA 2020).WMSDs commonly arise from prolonged exposure to heavy workloads, awkward body postures, and highly repetitive motions. Notably, the construction industry is most affected, representing approximately 77% of newly reported work-related illnesses compared to 33% across all occupations (Reddy et al. 2016), creating an urgent need to address this problem immediately.

Exoskeleton is a wearable assistive robot that facilitates human motion by channeling external torques directly to human joints via their connecting links (Kim et al. 2019). It demonstrates superior performance in facilitating posture control. A review reported that employing exoskeletons led to a decrease in muscle activity by 10%-40% (de Looze et al. 2016), emerging as a more robust and reliable solution for mitigating the risks associated with WMSDs.

While exoskeletons offer significant potential in mitigating ergonomic issues, their adoption in the construction industry is hindered by both physical challenges and mental reservations (Andrade et al. 2022; Kim et al. 2019). Traditional training methods, such as on-site practice, and off-site lectures, have been beneficial to a certain extent. However, these approaches exhibit limitations, particularly in equipping workers for the use of complex, interactive robots like exoskeletons. Virtual reality (VR) emerges as a compelling alternative, offering immersive environments that simulate a variety of conditions for interactive learning. VR enables users to safely engage with potentially hazardous actions in a controlled, risk-free setting, thus enhancing their understanding and preparedness for real-world scenarios.

Building on this understanding, it is evident that the development of VR training platforms, specifically designed for robotic technologies like exoskeletons in construction, is still in a nascent stage. This has resulted in a significant gap in specialized training resources. To bridge this gap, the primary aim of this research is to develop a VR training platform that realistically simulates construction environments and tasks during worker-exoskeleton interaction. This platform, enriched with interactive elements (such as guiding dialogue, controller instruction), fosters a human-centric immersive environment and has been evaluated through experimental procedures and expert assessments. The development of this platform marks a clear contribution to the field, as it allows workers to gain practical experience with exoskeletons in an environment that is safe and controlled, effectively bridging a crucial gap in existing training methodologies.

EMERGENCE OF EXOSKELETONS IN CONSTRUCTION AND THE NEED FOR APPROPRIATE TRAINING

Industrial exoskeletons revolutionize construction by enhancing human capabilities for demanding tasks. (de Looze et al. 2016). A range of exoskeletons have been specifically developed to provide specialized support. For instance, the Paexo Back (Ottobock 2024), Cray X (German Bionic 2024), and BackX (SuitX 2024) are specifically designed to offer lumbar support, aiding in tasks that involve lifting, and repetitive bending. For overhead tasks, such as ceiling installations, ShoulderX (SuitX 2024), Paexo Shoulder (Ottobock, 2024), and EksoVest (Eksobionics 2023) provide support to the shoulder area. Additionally, for activities that require sustained standing, such as drilling, leg support exoskeletons like legX (SuitX 2024) have proven their adaptability. Despite exoskeletons' benefits in construction, challenges like limited mobility and mechanical failures persist (Kim et al. 2019). To overcome these challenges, comprehensive training tailored to the specific demands of construction work is crucial. Such training ensures the safe and effective use of exoskeletons, maximizing their potential benefits in the workplace.

VR leverages immersive, interactive 3D environments to simulate real-world scenarios. This offers a hands-on, engaging approach to learning and skill development that transcends traditional educational boundaries, showing great potential for exoskeleton training in construction (Wang et al. 2018). Its applicability and positive impact within the field of construction training have been substantiated through numerous studies. Notably, it has been extensively utilized for construction safety training (Li et al. 2018). Additionally, VR has been employed for construction equipment, robotics, and operational tasks training (Zhang and Pan 2021; Zhou 2015; Adami et al. 2021; Dias Barkokebas et al. 2019). Despite the proven efficacy of VR in construction training, a distinct gap exists in specialized platforms for exoskeleton training for construction workers. Addressing this, this study introduces a VR training platform that simulates construction scenarios and worker-exoskeleton interactions. The proposed platform bridges the existing gap, offering a safe, immersive environment for practical, hands-on exoskeleton training.

DEVELOPMENT OF THE PROPOSED VR TRAINING PLATFORM FOR EXOSKELETON USE IN CONSTRUCTION

Overview. Figure 1 presents the research methodology employed in this study. Initially, the study involved identifying and evaluating the training content to ensure relevance and comprehensiveness. Subsequently, 3D models for use are implemented for simulation. Then, the human-centric VR training platform was developed adhering to a systematic approach. The final phase focused on assessing the VR training platform's effectiveness and efficiency through a structured experimental procedure.

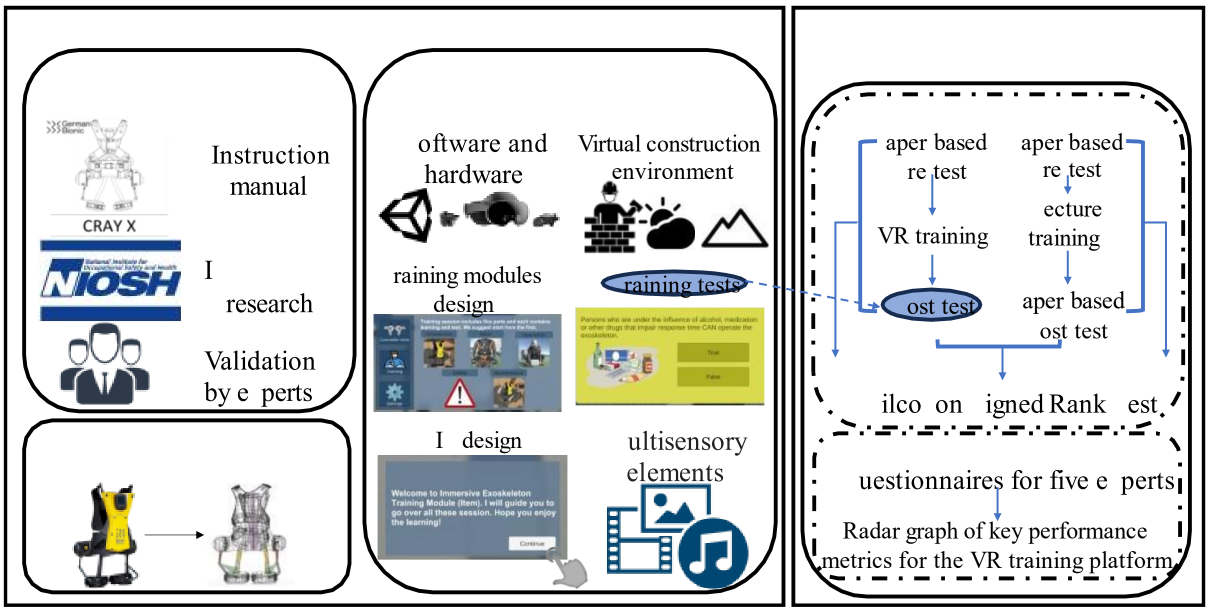

Figure 1. Overview of the development and evaluation process of the VR training platform.

Content Development and Expert Consultation. The study began by identifying and developing training content derived from the exoskeleton's instruction manual and the National Institute for Occupational Safety and Health (NIOSH) research on WMSDs. The training was critically assessed and refined through consultations with experts in the field of exoskeleton, including workers with exoskeleton experience, construction managers and exoskeleton companies, ensuring its relevance and accuracy.

Integration of Exoskeleton Model with Human Motion. A crucial aspect of the platform's development was the integration of the exoskeleton 3D model with human movement simulation. First, an armature for exoskeleton is created in Blender software to mirror exoskeleton mechanical design. Then, closed chain inverse kinematics (IK) constraint is deployed for the exoskeleton armature ensuring natural and accurate joint movements and alignments with human movement shown as equation [1].

$$E(q) = \min \sum_{i} \left|\left|F_i(q) - p_{i,\text{target}}\right|\right|^2 \quad (1)$$

q: vector of joint angles;
E: objective function representing the sum of squared Euclidean distances between the calculated positions and respective target positions of the end effectors;
$F_i(q)$: the i^{th} chain end effector calculated by forward kinematics functions;
$p_{i,\text{target}}$: the target position for the i^{th} chain end effector.

Development of the VR Training Platform. The next step involved the creation of the VR training platform. The Quest Pro VR headset (Meta 2022) was chosen for its immersive features, enhancing the training experience through its advanced head tracking and controllers. The platform was developed in Unity (Unity 2024), a game engine ideal for creating interactive media. The virtual construction environment was programmed in C#, encompassing the implementation of rigid body dynamics for realistic collision responses, the application of physics to materials like accurately simulating friction, and the development of an intuitive user interface. Multisensory elements (e.g. audio and visual effects) were employed to enhance workers' memory. ests were administered to evaluate the participants' understanding after all the training, and the performance was visually summarized in a radar graph.

Platform Evaluation: Data Collection and Analysis. Ten participants with no prior exoskeleton experience were selected for the experimental study. They were divided into two groups to undergo either VR training or traditional lecture-based training. To evaluate the platform's effectiveness, tests were administered before and after the training sessions. The post-training test for VR training platform is adopted from VR training platform final test and other tests are all paper based. The Wilcoxon signed-rank test was applied for statistical analysis, comparing pre-test and post-test results within and between the training methods. The overall functionality of this training platform is further evaluated by six training experts by questionnaires.

INTEGRATION OF EXOSKELETON 3D MODEL WITH WORKING SIMULATION

In this study, 3D model of the Cray X back-support exoskeleton is adopted for training purpose within the platform. An armature that encompasses all degrees of freedom (DOF) mirroring the exoskeleton's mechanical design is created within Blender and is then systematically parented to the character's rig, illustrating the interaction between the e oskeleton and human movements, as demonstrated in Figure 2. At the core of the armature, a 'spine' bone is established to control the fixed parts of the exoskeleton, which is linked to the character's spine bone. Branching out from there, a pair of 'hip' bones parented to character's hip bones e tend down then connect with 'limb' bones that are aligned with the character's upper leg bones. Each 'limb' bone connects with 'thigh' bone controlling the functioning of the connection pole with 1 DOF rotation around X-axis. Two 'actuator' bones are anchored on the e oske leton with 2 F rotation around Z and Y a es. To simulate the synchronized movement between the human operator and the exoskeleton, a closed-chain IK constraint is used to determine the positions of the 'thigh' and 'actuator' bones, ensuring their movement aligns with the trajectory of the 'limb' bone.

The design of VR training platform is modeled after actual construction scenarios (Figure 3). Dynamic situations are deployed such as inclement weather conditions, uneven terrain, or tight spaces to provide various experiences of an actual job site.

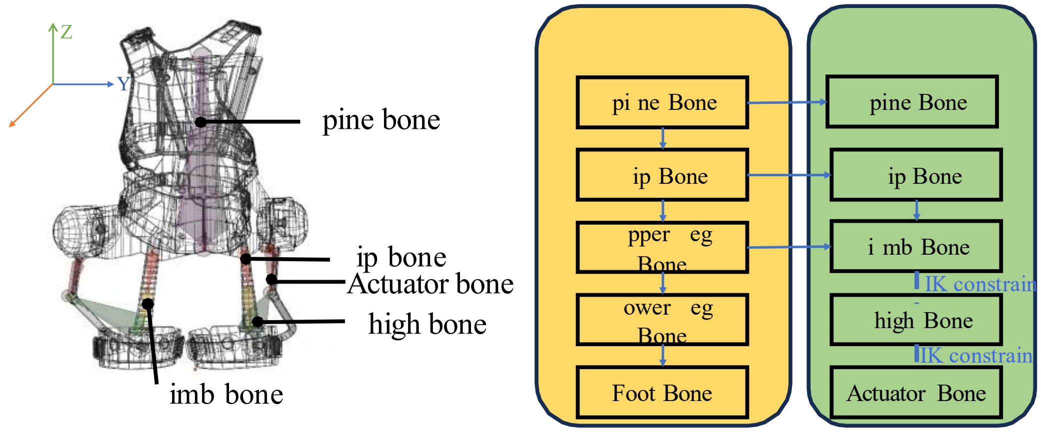

Figure 2. Skeleton armature diagram (left) and parenting level (right).

Figure 3. VR training in progress (left) and virtual construction environment (right).

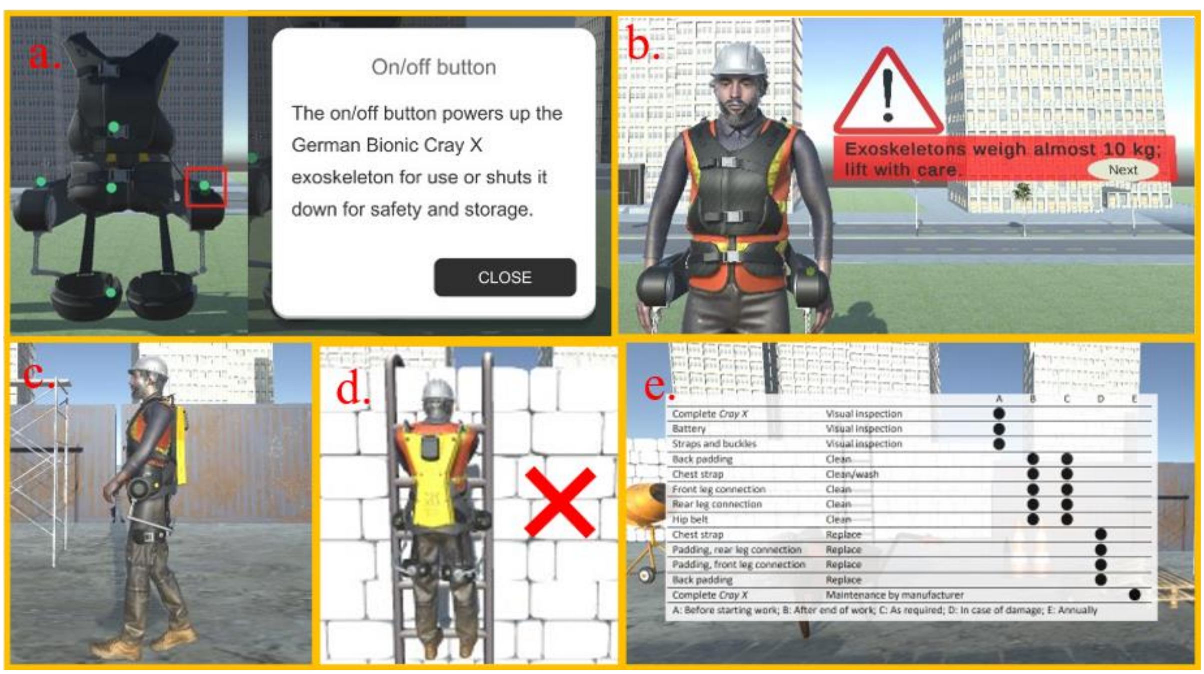

Figure 4. Sample scenarios for each module (a. exoskeleton orientation, b. wear instructions, c. practical operation, d. safety protocols, e. maintenance)

The training modules are designed to progress workers from novice to skilled levels. The modules focus on 1) exoskeleton orientation to introduce the basic structure and functions, 2) wear instructions to guide how to adjust and remove the exoskeleton comfortably and securely, 3) practical operation to train on ergonomic techniques for common tasks, especially those requiring back support (like bending and lifting) and using conditions, 4) safety protocols for prohibited scenarios and correct handling procedures, and 5) maintenance for key elements like batteries of exoskeleton . Figure 4 presents scenarios for each module that worker will experience during the training with the VR headset.

Tests are administered to evaluate participants' comprehension of the key concepts within each training module. The assessment consists of 30 questions, categorized as follows: 6 for exoskeleton orientation, 4 for wear instructions, 10 for practical operation, 6 for safety protocols, and 4 for maintenance. The cumulative performance of each participant is then depicted in a radar graph, providing a clear visual representation of their skill proficiency across different areas. Figure 5 illustrates a sample test and the corresponding radar graph result.

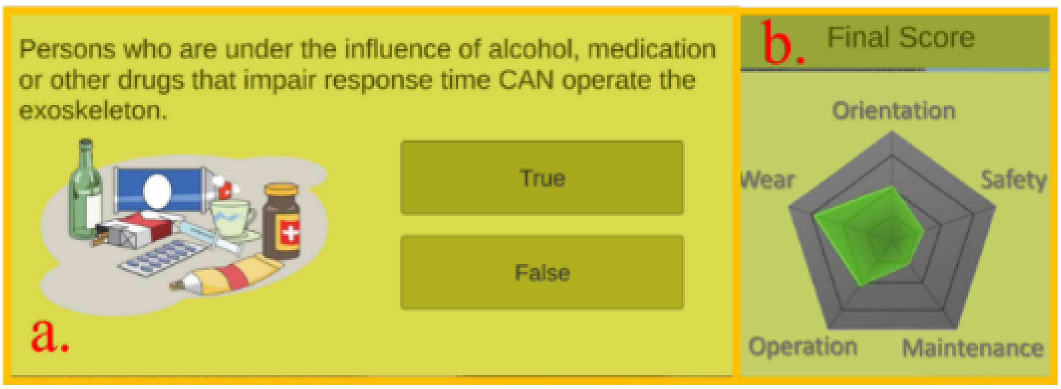

Figure 5. Sample test (a) and final competence evaluation (b)

RESULTS

In this study, the effectiveness and efficiency of the VR training platform were evaluated by comparing participant test scores which were categorized based on the training method (VR or lecture) and the timing of the assessment (pre-test and post-test). To determine statistical differences between experimental groups and at different experiment stages, a Wilcoxon signed-rank test, a non-parametric method, was chosen due to concerns about data normality. A significant level of 0.1 was set for statistical analysis.

The initial assessment showed no significant difference in knowledge levels between the VR and lecture groups. However, the post-training results revealed an increase in knowledge for the VR group in contrast to the lecture group. This improvement is visually represented in Figure 6, which details the knowledge progression both before and after training across both training sections. Significantly, the VR group demonstrated gains in areas such as wear instructions and practical use. This finding highlights the strength of VR in providing a more immersive and interactive learning experience, a feature less pronounced in traditional lecture-based methods. In contrast, the VR training showed no significant improvement in sections like maintenance, suggesting a limitation in its effectiveness for teaching more text-intensive or theoretical content.

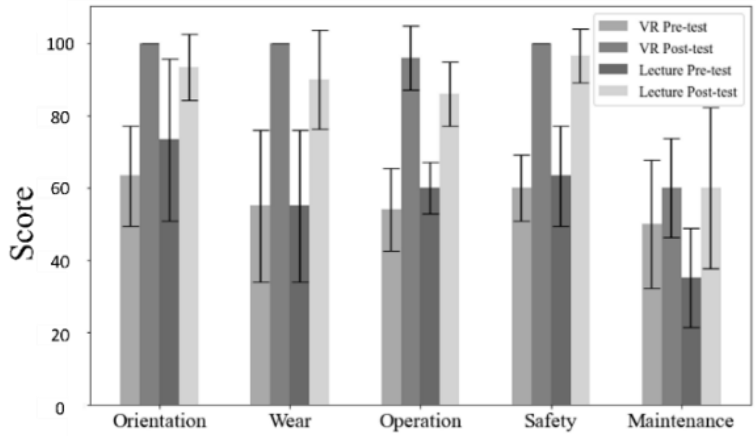

Figure 6. Segregated knowledge score for each evaluated sessions for both groups

Building on the quantitative analysis of participant scores, the VR training platform underwent further qualitative evaluation by five training professionals. They assessed the platform using a questionnaire composed of eight questions, each targeting different aspects of its design and functionality. Responses were recorded on a scale ranging from 1 ('absolutely useless') to 5 ('very useful').

Figure 7 showcases the results of this evaluation, particularly indicates a high level of efficacy across most assessed areas. The platform garnered strong endorsements for its user interface (UI) design, the accuracy of its simulations, the relevance of its training content, and the effectiveness of its testing modules. However, the feedback also pointed to a need for improvement in training engagement. It was suggested that the platform could be further enhanced to offer a more immersive and engaging experience, thereby maximizing its potential as a training tool. This feedback aligns with the earlier findings regarding the platform's effectiveness in certain training aspects and highlights areas for future development.

Q1: Are the user interface (UI) and interaction methods conducive to enhancing learning efficiency and operational accuracy?
Q2: How much useful is it to simulate the real construction sites
Q3: How important do you believe multisensory (visual, auditory) engagement is in VR training for enhancing learning outcomes?
Q4: Are the training varied enough to master the workers with a wide range of competencies within the exoskeleton training?
Q5: How effective is the training content in combining theoretical knowledge with practical operational skills?
Q6: How does the training content perform in terms of staying relevant to the latest industry standards?
Q7: Are the end-of-module tests effective in assessing participants' overall performance and skill mastery?
Q8: How does the training platform leverage current VR technology compared to traditional training methods

Figure 7. Analysis of questionnaire results from expert evaluations

CONCLUSION

The aim of this study was to create a VR training platform tailored for construction workers to master the use of exoskeletons. The efficacy of this VR training approach was evaluated against the traditional lecture-based method through a series of pre-tests and post-tests. The statistical analysis revealed that VR training led to a significant improvement in operational learning outcomes, highlighting its superiority in terms of effectiveness and efficiency over conventional methods. Additionally, the VR training platform garnered positive feedback from training experts, further validating its utility. The results of this study underscore the immense potential of VR in the realm of construction training. It offers an immersive, risk-free environment that is particularly beneficial for training in advanced robotic technologies including exoskeletons.

The findings of this study advocate for increased investment in VR-based training within the construction industry. Future research directions include broadening the sample size to derive more comprehensive insights. Furthermore, the integration of multisensory elements, such as haptic feedback, could significantly augment the realism and impact of VR training. Enhancing the sensory experience in VR could prove especially effective in accurately simulating the use of exoskeletons, thereby enriching the overall training experience.

ACKNOWLEDGEMENT

The work presented in this paper was supported financially by the National Science Foundation (Award No. DUE- 2402008 ‘Investigating the Impact of an Immersive VR-based Learning Environment for Learning Human-Robot Collaboration in Construction Robotics Education’). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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