Revolutionizing Human-Robot Collaboration in Construction: An Empirical Inquiry into the Role of Advanced Multi-Finger Haptic Feedback within Immersive Environments

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ABSTRACT

The advent of automated robotic systems in construction has the potential to significantly improve efficiency, safety, and productivity. However, integrating robots into construction job sites requires careful consideration of different aspects of human-robot collaboration. Prior studies have used immersive virtual environments as simulation testbeds, providing secure and controlled settings for investigations. While these conventional simulations offer a promising imitation of real-world tasks, they normally fall short of delivering the necessary interaction fidelity, especially in tasks requiring fine motor control. To address this gap, this study proposes the incorporation of haptic feedback into immersive human-robot collaboration to replicate real-world physical interactions. As such, an experiment was conducted to assess the impact of multi-finger haptic feedback via haptic gloves during a collaborative bricklaying task. Continuous monitoring of electrodermal activity using a wristband-type wearable sensor and the Presence Questionnaire was employed to measure user engagement and sense of presence. Results showed that haptic feedback enhances user engagement and sense of presence compared to conventional immersive simulations. The findings indicate the potential of haptic feedback for advancing user experience in immersive simulations, offering a guideline for future human-robot collaboration enhancements.

INTRODUCTION

The construction industry is revolutionizing with the increasing adoption of robotic technologies, shifting away from traditional methods (Bademosi and Issa 2021). These robots perform a variety of tasks like bricklaying, welding, and excavation with high accuracy, addressing the skilled labor shortage (Ma et al. 2022). However, many construction operations still require human expertise due to the flexibility and dexterity they demand. Consequently, human-robot collaboration, which combines human skills with machine efficiency, is becoming more prevalent in the construction sector (Liang et al. 2021). However, the integration of robots into dynamic construction sites brings new challenges, particularly regarding maintaining safety throughout human-robot interactions (Huck et al. 2021; Liu and Jebelli 2023). To overcome these challenges, intuitive human-machine interfaces (HMIs) are being implemented to facilitate effective interaction with robots.

Among these interfaces, immersive virtual environments are emerging as effective tools in bridging the gap between humans and robots in the construction industry. Virtual environments can provide construction professionals with real-time visual feedback and practical information, greatly supporting their interaction with robotic systems (Wang et al. 2021). They can simulate

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diverse scenarios, offering a safe and controlled testbed that is not constrained by the restrictions of the physical world (Rodehutskors et al. 2015). Further, virtual environments offer an intuitive means for users to interact with and control robotic operations more effectively. The integration of immersive technologies into human-robot collaboration practices not only enhances safety through realistic simulations and increased situational awareness but also has broad applications, such as in workforce training (Shayesteh et al. 2023).

While virtual environments offer significant benefits within the context of human-robot collaboration, their user interaction capabilities face challenges. More specifically, traditional interaction systems in virtual settings often struggle to mimic the natural interactions of real-world scenarios required for effective collaboration with construction robots (Lou et al. 2021). Therefore, to create a more immersive experience and improve user sensory perception in virtual scenarios, additional feedback mechanisms are needed. In this regard, haptic feedback shows the potential to enhance virtual interactive scenarios by adding a tactile element to interactions. This improvement has the potential to enhance different aspects of human-machine interactions. While previous studies highlighted the potential applications of haptic feedback, there remains a significant gap in research concerning the impact of haptic feedback on user experience and learning outcomes in the context of human-robot collaboration in construction settings.

To address this issue, this study examines the incorporation of haptic feedback into virtual interactive scenarios in the context of human-robot collaboration in construction. To this end, an experiment was designed and conducted to assess the impact of haptic feedback provided through haptic gloves during a bricklaying task where the human worker and the robot collaboratively built a masonry wall. Continuous monitoring of electrodermal activity (EDA) using a wristband-type wearable sensor and the Presence Questionnaire were employed to explore user engagement and sense of presence. As such, this study enhances existing knowledge by highlighting the crucial role of advanced, multi-finger haptic feedback in improving immersive environments for a variety of complicated construction tasks, from welding to material handling, due to the common need for precision, safety, and efficiency. This capability marks a shift from existing research that mainly concentrated on controller-based haptic feedback.

ROLE OF HAPTIC FEEDBACK IN VIRTUAL REALITY SIMULATIONS

Creating an immersive experience that closely resembles reality has been a principal objective in the development of virtual reality-based simulations. Haptic feedback, which is essentially the sensory response from kinesthetic and tactile receptors (Botden et al. 2008), can play a critical role in advancing user experience in immersive environments. This technology facilitates mechanical interactions within virtual simulations to enhance the sense of presence and realism (Burdea and Coiffet 2003). In educational and training scenarios, the adoption of a multi-sensory strategy can significantly enhance learning efficacy and memory retention by enabling learners to use various sensory inputs and develop strong cognitive frameworks (Patil et al. 2018). The effectiveness of haptic feedback is potentially due to providing learners with a tangible representation or feel of knowledge, which is often absent in conventional educational settings.

Recognizing the potential of haptic feedback, researchers across various fields explored how haptic feedback can enhance user experiences. For example, Grushko et al. (2021) created a hand-worn device that communicated a robot’s movements and status to a human collaborator,

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improving joint task performance. Additionally, Ni et al. (2017) introduced an AR interface for remote welding robot programming, incorporating haptic cues. These innovations highlight the benefits of combining immersive experiences with haptic feedback in robot control, enhancing teleoperation, and broadening industry applications. As such, incorporating haptic feedback into immersive human-robot interactions is a promising avenue in the construction industry, where bridging the gap between human operators and robots is increasingly important. However, despite advancements in virtual reality and haptic technologies, their combined application in construction settings is relatively unexplored. Therefore, research is needed to investigate the benefits of haptic-enhanced virtual environments for improving human-robot collaboration in construction.

RESEARCH METHODOLOGY

This study evaluates the role of haptic feedback in virtual human-robot collaboration scenarios. It introduces a novel immersive platform featuring multi-finger haptic feedback where users can collaborate with a virtual robotic system to perform a bricklaying task. Through an experimental process, the study investigates the impact of haptic feedback on user engagement and sense of presence, employing a combination of quantitative and qualitative methods. An overview of the research methodology is depicted in Figure 1.

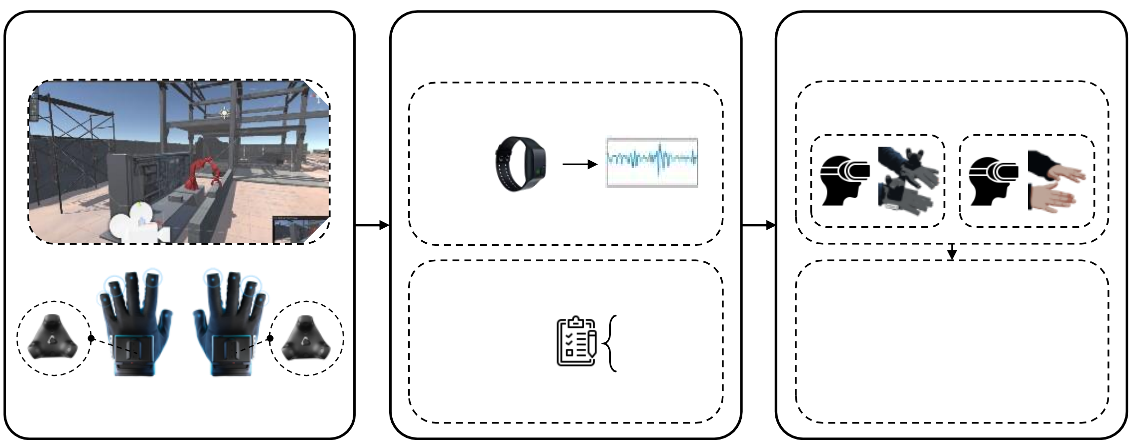

Figure 1. Overview of the proposed research methodology.

Haptic-enabled Immersive Platform Development. The proposed immersive environment was generated using the Unity game engine, creating a virtual setting that simulated a construction job site for human-robot collaboration tasks. This setup offered a risk-free testbed for human-robot collaboration, which is crucial in industrial contexts where safety is vital. The Unity scene editor was utilized for constructing the virtual site, integrating 3D models, textures, animations, and sound effects to enhance realism. An essential component of the site was the virtual construction robot, modeled after the semi-automated mason (SAM) bricklaying robot (Construction Robotics 2024), with scripted motions and action. To facilitate meaningful human-robot interaction within the immersive environment, a virtual embodiment of the user was created. This feature enabled users to perform tasks like grabbing and manipulating objects, thus significantly enriching the user experience within the immersive environment (Shayesteh and Jebelli 2022).

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To integrate the haptic response into the immersive platform, the authors utilized the Manus Prime 3 Haptic XR gloves. The selected system could provide an immersive haptic experience, allowing users to interact with virtual objects without needing physical prototypes. To achieve this, the Manus Core software was installed and related libraries and packages were imported into Unity to link the device to the host computer and manage its data. A skeletal mapping algorithm was used to translate the user's hand movements onto a virtual hand model. Motion-tracking sensors (i.e., Vive Trackers) were connected to each glove and employed for spatial orientation and positioning. This setup enabled the virtual hand model to animate dynamically based on data from the motion trackers and gloves. Additionally, scripts were incorporated into desired virtual objects in the scene to make them responsive to haptic interactions. Figure 2 demonstrates the process of integrating haptic feedback into the developed immersive platform.

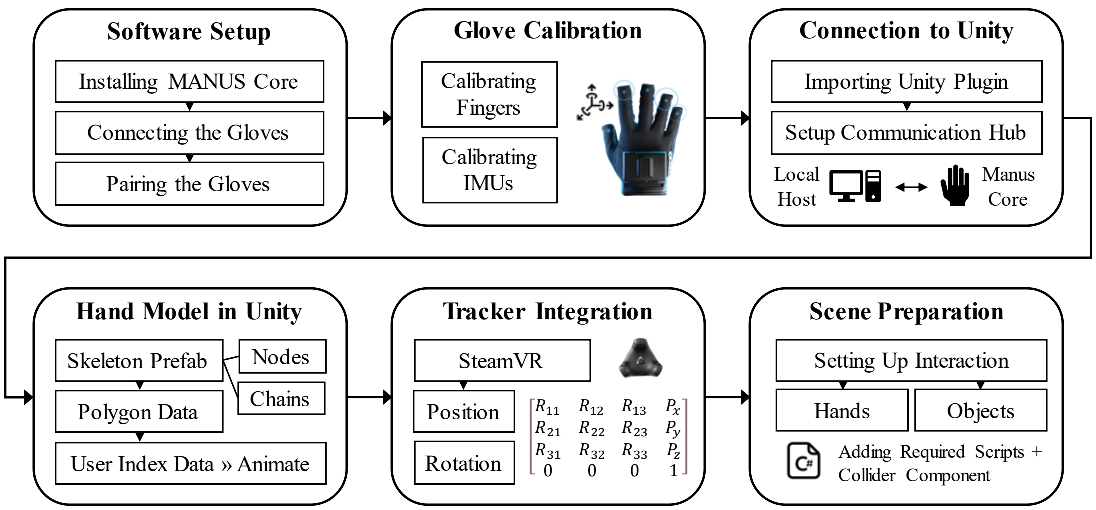

Figure 2. Integration of haptic response to the immersive environment.

User Response Measurement. This study leveraged a combination of quantitative and qualitative approaches to evaluate user engagement. To that end, the authors utilized continuous monitoring of EDA signals as the quantitative approach (Huynh et al. 2018; Ojha et al. 2023) to measure user engagement, and the Presence Questionnaire (PQ) (Witmer and Singer 1998) was employed as the qualitative approach to measure the sense of presence during selected human-robot collaboration scenarios.

In this study, the authors used a commercially available wristband biosensor, specifically the Empatica E4, to capture EDA signals at a frequency of 4 Hz. To ensure the reliability of EDA data, first, a preprocessing approach was performed to remove signal artifacts caused by user-related issues and environmental factors (e.g., user muscle movements or electromagnetic fields). This involved applying a high-pass filter set at a 0.05 Hz cutoff frequency to reduce low-frequency environmental noise, and a moving average filter to diminish high-frequency noise in the EDA signals (Shayesteh et al. 2023). Following the preprocessing procedure, the EDA signals were decomposed into tonic (EDL) and phasic (EDR) components using the convex-optimization-based EDA (cvxEDA) technique (Greco et al. 2016). Accordingly, several metrics, including mean value, root mean square (RMS), and root sum square (RSS) (Ojha et al. 2023), were extracted from EDA components. Consequently, the changes in EDA metrics compared to the baseline were adopted as the key indicators for assessing user engagement.

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In addition to the quantitative approach, the study incorporated the Presence Questionnaire to evaluate ’ v d sense of presence during task performance. The concept of presence in this context refers to the feeling of being physically present in a virtual or non-physical world. This questionnaire is often used in research related to virtual reality and similar immersive technologies. It consists of a series of questions and statements that respondents rate based on their experiences in the virtual environment on a 7-point scale. These questions cover various aspects of the user’s experience, such as sensory engagement, realism, and the ability to act within the virtual environment. Key questions included inquiries such as “How natural did your interactions with the environment seem?”, “How compelling was your sense of objects moving through space?”, d “How much did your experiences in the virtual environment seem consistent with your real-world experiences?” (Witmer and Singer 1998).

Performance Assessment. To assess the performance of the developed haptic-enabled immersive platform, an experiment was conducted involving 6 healthy participants aged between 29 and 25 years (mean = 26.5 and SD = 1.61). The participants were asked to provide their demographic information and prior experience with virtual reality-based simulations, with no reported medical conditions affecting their performance in the immersive virtual environment. After receiving detailed information about the experimental procedure and giving informed consent, participants were equipped with a Meta Quest Pro VR headset. The headset featured a resolution of 1800×1920 pixels per eye, a 106° field of view, and a 90 Hz refresh rate, operating as a standalone system without the need for a computer tether, thus enhancing user mobility in the virtual environment. They were also equipped with a pair of Manus Prime 3 Haptic XR gloves for multi-finger haptic feedback and an Empatica E4 wristband for data collection.

Following the setup and calibration of the equipment and biosensors, participants had the opportunity to familiarize themselves with different aspects of the immersive environment and the interaction mechanism. During this process, participants were closely monitored to identify and address possible issues. Once the participants were prepared, they were asked to start the task performance, which involved working together with a construction robot to lay bricks. In this task, participants were in charge of handling and passing blocks to the robotic arm, which then used these blocks to build a masonry wall. This collaborative task necessitated both the human and the robot to operate jointly in the same physical space of the virtual environment. Each participant performed the same task with and without providing haptic feedback in random order. Each session lasted about 5 minutes during which the EDA signals were continuously captured using the E4 wristband. After each session, participants were requested to fill out a questionnaire to indicate their perceived sense of presence during the collaborative virtual scenario. Figure 3 shows the experimental procedure for data collection in this study.

RESULTS AND DISCUSSION

In this study, the electrodermal activity (EDA) signals captured using the Empatica E4 wristband were leveraged to compare user engagement with and without incorporating haptic feedback into the immersive human-robot collaboration scenario. To that end, key metrics were extracted from processed data, including mean value, root mean square, and root sum square. Figure 4 shows the comparison of calculated metrics in two experimental conditions. As seen in the figure, there is an increase in the mean value and RSS values of the EDA during the tasks involving haptic feedback in the immersive environment. Previous research suggests that an increase in those metrics is an indicator of a heightened level of user engagement level (Ojha et

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al. 2023). As such, the results show an improved level of engagement in using haptic feedback engagement compared to tasks without haptic feedback.

Figure 3. (a) Experimental equipment and (b) a participant performing the human-robot collaboration task in VR with and without haptic feedback.

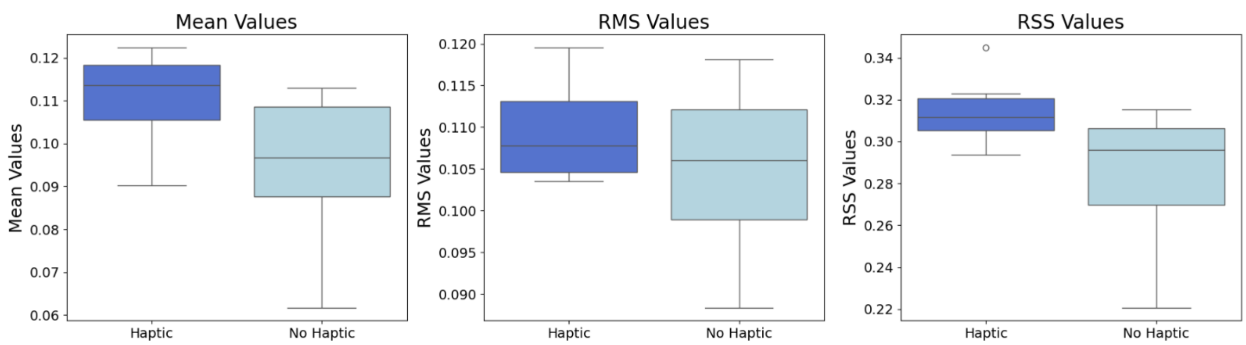

Figure 4. Metrics calculated from EDA signals, including Mean value, RMS, and RSS for VR scenarios with and without haptic feedback.

To indicate any significant differences among the levels of user engagement, the Wilcoxon signed rank test was performed on the metrics as a non-parametric test. Due to the low sample size of the experiment, the lack of normal distribution was a concern in this study, leading to the adoption of the non-parametric test. A significant level of 0.05 was chosen for this study. Based on the results of the test, there was a significant difference (p-value = 0.03125) in the mean value between the two experimental conditions. The lack of significant differences in the other two metrics can be attributed to the absence of required external stimuli in the experimental condition featuring haptic feedback.

In addition to the user engagement, the authors utilized the Presence Questionnaire to gain h ’ v d . The questionnaire consisted of 19

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questions that participants rated on a 7-point Likert scale. The questionnaire can be categorized v b , d ‘ ’, ‘ b y ’, ‘q y ’, ‘ b y x ’, d ‘self- v ’. The scores for three of the items (related to the ‘q y ’) were reversed due to the negatively phrased nature of the questions. Participants generally reported a higher sense of presence when engaged with the human-robot collaborative task involving haptic feedback (Figure 5). Specifically, responses to questions regarding the naturalness of interactions and compelling sense of objects moving through space were notably higher in the scenario featuring haptic feedback. For instance, the average rating for h q “How natural did your interactions with the environment seem ” w 5.83 in the scenario with haptic feedback, compared to 4.5 in the scenario with no haptic feedback.

The combined result of quantitative and qualitative analysis suggests that the incorporation of haptic feedback in immersive environments can significantly enhance user engagement (as evidenced by EDA metrics) and perceived sense of presence (as indicated by PQ ratings) among users. These findings demonstrate the potential of haptic feedback in elevating the user experience in human-robot collaborative tasks, particularly in virtual or simulated settings. The increase in engagement and sense of presence metrics in scenarios featuring haptic feedback underscores the effectiveness of tactile feedback in making virtual interactions more immersive and realistic.

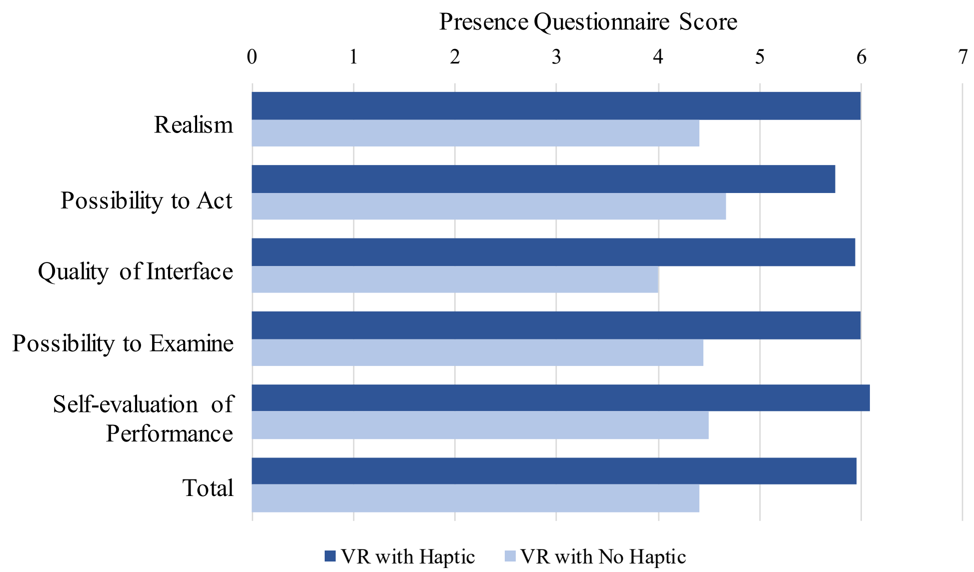

Figure 5. ’
Presence Questionnaire for VR scenarios with and without haptic feedback.

While this study offered valuable insights into the adoption of multi-finger haptic feedback in virtual human-robot collaboration, it also highlighted several areas that need further exploration in future research. F y, h d y’ h y might limit the generalizability of the findings. Future research should focus on incorporating a broader range of measures to understand user response. Additionally, the impact of using haptic feedback in training and knowledge transfer to real-world tasks are important areas for future research. Investigating these aspects could provide insights into the effectiveness of haptic feedback in skill acquisition, retention, and application in real-world scenarios. Moreover, the sample size

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and the demographic characteristics of the participants may limit the generalizability of the findings. A more diverse participant pool would provide more comprehensive insights into the findings of the study. Lastly, exploring the psychological aspects of haptic-enabled virtual simulations, such as the development of trust and comfort with this technology, is crucial. Understanding these factors will be essential in designing user-centered robotic systems that are both efficient and well-received by users.

CONCLUSION

This study explored the application of multichannel haptic feedback in immersive environments to improve human-robot collaboration in simulated construction operations. The proposed method involved using a haptic feedback system to provide a more realistic user interaction mechanism during the virtual reality-based simulation and evaluating user engagement and perceived sense of presence through quantitative and qualitative approaches. The results revealed that incorporating haptic feedback could significantly increase user engagement and sense of presence compared to the condition lacking haptic response. This finding is crucial, as it suggests that including tactile sensations can make virtual environments more realistic and effective, especially for precise tasks in construction. The study contributes to the field of human-robot interaction by demonstrating the potential of haptic feedback in making robotic systems more intuitive and user-friendly. It also highlighted the potential of the proposed method to provide a more immersive and interactive training platform that could lead to more skilled workers. This potential creates new opportunities for employing such technologies in training and operation scenarios, leading to better safety and productivity in the construction industry as well as other domains.

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