Effect of Tactile Affordance During the Design of Extended Reality-Based Training Environments for Healthcare Contexts

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Abstract. In this paper, the effect of tactile affordance during the design of Extended Reality (XR) based environments is presented. Tactile affordance is one of the Human eXtended Reality Interaction (HXRI) criteria which help lay the foundation for human-centric XR-based training environments. XR-based training environments developed for two surgical procedures have been used to study the role of tactile affordance. The first XR environment is developed for the Condylar plating surgical procedure which is performed to treat the fractures of the femur bone and the second XR environment is developed to train users in endotracheal intubation. Three studies have been conducted to understand the influence of different interaction methods to elevate tactile affordance in XR-based environments. The studies and the results of the studies have been exhaustively discussed in this paper.

Keywords: Affordance · Tactile Affordance · Human eXtended Reality Interaction · HXRI · Virtual Reality · Extended Reality (XR)

1 Introduction

Extended Reality (XR) is an umbrella term used to collectively describe Virtual Reality, Mixed Reality, Augmented Reality, and other supporting technologies such as haptic technology. The Healthcare domain has benefited from the use of XR technologies in the last two decades. There has been an exponential technological advancement, especially in the last five years, with the introduction of low-cost VR headsets such as Vive and Quest, AR-capable smartphones and tablets, and Mixed Reality headsets such as Hololens and Magic Leap. Such advancements have enabled designers to create VR, MR, and AR-based training simulators for a wide range of applications ranging from less invasive laparoscopic surgery to complex procedures such as brain and cardiac surgery [1–15].

As more researchers invest time and resources towards technological advancements, the research focusing on the human-centric aspects of an XR-based environment has taken a backseat. This paper explores the impact of a Human eXtended Reality Interaction (HXRI) criterion during the design and development of XR-based environments. HXRI can be defined as the application of current HCI-based principles and the formulation of novel principles for the creation of effective XR-based applications. Only a few researchers have focused on understanding the HCI-centric aspects of the XR platforms and devices [6, 16–19]. In this paper, the HXRI criteria termed tactile affordance is being described and its impact on both VR and MR-based environments developed for two healthcare-related training scenarios is being studied. The word affordance was first coined in [20] by psychologist James J. Gibson who defined it as what the environment offers to the individual. In the context of Human-Computer Interaction, the term affordance was defined by Norman as action possibilities that are perceivable readily by an actor [21]. Gaver delineated affordances as the world's properties, which are defined with respect to how people interact with them. Gaver provided an analysis of the relationship between affordance and perceptual information about the information which led to four possible combinations viz. Perceptible affordance, false affordance, hidden affordance, and correct rejection [22].

While designing and developing XR-based applications, designers focus on spatial, manipulation, and feedback affordances. Head-mounted XR-based displays provide natural movement of the head and body, enabling users to sense the depth of images intuitively, creating a sense of presence. Researchers, in the past, have studied affordances related to the XR-based environments. A test for objective assessment of judgment and action-based measures to measure perceptual fidelity in AR using HoloLens [23]. A similar study in which HoloLens-based XR environment was used to understand the effect of varying wide and deep gaps on users was presented in [24]. During the interactions with XR-based environments for surgical training, a user has to perform complex tasks; however, past researchers focused on how basic tasks such as passing through a door, or an aperture, and observing gaps affect affordance in virtual and augmented reality [25–27]. There has been a lack of research focusing on tactile affordance during complex tasks. As most XR environments, especially in the surgical domain, are designed such that users can perform complex tasks, it is important to understand how tactile affordance affects the users when such tasks are being performed. Other researchers have elaborated on the learning affordance in an XR environment using various subjective and objective questionnaires [28, 29]. These affordance questionnaires only serve as basic knowledge-based questions regarding the process without highlighting the importance of understanding the relationship between various objects of interest (OOIs) and various interaction methods in the XR environment.

In a previous publication [31], affordance was classified into two main categories (Visual and Tactile Affordance). In this paper, the focus is on understanding the impact of tactile affordance during the design of XR-based simulators. Tactile Affordance (TA) can be defined as the function of a scene's ability to support comprehension through the sense of touch.

XR-based training environments developed for two surgical procedures have been used to study the role of tactile affordance in knowledge and skills acquisition. The first XR environment is developed for the Condylar plating surgical procedure which is performed to treat the fractures of the femur bone and the second XR environment is developed to train users in endotracheal intubation. Three studies have been conducted to understand the influence of different interaction methods to elevate tactile affordance in XR-based environments.

The rest of the paper is organized in the following manner. In Sect. 2, the design of the XR-based environments is presented. The design of the study is elaborated in Sect. 3. In Sect. 4, the results from the studies are presented and discussed.

2 Design of XR Based Environments

The HCI-based XR environments were designed for using Virtual, Mixed and Haptic-based technologies. Orthopedic surgical training. The VR-based environments were developed for Vive Pro immersive platform and the MR-based environments were developed for the HoloLens 2 platform. The VR and MR environments were developed using the Unity 3D engine. Steam VR tool kit was used for the development of VR environments and Mixed Reality Toolkit (MRTK) was used for the development of MR environments. Training environments were developed for Condylar plating surgery and endotracheal intubation.

2.1 Condylar Plating Training Environment

The HCI-based XR environments were designed for using Virtual, Mixed and Haptic-based technologies. Orthopedic surgical training. The VR-based environments were developed for Vive Pro immersive platform and the MR-based environments were developed for the HoloLens 2 platform. The VR and MR environments were developed using the Unity 3D engine. Steam VR tool kit was used for the development of VR environments and Mixed Reality Toolkit (MRTK) was used for the development of MR environments. Training environments were developed for Condylar plating surgery and endotracheal intubation.

Dynamic Plate Compression Environment. The dynamic Plate compression environment is the most complex training environment among the three environments. In some critical femur fractures, dynamic plate compression is performed to reduce the bones and complete the treatment. In dynamic plate compression, the two fractured bones are transfixed by exerting dynamic pressure between the bone fragments. Figure 1 shows the views of VR and MR-based training environments developed for dynamic plate compression. During the training, the users learn to complete a complex set of procedures including plate positioning, drilling, and screw insertion. During the training, the users first insert the plate in the correct position and orientation based on the location of the fracture. Secondly, the users fix the plate in the position using clamps. Subsequently, an eccentric drill guide is used to drill holes in the bone. Finally, screws are inserted, that compress the bone segment together and transfix them. For the VR-based training, the users interacted with the environment using Vive Pro fully immersive headset. Wireless handheld controllers were used to perform the training activities. For the MR-based training, the users interacted wearing the HoloLens 2 platform. The users interacted with the physical mockup of the training tool and equipment by following the MR-based instructions on the HoloLens 2 headset. The users can be seen interacting with the VR and MR-based training environments in Fig. 4.

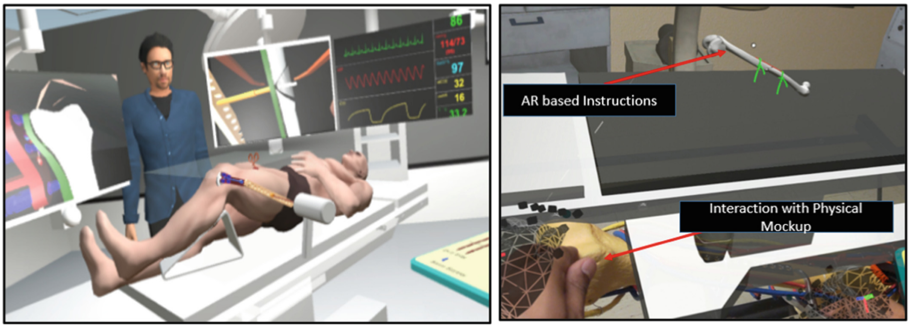

Fig. 1. VR and MR based Training Environments for Dynamic Plate Compression

2.2 Endotracheal Intubation Training Environment

Performing an endotracheal intubation is a complex and challenging medical procedure. An extensive amount of training is required in order to acquire the skills necessary to perform endotracheal intubation. As part of the medical procedure, an endotracheal tube is commonly inserted into the patient's trachea to provide artificial respiration to the patient by optimizing the airway. In the process of inserting the endotracheal tube, scrapes can occur in the esophagus. Consequently, the patient is at an increased risk of infection. In order to reduce the risk, a laryngoscope will be used to help the doctor place the endotracheal tube. By using a laryngoscope, the doctor is able to see the vocal cords more clearly and place the endotracheal tube more safely and consistently. In order for the endotracheal tube to function correctly, the doctor will secure the tube and clear the airway of obstructions [17]. The virtual environment (Fig. 2) allows users to perform each step of the procedure providing visual cues and feedback during each step.

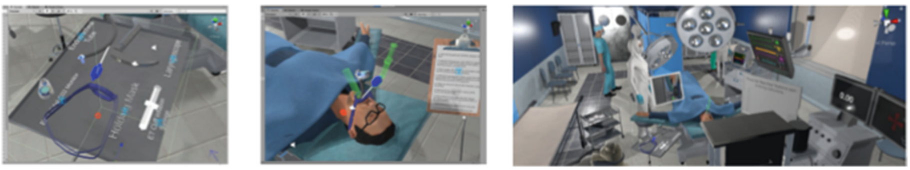

Fig. 2. VR-based Training Environments for Endotracheal Intubation

3 Design of Studies

Three studies were conducted in the two training environments (condylar plating and endotracheal intubation) to understand how various interaction methods impact the tactile affordance of an XR-based training environment. A discussion of the three studies follows.

3.1 Comparison of Haptic and Non-haptic VR Environments

The goal of this study is to compare haptic-based interactions and non-haptic-based interactions in a VR environment. The VR environment developed for the condylar plating surgical procedure was used for such comparison. The users were provided two types of interaction capabilities in this study. The users were able to use a haptic device that provided tactile vibration during the interaction in the first case. In the second case, the users interacted with the environment using the non-tactile Vive controller. The views of users interacting with the haptic device and Vive controller are shown in Fig. 3.

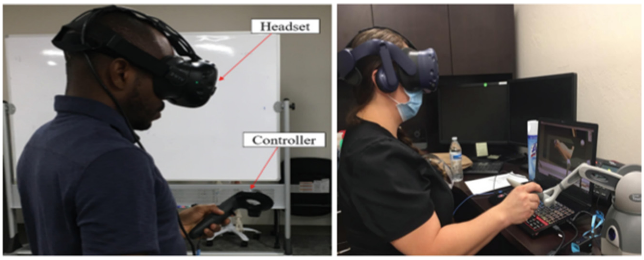

Fig. 3. Users interacting with controller-based non-haptic environment and haptic-based environment

3.2 Comparison of Non-haptic VR and Fully Haptic MR Environments

The goal of this study is to compare non-haptic interactions and fully haptic (using the physical tools and equipment) in an XR environment. Both VR and MR environments developed for the condylar plating surgical procedure were used for such comparison. The users were provided two types of interaction capabilities in this study. In the first case, the users interacted with the environment using the non-tactile Vive controller, and the users interacted with physical tools and equipment in the second case. The views of users interacting with the vive controller and physical tools are shown in Fig. 4.

For studies 3.1.1 and 3.1.2., assessments were conducted to assess the impact of interaction methods on users' knowledge and skills acquisition to understand how such interactions affect the tactile affordance of an XR environment. A complete description of the knowledge and skills assessment used in this paper is presented in [32].

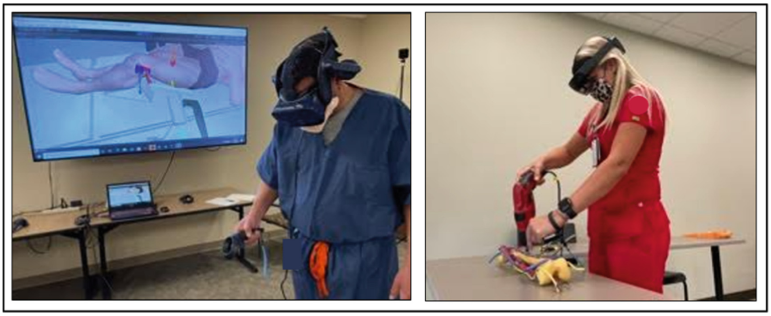

Fig. 4. Users interacting with VR and MR-based Training Environments

3.3 Use of Visual-Propreoception Feedback

The objective of this study is to create a VR learning simulation that provides accurate hand movements and real-time feedback during endotracheal intubation. Endotracheal intubation can be performed in a realistic virtual reality scenario using a laryngoscope and other necessary steps. However, because the virtual patient's mouth is small and the Vive controllers are bulky, the controllers will bump together in the virtual environment. This will ruin the sense of presence and immersion. A haptic retargeting solution can solve this problem (reference omitted for anonymity). In this study, visual input primarily influences proprioception feedback. Ultimately, this was what enabled us to solve the bumping problem, thus resolving it. We introduced a visual proprioception conflict model by offsetting the virtual hands from the real hands. By using this model, virtual hands can be closer together rather than separated by a small distance in the real world. This offset between the simulated and actual hands was not noticed by users, as they were not aware of it. There are two different scenarios which were designed to measure the effectiveness of the haptic retargeting model in order to evaluate the results.
Reference condition
Visual proprioception conflicts were not perceived in this condition. The virtual hands of the participants were aligned with the actual hands of the participants. Real hand offset equaled virtual hand offset. This condition was perceived as conflict-free by participants.
Conflict condition
As a result of this condition, the virtual hand will have an offset of six centimeters from the real hand. It has been found that when this value is applied to a subject, he or she is unable to distinguish their virtual hand from their actual hand. It is important to emphasize that although the virtual hand moved with the same speed as the actual hand, its position was different from that of the actual hand As a measure of the effectiveness of the haptic retargeting model in our experiment, we used the presence questionnaire to gauge its effectiveness.

4 Results and Discussion

The assessment activities were conducted at two medical centers and a university. The results of the three studies follow.

4.1 Comparison of Haptic and Non-haptic VR Environments

A total of eighty participants interacted with two environments (task 1: plate insertion and task 2: dynamic plate compression) in this study (Table 1).

Table 1. Participants' categorization for comparison of haptic and non-haptic environments

	Haptic Device	**Vive Controller**
Task 1	Subject 1–40	Subject 41–80
Task 2	Subject 41–80	Subject 1–40

The result of the comparison study is shown in Fig. 5. According to the result of the t-test, the group interacting with the Vive controller (M = 66.3, SD = 9.38) received significantly higher score compared to the group interacting with the haptic device (M = 53.25, SD = 10.5), t (158) = 8.3, p = 0.001.

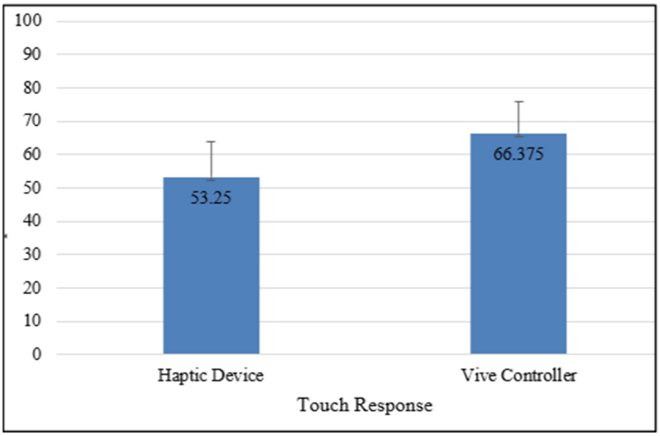

Fig. 5. Results for comparison of haptic and non-haptic environments

Although the haptic device provided the sense of touch, there is a limitation in motion during the interaction. The Vive controller, on the other hand, provides the users with unrestricted motion. This could be the main reason behind the result. However, when asked about their preference during force-based tasks such as drilling, more than 80% of the participants preferred the haptic device over the Vive controller. The haptic-based interface through vibrations and force feedback provides a more realistic replication of the actual drilling procedure.

The statistical results which favor the vive controller do not completely justify the role of haptic interfaces in surgical training. The substantial preference for the haptic interfaces shown by the users is a confirmation of the need for haptic interfaces. Haptic interfaces can be very useful in surgical procedures where force feedback becomes necessary such as drilling, and fracture reduction, among others. Currently, haptic devices are widely used in laparoscopic and orthopedic simulators [1, 2, 7] despite the restricted motion associated with the haptic interfaces. Haptic interfaces have the potential to co-exist in an integrated manner with other XR interfaces.

4.2 Comparison of Non-haptic VR and Fully Haptic MR Environments

A total of eighty participants interacted with MR and VR environments with two levels of complexity. The low complexity task was plate assembly, and the high complexity task was dynamic plate compression. The design of the experiment is shown below. The participants were divided into groups of nursing students and practicing nurses. The participants performed low complexity task first; subsequently, they performed high complexity task (Table 2).

Table 2. Participants' categorization for comparison of non-haptic VR and fully haptic MR environments

	VR	**MR**
Task 1	Subject 1–40	Subject 41–80
Task 2	Subject 41–80	Subject 1–40

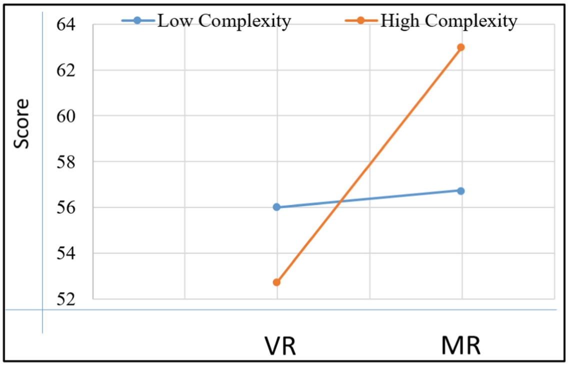

Fig. 6. Results for comparison of non-haptic VR and fully haptic MR environments

The results of the experiment for comparison of MR and VR environments are shown in Fig. 6. It can be seen from the figure that the difference in score depended on the complexity of the environment. Two t-tests were performed to further analyze the results. For the low complexity environments, no significant difference was observed in scores between the group interacting with VR ($M = 56$, $SD = 11.26$) and the group interacting with MR environment ($M = 56$, $SD = 8.88$), $t(78) = 0.33$, $p = 0.37$. However, for the high complexity environments, a significant difference was observed in scores between the group interacting with VR (M = 52.75, SD = 8.65) and the group interacting with MR environment (M = 63, SD = 87.81), t (78) = 5.56, p = 0.001.

The results indicate that the interaction methods do not contribute much when the users are performing a low-difficulty task. However, the interactions with the physical tools and equipment become crucial when the users are trying to learn a more complex procedure. After the interactions with the MR and VR-based training environments, the eighty participants responded to a NASA Task Load Index (TLX) [31] survey. In the survey, the participants were asked to rate the MR and VR environments in terms of effort, frustration, mental, physical, and temporal demand they faced during the interactions. The results of the NASA TLX survey show that the experienced nurses preferred MR environments whereas the nursing students preferred VR environments for the interactions. This leads to the understanding the experience level also impacts the choice of interaction method. As nurses are more used to interacting with physical tools and equipment compared to the students, they preferred the MR environment which provided higher tactile affordance compared to the VR environment.

4.3 Use of Visual-Proprioception Feedback

A total of seven participants interacted with the VR-based endotracheal intubation environment to assess the effectiveness of the haptic retargeting model.

It is shown in Fig. 7 that the mean value of the presence questionnaire was calculated for different 7 participants. Compared to the reference condition, the image below shows that subjects perceive more realism under conflict conditions than they do in the reference condition. Additionally, the subjects perceived that they had a greater possibility of acting in the conflict condition. It is important to note, however, that the quality of the interface was almost the same for both conditions. The group also estimated that they had a better performance in conflict conditions compared to non-conflict conditions.

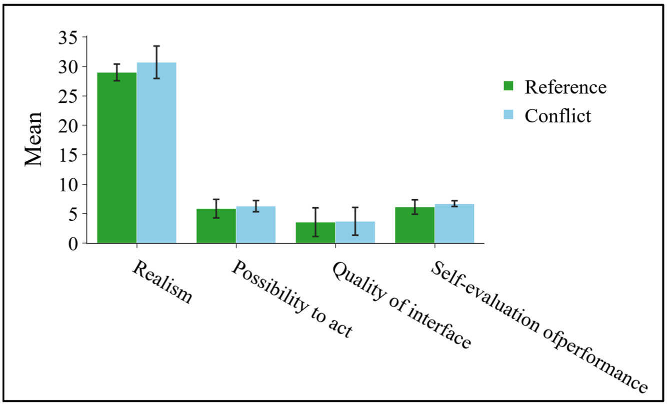

Fig. 7. Analysis of the presence questionnaire in different conditions, Y-axis indicates the mean value of 7 participants while the x-axis shows the calculated features from the presence questionnaire

Endotracheal Intubation Simulation suffered from a significant quality and usability problem. Simulation has a problem where controllers bump into each other and cause immersion to break. This problem was caused by two major factors. One of the main limitations of the simulation is that both hands must be placed in the patient's mouth at the same time. A second issue is that HTC Vive controllers are significantly larger than human hands. While it is still possible to complete the simulation in spite of this problem, it is much more difficult and strenuous than before. To solve the problem, a no-fee, simple coding base solution was proposed. The solution presented here is a great alternative to highly expensive solutions such as virtual reality robotic hand gloves. Virtual reality applications and fields may benefit from the use of this method. By using this method, VR developers can enhance the sense of presence of the user without requiring additional devices and equipment.

5 Conclusion

In this paper, the effect of tactile affordance during the design of Extended Reality (XR) based environments was presented. Tactile affordance is one of the Human-Computer Interaction criteria which help lay the foundation for human-centric XR-based training environments. Two XR-based training environments were used to understand the effect of tactile affordance viz (i) VR and MR-based Condylar plating training environment and (ii) VR-based endotracheal intubation training environment. Three studies have been conducted to understand the influence of different interaction methods to elevate tactile affordance in XR-based environments. The first study focused on the comparison of haptic and nonhaptic interactions in VR, the second study compared nonhaptic VR and fully haptic MR and the third study was related to the use of proprioception feedback. The results of the study underscore the importance of having proper tactile affordance during the interactions with the XR environments.

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