Surgical Training Using Proxy Haptics; A Pilot Study

by

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Abstract

In recent years and with the advancement of technologies, the applications of Virtual Reality (VR) have been used in many fields. Technologies such as high-resolution digital displays, GPUs and CPUs, are now able to render complex virtual worlds in real-time. Modern VR systems can create high-quality VR environments that can be used in numerous applications such as entertainment, education, and medical training.

VR has been used in surgical training to either replace more expensive training techniques (such as cadavers) or serve alongside additional training techniques to increase a surgeon's skills. As VR technologies evolve, one can trick the brain into thinking that a user is seeing and touching real-world objects. To trick the brain at a believable level, one needs to be able to generate feedback to multiple human senses (vision, haptic, sound) that are realistic and consistent with behaviors and sensations in the real world. Because of these requirements, many systems have been proposed to deal with the multi-sensory outputs VR needs to produce in order to be useful for real-world applications such as surgical training. Visual perception can be dealt with very well using modern Head-Mounted Displays (HMDs) and advanced rendering software.

On the other hand, haptic perception is still at its infancy and has not reached the same level of realism that HMDs can provide. Many haptic systems use force-feedback devices to create a sense of touch, most of them require to hold a wand attached to a small robot or wear a glove that provides forces or friction to a user's hand movement. The problem with standard haptic

devices is that they do not provide haptic feedback to all parts of the body hence reducing the sense of immersion and making their use impractical in complex simulations.

This thesis propose a solution to the realism of haptic perception in VR by using the concept called "proxy haptics." In proxy haptics, real physical props are placed around the real environment to match their virtual counterparts. If the physical props are co-registered with the virtual world, a compelling sense of tactile sensation can be achieved, for example, how a mannequin can be used to represent a virtual patient. If the mannequin is co-registered in 3D relative to the virtual user locations, one can be tricked to believe that they are touching a real patient. A prototype proxy haptic system was developed and a pilot study was performed to determine the effects of our system for simple surgical training tasks. The goal of this pilot study was to determine if people think our system is more believable than standard VR by asking them to do simple tasks such as moving the patient's hand or pointing a syringe to specific target locations. In the pilot project, we compared the results of using our system against a standard VR system with no haptic feedback (i.e., wand controller only). In the end, our results show that the amount of time the users need to complete the pointing tasks is longer in the system with proxy haptics than using the VR wand. This makes sense as in the virtual world objects are ghosts and one can move freely without collisions. In the proxy haptic world, objects are real and the laws of physics do apply. Our results also show that from a user perspective, our system is more believable and closer to the real world than the standard VR interface.

Acknowledgements

I would like to thank my supervisor, Prof. Pierre Boulanger, who always supported me during my program and guided me during my program. I would also like to thank two of my friends, Pouneh and Arash, who participated in my research, travelled to Iran to get married, and tragically passed away in a plane crash on their way back. May they rest in peace.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Problem Definition

Throughout history, humans have tried to come up with new ways of dealing with things that could make a particular task safer, easier, and more enjoyable. In recent years and with the help of current technology developments, a new generation of low-cost VR system has emerged in which a user can explore or interact with a synthetic world in real-time. Modern VR systems are capable of creating multi-sensory outputs (vision, haptic, and sound) that is capable of giving the illusion of real-world perception. VR system uses Head-Mounted Displays (HMDs) that can track head motion and update the visual display mounted inside the HMD in real-time. By wearing an HMD, a user can look around the environment and in some cases, interact and move in the environment using two tracked VR wands (one for each hand). Using HMDs users are immersed in a virtual world that is completely disconnected from the real-world. Developers can create their immersive worlds and show it to the users using advanced graphic software such as Unity 3D. Current VR technologies are used in many applications such as training, medicine, 3D cinema, video games, etc.

One application of VR is in surgical training. Surgery is a critical task in which a small mistake might cause a very bad outcome. Moreover, surgical training requires apprenticeships that are expensive and not always available. For some part of the training, the trainees must watch the trainer operate on a patient and learn from viewing and repeating the experience, “See one do one teach one." Unfortunately, only a few trainees can be present in the operating room during surgery, limiting the number of surgeons one can train in a year. Additionally, for the trainees to learn the surgery, they need to perform the surgery on a real patient under the supervision of a professional surgeon. However, this comes with the chance of a patient getting injured or the procedure not done properly.

Due to all these reasons, there has been a shift towards using different technologies such as VR and robotics in surgeries. Using VR, one can create a simulation environment for the trainees to perform surgery and learn. The advantage of using VR is that, first, since it is a simulation, there is no risk of injury to the patient. Second, once the environment is developed, the only limit on the number of trainees who can train at the same time or who can watch a professional surgeon perform surgery is the number of equipments available. Moreover, VR can be used in surgical planning which allows the surgeons to practice the surgery, observe the outcomes, and plan for the surgery. Additionally, it can be used to measure the surgical skills of different surgeons and detect the surgeons who are mentally not prepared for the surgery or distinguish between experienced vs. inexperienced surgeons [19].

However, currently, VR technologies do not provide good enough haptics feedback to be convincing, especially for open surgery. Many of them do not provide haptic feedback at all. This is troublesome since haptic feedback is one of the main senses surgeons need to perform this task. Good haptic rendering can help us sense the texture of things and their temperature. It also helps us detect and manipulate objects in the absence of eyesight or reduced eyesight (e.g., in the dark). As a result, researchers have tried, especially in medical simulators, to add haptics feedback to the VR world to make the experience even more immersive and real. Some examples of haptic technologies include force feedback and proxy haptics objects. In the force feedback method, the users are required to grab a robotic arm. The robotic arm can then apply forces and restrict the movement of the user's hands and/or arms to give them the illusion of haptic feedback. For instance, it can provide force so that the users will not be able to move the robotic arm to give them the illusion that they have hit something solid and cannot get past it. Some examples of this approach are [18] and [5]. In proxy haptics on the other hand, real-world objects are used to give the users the haptic feedback. In this method, the objects are not necessarily the same as the virtual object displayed in the virtual world. They need to be close to that object. From a haptic viewpoint for example, one can create a box with the same weight as a personal computer case and use it as a proxy to its variation in the virtual world. An example of this approach is described in [25]. The advantages of this method are that first, the users do not need to hold on to a robotic arm and they have more freedom to move their hands. Second, it is relatively cheap as there is no need to use expensive robots to achieve haptic feedback.

1.2 Proposed System

In our proposed system, we explore further the concept of proxy haptics by having a mannequin as a proxy for a patient and an HTC Vive controller as a proxy for a syringe. We then tracked the movement of the mannequin/patient's right arm to make sure that it is synchronized with the virtual world. We also developed a virtual operating room and made sure that the bed, the syringe, and the patient are registered in the same coordinate systems. By adding real physical limitations, we expect the proxy haptic tasks to take longer than their VR counterpart as they are performed in the real-world. On the other hand, we expect the proxy haptic environment to be more believable and accurate. Finally, we devised some everyday tasks such as grabbing objects, moving objects, and pointing objects to test our hypothesis. We will discuss the procedure in the following chapters in more detail.

1.3 Thesis Structure

The rest of the thesis is organized as follows:

- **Chapter 2: Related Works**

  In this chapter, we will review the literature and discuss the works that are similar to our project in some aspects.

- **Chapter 3: Virtual Proxy System for Medical Training**

  In this chapter, we will explain how our system works, justify our design choices, and discuss the potential pros and cons of our proposed system

- **Chapter 4: System Testing for Simple Tasks**

  In this chapter, we will show the results of our experiments, compute various statistics on our data to test our hypothesis, and in the end, explain our results.

- **Chapter 5: Conclusion**

  This chapter is dedicated to summarizing our work and findings and explain what others can do to improve on the basis of our work.

1.4 Thesis Contributions

The contributions of this thesis are as following:

- Designing an experiment to test the speed of doing different tasks in the completely virtual world compared to the proxy haptics world

- Finding out which environment is more close to the real world in the eyes of the users

- Finding out the advantages and disadvantages of our system based on our experiment and responses to our questionnaire

Chapter 2

Related Work

When ones talked about VR, many people think that it only consists of an immersive experience disconnected entirely from the real-world. However, Milgram *et al.* [23] defines the concept of Mixed Reality described as " a particular subclass of VR related technologies that involve the merging of real and virtual worlds." Mixed reality is part of a "VR Continuum", a spectrum in which there are the real environment at one end and the virtual environment at the other end. Our work falls somewhere in between this spectrum as in our application; the virtual world is superimposed and registered to real-world objects. In this chapter, we will review briefly various techniques to create haptic perception and its applications to surgical training.

2.1 VR and The Sense of Touch

Many researchers have tried to come up with new ways to make the VR experience more real. In conventional VR devices, most systems focus on the senses of sight and auditory (i.e., as it is our dominant senses). Many commercial

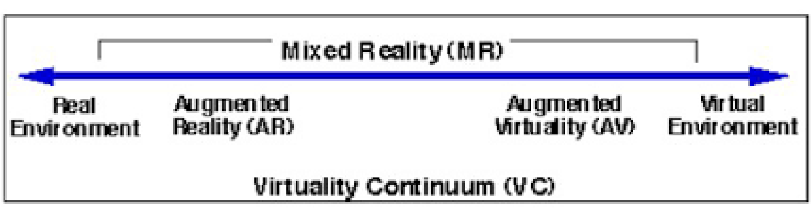

Figure 2.1: Milgram's Taxonomy [23]

systems such as Oculus (`www.oculus.com`) and HTC Vive (`www.vive.com`) have been developed based on those two senses only as they are easy to create realistic experiences. Very few systems have used the sense of touch (i.e., haptic feedback) to complement vision and audition.

2.1.1 Haptic Robot

One approach to creating haptic feedback is by having the user hold a wand-type object connected to a robotic arm that can provide forces generated by a haptic rendering algorithm. An example of this approach is described in [18] Massie *et al.*. In this system, users need to hold a stylus-like object allowing them to move and rotate objects in the virtual world. A force (using the robot's motors) is applied contrary to the direction of the to stylus to give the illusion that a solid object was touched. While it is a good way to provide haptics feedback in tasks where the user is required to hold a stylus-like object in a simulation, like an endoscope, but in general, these haptic systems are unrealistic, complex, and very costly. [15] talks about some of the haptic systems available today. One of the key limitations of those systems is that the users are bound to holding a stylus limiting his/her range of motion to the range of motion of the stylus, which is typically small. Although it is sufficient for some applications like minimally invasive surgery training where a robot is attached to an endoscopic tool, for most surgical procedures, these haptic devices cannot deal with the wide range of motion involved in open surgery. This is because, in most of those surgical haptic training systems, hands and fingers haptic rendering is not possible. For instance, you cannot get the haptic feedback of grabbing a scalpel.

2.1.2 Haptic Glove

To provide haptic feedback to hand and fingers, users must wear a device (often in the shape of a glove) that can provide forces to different parts of the hand or fingers. An example of this approach was developed by Bouzit *et al.* who have made a glove that can provide forces of up to 16 Newton (N) on each thumb, index, middle, and ring fingertips [3]. Blake *et al.* [1] introduced a

Figure 2.2: PHANTOM haptic device [18]

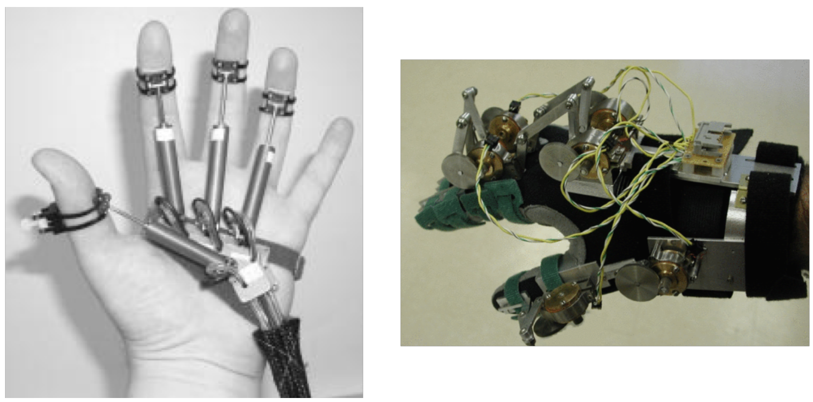

Figure 2.3: Wearable haptic devices
To the left is the glove developed by Bouzit et al. [3] and to the right is the MR brake glove [1]

glove weighing 640g which uses brakes to restrict the movement of the fingers and is capable of creating the illusion of holding an object. Although this approach doesn't restrict users like the wand-type system, there are some cons to this approach. First, the user is restricted from wearing a glove which may not be very light and comfortable to use. Second, the force is usually applied to single points on the hand, mainly the fingertips which means that the user can only get haptic feedbacks at their fingertips. This means that often, the users cannot get the feeling of touching something since the force is only applied to certain points on the hand and if the hand is fixed and the arm is moving from other joints (e.g., elbow), then they will not be able to get the feeling of touching something. Third, they cannot run their hands on a surface and feel the surface texture.

2.1.3 Proxy Haptic

Another way of providing haptic feedback is by using proxy haptics. In a paper published by Oskouie *et al.* [25] used proxy haptic for doing simple tasks such as typing. In this research, two ways of typing were compared against each other. One using a controller to select letters on a keyboard and the other touching a sponge attached to the wall, acting as a proxy to keys, and typing using the concept of proxy haptic. Their work shows that the users made fewer mistakes when using the proxy haptic for typing compared to using a virtual reality wand. The work of Simeone *et al.* [27] is another example of using proxy haptic. In this research, they created two different virtual worlds, a medieval room and a spaceship, based on a physical room. They tried to match the objects in the virtual world to the objects in the physical world with some degree of discrepancy. Their results showed the participants did not report mismatch if the parts of the object they were interacting with was close to the physical object. For example, if they were mostly going to interact with a handle on a box, as long as the handle in the physical world was close to the handle in the virtual world they did not report mismatch between those objects even if the other parts of those objects were not that similar. Figure 2.4 shows their developed environment. In another paper published by Henderson *et al.* [11] they use the concept of proxy haptic in an AR environment in which they use objects available in an environment to provide haptic feedback for interacting with the system. For example, in order to change the value of a virtual text box, they used the collar of an antenna connector. Their results showed that users could perform the tasks in their experiment faster than the baseline technique which was virtual buttons an UI elements projected on an undifferentiated surface.

2.2 VR Surgical Training

VR have be used in healthcare for the purposes of surgical training [7], [10], phobia treatment [14], [9], [2], surgery simulation [31], [17], and robotic surgery [28], [20]. Also, it is used for other educational and training purposes such

Figure 2.4: A VR environment using proxy haptic [27]

Figure 2.5: An example of using proxy haptics for typing [25]

as educational games, VR documentaries and videos, simulators (e.g., flight simulators) [30], [34]. Moreover, It is also used in entertainment such as video games, e-commerce, and movies in VR [16], [13]

VR can be used for surgical training to make this process cheaper, safer, and more accessible. Also, VR training has shown to improve performance in minimally invasive surgical tasks. In the work of Seymour *et al.* [26], virtual reality training for endoscopic surgery has shown to improve performance and abilities significantly. To demonstrate its effectiveness, they used a MIST VR system [33] where eight surgical residents used the system for training. All residents had access to the standard programmatic training (ST) before. For comparison, another eight surgical residents who only had access to ST training but not VR were chosen. For the VR training, they asked four surgeons to complete ten trials on MIST VR trainer and then trained the trainees using those trials as the criterion level. After both groups were trained they were asked to do laparoscopic cholecystectomy under an expert surgeon's supervision. The surgeon was unaware of the group the trainee belonged to. The surgery was videotaped and later, a team of surgeons reviewed the videotapes to determine the number of errors and the type of errors each person had made. After gathering the data, they did statistical testing for both groups and realized in some aspects that the VR trained group did better. For instance, Gallbladder dissection was 29% faster for VR-trained residents and they were less likely to injure the gallbladder.

In another research, Fried *et al.* [6] have shown that using a virtual reality endoscopic sinus surgery simulator can improve performance significantly. They studied the effects of endoscopic sinus surgery simulator (ES3) manufactured by Lockheed Martin, Inc (Akron, OH). Using this system, the trainee can navigate in the virtual world and explore the anatomy of the virtual patient. The system also helps the trainee to learn by giving some cues and navigation aids. The trainees' mistakes were shown to them by the virtual instructor. Moreover, the task completion time and the overall performance of the trainees relative to an optimal model were measured. If the trainees took excessive time to complete a task or disrupt surgical hazards, they were notified and the system imposes some penalties. Their results showed that the task completion time was lower for the participants who used the ES3 system. Also, they had higher confidence in manipulating the instrument and made fewer mistakes.

Gal *et al.* [8] studied the effectiveness of the haptic simulator IDEA (`https://www.3dsystems.com/scanners-haptics/application-gallery/idea`) which provides a VR environment with haptic feedback using the Phantom Omni haptic interface. They divided their participants into two groups. The first group was composed of dentists who also served as teachers and the second group consisted of randomly selected fifth-year dental students. Using this system, they asked their participants to do drilling tasks on different surfaces. The tasks consisted of drilling a straight line, drilling a circle, drilling a straight line using a mirror, deformed heart shape, and a rectangle. After the experiments, they asked the participants to fill out a questionnaire asking about the usefulness of the system. They realized that both groups ranked the usefulness of the system positively with students rating the system higher than the teachers. This study also showed that both teachers and students think that using a VR system with haptic feedback is potentially helpful in dental training.

Additionally, in an experiment conducted by Broeren *et al.*, they showed that using virtual reality alongside haptic feedback in training can improve motor rehabilitation [4]. In their research, they asked the patients to play a computer game in VR with haptic feedback, provided by PHANToM haptic device, in easy mode. In that game, the users was supposed to hit a ball at some bricks and get points for knocking them down. The difficulty level was increased when the patient reached a particular score. Then they used three tests and a subjective interview to measure the patient's performance in three different phases: 1) pre-training (baseline) 2) post-training and 3) after a 20-week follow up. The first test was the Purdue pegboard test in which the movement of arm, hand and finger in addition to finger dexterity are measured. In the second test, they measured the hand gripping strength and in the third test, they measured the upper-extremity movement. As a reference point, they asked nine healthy men to do the same test. In the end, they saw a significant improvement in the subject's dexterous skills. For instance, they realized the result of the first test was improved by 11% at the end of the training continued to improve to 22% at follow-up. The results of the second test improved to 22% from baseline after the training and did not change much at follow-up. The mean-grip force was also increased from 13% of the grip force in the reference points to 57% at follow-up. This research is one of the few research that shows the benefit of virtual reality in health and rehabilitation. Using haptic feedback takes virtual reality closer to reality.

Using a stylus for haptic feedback does not give the user the freedom to move their fingers freely. Hence, using another type of haptic feedback (like proxy haptics or haptic gloves) might make the experience more real and provide better results after the training.

In this chapter, we discussed a few papers which have used VR with or without haptic feedback to test its effect on training. However, haptic is a vital part of these types of systems especially for surgical training. Okamura [24] discusses the need to introduce creative solutions to provide force feedback and tactile perception. As a result, we tried to add an affordable, accessible, and easy to build a system that can provide haptic perception. In the next chapter, we will discuss the components of our proxy haptic approach and explain how the proposed system works.

Chapter 3

Virtual Proxy System for Medical Training

In order to be able to test our hypotheses, we developed two systems; one completely virtual and the other one with the proxy haptic feedback. In this chapter, we will describe our developed systems and give justifications for our design choices.

3.1 Proposed System Architecture

3.1.1 Proxy Haptic System

As illustrated in Figure 3.2, the input from user interaction with the HTC Vive trackers and controllers is transferred to the computer running the simulation. SteamVR (`https://store.steampowered.com/steamvr`) captures that data and the data is transferred to Unity where the positions and orientations of the HTC Vive trackers and controllers are updated in Unity. Next, RootMotion (`http://root-motion.com/`), an inverse kinematics Unity plugin, uses the position of the HTC Vive trackers that we are using as the end-effectors of the right hand and updates the orientation of different joints. Finally, the change in geometry is updated in the system and rendered. For the VR glove interaction, the input from the gloves is sent to the Noitom Hi5 Unity plugin. Using that input from the plugin and the position and orientation of the HTC Vive trackers attached to the gloves, the hand's position, and orientation are updated in Unity and then rendered. One can see in Figure 3.1 a high level diagram of the architecture

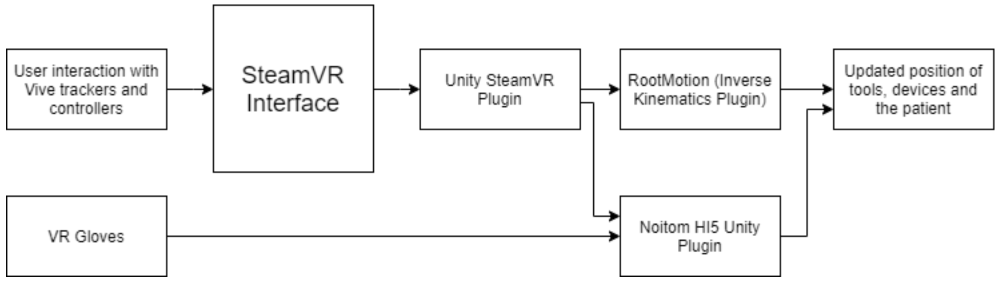

Figure 3.1: Proxy Haptic System Architecture

Figure 3.2: Proxy Haptic System

3.1.2 Virtual Reality System

For the virtual reality system, we used the same environment as the system with the proxy haptic feedback. However, the difference was that since this was a completely virtual system, the users only interacted with the HTC Vive controllers and used them to grab and move objects. As in Figure 3.3, once the users grabbed an object in the virtual world, the position of that object was updated in Unity based on the position of the controller as long as the users were holding the grab button on the controller. For the case of moving the patient's arm, we created a virtual object in unity and used it as an end-effector for RootMotion. The users were in reality moving the end-effector object but what they saw was the patient's arm being moved with the movement of the controller. Figure 3.4 shows how our system looks like.

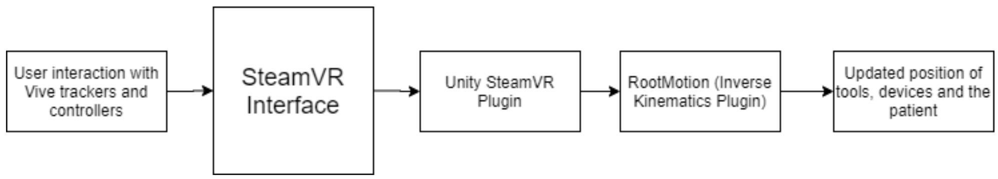

Figure 3.3: Virtual System Architecture

Figure 3.4: Virtual System
The user did not have any interactions with the mannequin in this scenario. The mannequin can be seen in the picture due to our lack of space.

3.1.3 Integration with Unity 3D

To integrate our system with the virtual world, we used the available SDKs for HTC Vive and Noitom Hi5 VR gloves. By using the HTC Vive SDK, we were able to see the position and orientation of the trackers and the controllers. The Noitom Hi5 VR gloves SDK allowed us to see an avatar of the hand in Unity as well as the movement of the fingers. It also enables the user to be able to grab objects in the virtual world. For inverse kinematics, we used the RootMotion library available on the Unity asset store. This library provides many different components and codes to implement the inverse kinematics. Finally, we manually synchronized the mannequin and the patient to make sure that their body parts are the same size and are in the same position. However, we could not do this correctly since the patient model was not a 3D scan of the mannequin and naturally, they were not precisely the same in shape.

3.2 Optical Targets Tracking System

3.2.1 System Configuration

For the VR headset, we used HTC Vive. There were a few reasons for our choice. First, it is a high-quality headset, and the base stations do a good job of tracking the headset and the controllers. Second, HTC Vive offers trackers that can be attached to objects to track them and see them in the virtual world which was a crucial part of our project. We needed to be able to track the position and orientation of objects such as hands (gloves), syringes, and the mannequin's hand and HTC Vive trackers provide this feature.

For the proxy haptics part, we used the real-world objects of the one seen in the virtual world, mainly the ones that were going to be interactable. For the syringe, we used an HTC Vive controller since it already was being tracked (i.e., we did not need additional trackers) and because of its shape proximity to a syringe. The mannequin that we chose can be moved from most of its joints. Although it does not offer the same degrees of freedom as an average human, its body parts can be moved in various angles similar to its human counterpart. Also, since we wanted to have the ability to move the right hand of the mannequin, we had to provide a way to track the movement of the hand in VR to make sure that the movement of the hand in the real world and VR are approximately the same. For this purpose, we used an inverse kinematics approach. We attached an HTC tracker to the right hand of the mannequin to use it as a target for inverse kinematics. We will provide more details on this in the following chapters. For the interaction part, we used Noitom Hi5 VR gloves (`https://hi5vrglove.com/`). These gloves allow the user to see their finger movement in the VR world. Also, they can grab objects in VR using these gloves.

3.2.2 Dealing with Occlusion

Before using HTC Vive and HTC Vive trackers, we tried a different method. We tried using Optitrack motion capture (`https://optitrack.com/`). The idea was to set up the Optitrack motion capture cameras and track the objects that we wanted using passive markers. Passive markers, unlike active markers, do not emit radio waves. Instead, they are coated with a material that reflects waves (usually infrared waves) that can be easily detected by 12 cameras. The motion capture software by receiving the data from cameras will recognize these markers. After that, it can do some other processing to capture a rigid body or a skeleton movement. Initially, we were thinking of using the skeleton tracking approach. In this approach, a human or a humanoid model wears a black suit and with markers attached to specific locations. After defining the skeleton using the software, the model does a particular pose with their hands raised by their side (also known as a T-pose) and then the software would start tracking their movement. However, we could not do the T-pose with our mannequin since It could not do a T-pose by itself.

Moreover, we wanted to use our mannequin in a sleeping position while the skeleton approach is more for a standing position. Therefore we decided to use inverse kinematics instead and define rigid bodies as the targets of the inverse kinematics. Using the optical tracking system, the markers could get occluded easily and therefore, and occlusion turned out to be a big problem. In our case, occlusion of a marker could cause in change in the rotation or position of the rigid-body or not transmitting any of the rigid-body data. Moreover, it often caused the movement of the objects to not be smooth. Due to all those issues and since we only needed a few Targets to be tracked (mainly for the user's hands and the mannequin's right arm), we decided to use HTC Vive trackers for that purpose and the fact that we found it to be more smooth and more accurate.

One of the biggest problems with optical tracking is occlusion, but fortunately, there are ways to deal with that. A very well-known approach for these types of problems is Kalman filters. Kalman filter is an approach introduced by RE Kalman in 1960 [12]. This algorithm is very useful when we cannot measure something directly but an indirect measurement is available or when there are multiple sources of measurement and we want to combine all of them. It uses different known attributes of the system (e.g. system's dynamic model) to estimate its future state and deal with the noisy data. It gets a weighted average of the system predicted state and the new measurement [32]. For example, if we want to measure the position of a VR controller, we have a data from the base stations for the controller's position. However, due to occlusion we cannot trust this data very much. Therefore, for each measurement we can show the position as a Gaussian distribution with a mean and a variance and the actual value can be anywhere in the distribution but it's more likely that it is located in the mean. In addition to that, we have a model of the system using data such as velocity and/or rotation of the controller calculated by some sensors inside the controller. Using that model we can get the estimated position at a given time step. However, that is also not accurate since there are many more variables and our measurements might not be completely accurate. Using this measurement we can also get an estimation of the controller's position at a given time step. This estimation also has a Gaussian distribution. The Kalman filter then combines the two distributions, the one from the base stations and the one from our model of the system, by multiplying them and gives us an optimal estimate of the actual position of the system with less noise.

3.3 Registration Algorithm Between the Virtual and the Real-World

3.3.1 Skeleton Approach

As mentioned earlier, in this approach, a person wears a black suit and attach passive markers to specific parts of the body. The marker configuration is not symmetric because, in this case, it would help the system figure out left and right. After they have attached the markers to the specific parts, they can do different poses such as T-pose in which the person stands straight with their arms raised to their shoulder level and are parallel to the ground. After that, if the cameras can see all the markers, by using the software one can create a skeleton. After that, when the person moves, the movements are mirrored in the skeleton as well. In the end, a 3D model can be added to the skeleton to create a humanoid animation for a specific model. Some applications of this method are creating humanoid animation in video games or creating animation for a CGI character in a movie. The Figure 3.5 shows an example of skeleton tracking in Optitrack Motive.

3.3.2 Inverse Kinematics Approach

Inverse kinematics is somewhat opposite of forward kinematics. In forward kinematics, one has the angles of each joint in a robotic arm and by knowing the angles, one can calculate the end-effector (the end of a robotic arm which can interact with the world) of the robotic arm. However, inverse kinematic has information about the end-effector position and has to calculate the angles of each joint so that the end-effector would end up at the given position. For instance, in our case, the robotic arm is the arm of the mannequin. To transfer the movement of the hand to the real world, one can either calculate the angles at each join (e.g. elbow) or attach a tracker to the hand and use inverse kinematics to calculate the angles of each joint. Fortunately, we found a library in Unity Asset Store which receives the position of the end-effector,

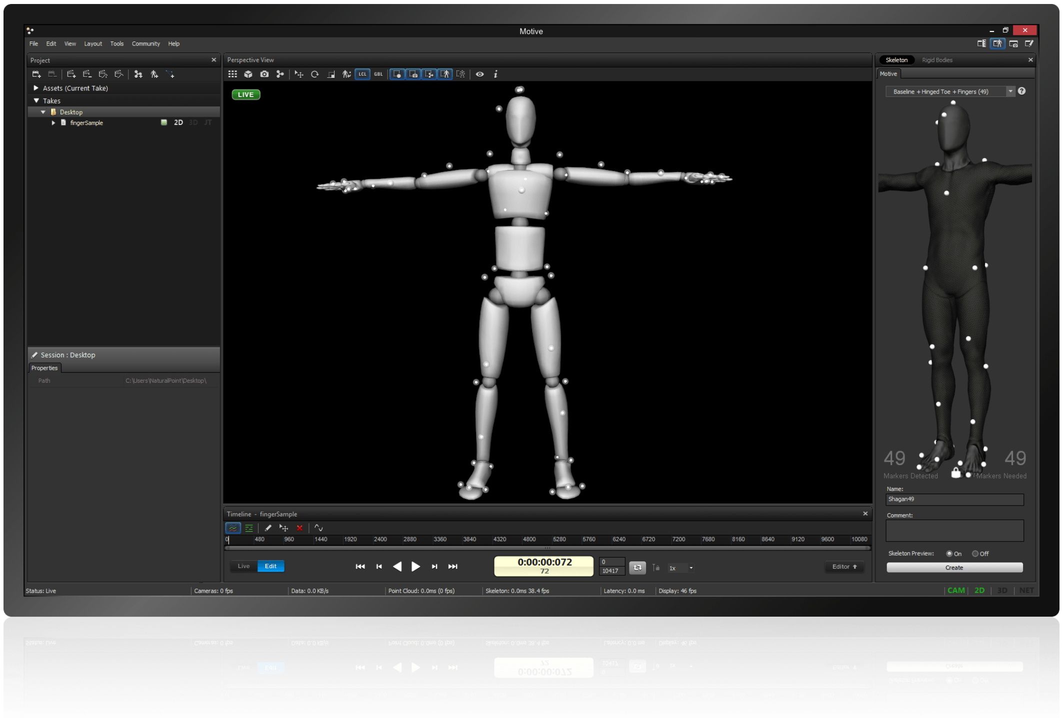

Figure 3.5: Optitrack skeleton tracking

in our case the HTC Vive tracker attached to the hand, and some parameters and animates the movement of the arm of the patient so that the hand would end up at the given position.

If we wanted to use forward kinematics, we had to figure out the angles between each joint in the arm. To do that, we had to assign two trackers for each joint and calculate the angle between those two trackers. As a result, we needed at least four trackers for the arm whereas with inverse kinematics, we only needed one or two. Not only was forward kinematics more expensive and less feasible, we believe in our case, it was more error-prone. For instance, a slight change in the position of one tracker in the shoulder could cause a huge movement in the arm. Moreover, in our experiment, we mostly cared about the end position of the hand since one of our tasks was to grab the arm and place the hand at a given target. Due to the nature of inverse kinematics, the position of the hand was more accurate than the forward kinematics approach.

3.3.3 Optimization of the Inverse Kinematic Parameters

To measure the degree of registration between the proxy and its VR equivalent, we attached two markers to the end of our tables, and using Unity methods found the distance between those markers in the virtual world. Then, we measured the actual distance between those two markers in the real world. The distance between the two sample markers in Unity was 174 cm, and the measured distance was in reality: 176 cm, in Unity, each world unit was calibrated to 1.01 m. To optimize our parameters, the first thing that we needed to do was to develop a method to get the error between the position of our markers in the real world and their corresponding positions in the virtual world. For this purpose, we attached markers to the shoulder, elbow, and arm of the mannequin. We only did this for the right arm. Then we created virtual markers in unity and made sure that their starting position match the real markers. We also made sure that those markers are positioned relative to the arm so that their positions are fixed relative to the arm of the mannequin. Then we moved the arm of the mannequin and measured its attached markers' positions in Unity. We then recorded 8 of those positions as our sample position which we plan to use later to calculate the error.

Having some sample positions for our IK and the corresponding elbow and shoulder marker position for each of those IK positions, we iterated through our samples and got the average error. The way we calculated the average error was that we calculated the average distance errors between real and virtual markers for all the markers for sample ith (e_i), and then got the average over all of those e_i for all the 8 samples. Next, we initialized the 10 IK parameters randomly and used a gradient descent approach to find a set of parameters that give us the minimum error. For each set of parameters, we calculated the gradient for each parameter and changed the parameters in the opposite direction as the gradient multiplied by a small step size. Using this approach we could find a local minimum, but in order to increase our chances of arriving at a global minimum we ran the optimization several times, each time with

randomly initialized parameters. In the end, we chose the set of parameters that gave us the lowest error overall. Figure 3.6 shows an example of our run. As you can see in this figure, the average error was decreased overtime and was probably converging to a local minimum.
Although the algorithm seems to be straightforward on paper, it wasn't easy to implement in Unity. The reason for this is that since we were dealing with Unity we had to do some calculations in each frame, then wait for the next frame to update position arm based on our changes in the last frame. As a result, we couldn't have a single function do all the calculations and we had to write our algorithm in a way that in each frame a part of it executed.

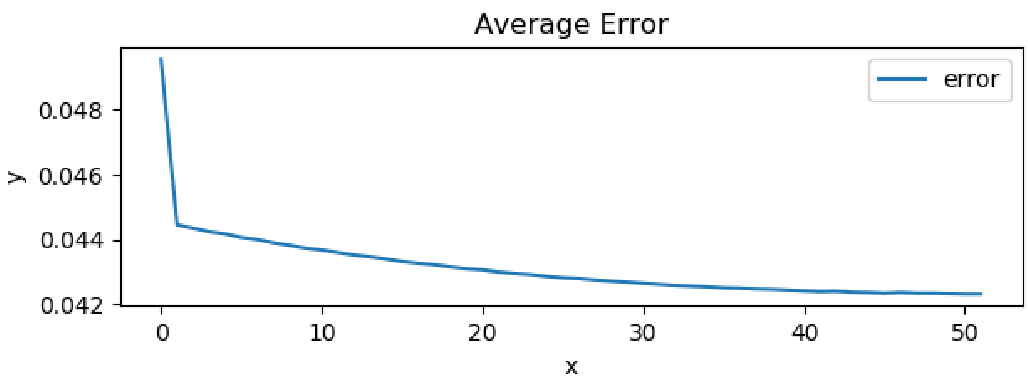

Figure 3.6: The average error of the Inverse Kinematics over time
x axis is the number of trial and y axis is the average error in Unity metrics, with 1 in Unity metrics being almost the same as 1 meter, for each trial

3.4 Hand, Head, and Tool Tracking

As we discussed before, we tried two systems to measure the positions and orientations of hand, head and tool tracking: Optical hand tracking and HTC Vive. We will discuss them below.

3.4.1 Optical Hand Tracking

As discussed previously, we started to use optical markers to track hand, head and tools. For this system, we attached markers to our HMD and tracked its position using the markers instead of its base stations. In this case, the occlusion of markers caused sudden jumps which might have made the users nauseous. For tracking hands and tools, we placed multiple markers on each of them and defined rigid bodies. Rigid bodies are a set of markers (minimum three markers) that have the same distance between each other (i.e., they are stationary relative to each other). Then we can get the position and rotation of a rigid body in Unity and update hands or head position based on the position of the rigid body. The problem with this approach, other than having to write code to deal with occlusions, was that we could not track fingers. The gloves that we had (Noitom Hi5 gloves) only worked with HTC Vive trackers. To track fingers solely using markers, we had to place at least three markers at the tip of each finger. Not only was this not very convenient to use, but it also would have made us place the markers very close to each other which could have resulted in the system identifying multiple markers and one large marker. Figure 3.7 shows an image of the early version of our gloves. The white spheres are the markers used for tracking.

Figure 3.7: The first version of our hand tracking made using Optitrack tracking system

Figure 3.8: The proxy haptic system
The hand in the virtual world is the same as the user's hand in the real world. In this image, the user was lifting the hand of the mannequin which they viewed in the VR world as patient.

3.4.2 HTC Vive with Gloves

In this approach, we used the already built-in functions and plugins of HTC Vive to be able to update the position of the HMD and the controllers. To track the tools, we attached HTC Vive trackers to them, which is in a sense, a rigid body to their system. For tracking the hands, we ordered Noitom Hi5 gloves which uses pressure sensors for each finger to do the finger tracking. For tracking the position and orientation of the hand, it relied on HTC Vive trackers. Although HTC Vive trackers could still get occluded, the nice thing about them was that they already had some algorithms to deal with the occlusion and make the movement of the objects smooth and without sudden jumps.

3.5 Discussion

We tried our best to make the best decisions in our view for each part of the project. However, that does not mean that our system does not come with issues. There were many trade-offs in our system, and another person could have argued reasonably to take another approach. For us, ease of use, availability, and cost of tools and technologies played a big part in our decisions. For instance, we used HTC Vive which used an optical tracking system to track objects. However, this is not the only way of tracking objects. Another way to track objects is by using magnetic tracking [21]. The good thing about magnetic trackers is that they do not get occluded. On the other hand, they usually do not provide as much freedom of movement as optical tracking systems. Another issue was that, as discussed previously, our patient in the virtual world was not the exact replica of our mannequin and this caused the 3D model and the mannequin not being 100% alike. Also, even though our mannequin provided human-like movement in many of its joints, its movement was limited and it did not have the freedom of an actual human. Moreover, our mannequin was made of hard plastic and while it provided haptics feedback, it did not provide the feel of touching actual skin. One could use a more expensive model of a medical mannequin to make the experience even more immersive and closer to reality.

In general, our system provides an easy to use and develop, cost-effective, and simple way of adding a sense of touch and haptic feedback to a medical training applications in the VR world.

Chapter 4

System Testing for Simple Tasks

In our research, we introduced two hypotheses that must be tested. Due to the reason that we wanted to test our hypotheses under different settings, we devised three different experiments that were everyday operating room tasks; 1) Moving the avatar's hand to a specific location on the chest 2) Surgical tool manipulations with a fixed arm location 3) Ambidextrous Surgical Tool Manipulation. Each task consisted of 5 practice trials followed by 10 experiment trials. For each of these tasks, we had the following hypothesis to verify:

1. **H1:** The time to do each part of the task is longer when using the system with proxy haptics than with VR controllers.

2. **H2:** The proxy haptics system is more believable in terms of being closer to reality.

To test these hypotheses, each of those tasks was done by using proxy haptics and standard VR controllers. Also, since using the right hand or the left hand might have added a difference in the results, we decided to do each experiment with both hands. In the end, each task was done four times; **p_right** (proxy haptics with the right hand), **p_left** (proxy haptics with the left hand), **c_right** (controller with the right hand), and **c_left** (controller with the left hand). We randomized the order of these settings for different participants to reduce the learning effect on our results. Then depending on the order for each participant, we asked them to do the different parts of the experiments. In the end, we asked them to answer a questionnaire about some general questions on participants' information such as their age and their hand dominance and some questions about their experience with different tasks both using proxy haptics and controllers.

In our experiment, since it was a pilot test, we had only 12 participants (8 men and 4 women) all students at the University of Alberta, Computing Science Department aged between 23 to 33 (M=26.6; SD=2.6) all of whom saw in stereo. When asked about hand dominance 11 of them indicated that they are right-dominant and 1 of them indicated that they are left-dominant. For the question asking "how often do you play video games", 2 of them indicated that they play video games often, 7 indicated that they play sometimes, and 3 indicated that they never play video games. Moreover, 3 of our participants wore glasses.

Since we had 12 participants, and each task had 10 trials, we had 120 time-data for each task for each different setting. To find outliers in our data, we used the interquartile range method [29]. In this method, we compute the median, the 25th percentile, and the 75th percentile of the 120 data points. Then we subtracted the 25th percentile from the 75th percentile to find the distance between them. Next, we multiplied that distance by 1.5 and added that to the 75th percentile and also multiplied the distance by 1.5 and subtracted it from the 25th percentile. We removed any data that was not in this range and call them outliers. For each section we report the number of data points after we removed the outliers. Since for each task we initially had 120 data point, the difference between those numbers indicates the number of outliers we had for task.

In the end, we analyzed the remaining data by finding the Normal and Gamma distributions with the best parameters using the Python Scipy library (`https://www.scipy.org`). Next, we used the distributions found and did a Kolmogorov-Smirnov test and chose the distribution with the best p-value as the distribution over our data. In the end, we ran an unpaired t-test to compare the speed of using the controller vs. the proxy haptics system. If the best distribution found in any part of the research was Gamma distributed, then we got the mean and STD from the distribution using the Python Scipy library and performed the t-test using the means and STDs. In the following sections, we discuss the results for each part of the tasks in more detail.

4.1 Task 1: Moving the Avatar's Hand to a Specific Location on the Chest

4.1.1 Description

In each trial, the participants were supposed to stand at a certain starting location shown in the virtual world (Figure 4.1). Then upon giving a signal by the experimenter, a timer started, a target appeared the patient's right thigh, and the participants started moving towards the patient. Next, they grabbed the patient's arm and moved it to make the thumb of his right hand touch the target. After that, the target disappeared, and they were told to move back to the starting position for the next trial. In this task, we measured the time between different parts of the experiment shown in Table 4.1. All times were measured automatically in Unity. Figure 4.2 shows the physical environment and the virtual environment for both VR controllers-only and proxy haptics settings.

Figure 4.1: Starting position in the virtual world
You can see that the participants can see their shoes.

ID	Description
experiment1_time_to_grab_arm	The time between the start of the trial (i.e. the time when the signal is given to the participants) and the time the participants touch the patient's arm
experiment1_time_to_move_arm	The time between the end of experiment1_time_to_grab_arm and the time the patient's right thumb touches the target on their thigh
experiment1_time_to_return_arm	The time between the end of experiment1_time_to_move_arm and the time the patient's arm is placed on the bed on its original position

Table 4.1: Experiment 1 measured times

4.1.2 Results

Grabbing the Arm

For experiment1_time_to_grab_arm, the best distribution found for c_left and p_right was Normally distributed with p-value 0.1325 and 0.7789 respectively. For c_right and p_left the best distribution found was Gamma distributed with p-value 0.7796 and 0.9779 respectively. The results are shown in table 4.1.2.

Since the p-value for c_left is below 0.5, we only do the comparison using unpaired t-test for the right hands. Since c_right does not have a Normal distribution we calculated the mean and STD using the Python Scipy library. The calculated mean and STD for c_right was 1.2193 and 0.3667 respectively. Figure 4.3 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

After running unpaired t-test, our p-value was 0.0031 (a=0.05, t = 2.9919, df = 237, standard error of difference = 0.050) and therefore, based on our

Figure 4.2: Experiment 1 physical and virtual environments
Top left is the participant doing the task using proxy haptics. Top right is what the participant sees when using proxy haptics. Bottom left is the participant doing the task using controllers. Bottom right is what the participant sees when using only controllers

results, in this part of the task, the system with proxy haptics (using the right hand) is slower than the VR Wand system (controller with the right hand).

Moving the Arm

For experiment1_time_to_move_arm, the best distribution found for c_left, p_left, and p_right was Gamma distributed with p-value 0.7704, 0.4425, and 0.9563 respectively. For c_right, the best distribution found was Normally distributed with p-value 0.6550. The results are shown in table 4.1.2.

Since the p-value for p_left is below 0.5 we only do the comparison using unpaired t-test for the right hands. Figure 4.4 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution,

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Normal	0.1325	1.2393	0.4080	0.1014	263.6384	0.0253	120
c_right	Gamma	0.5839	1.2193	0.3616	0.7796	13.0656	0.1015	120
p_left	Gamma	0.8945	1.4169	0.3651	0.9779	127.3759	0.0323	120
p_right	Normal	0.7789	1.3702	0.4119	0.3273	26.9014	0.0799	119

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.2: Experiment 1 Grabbing the Arm

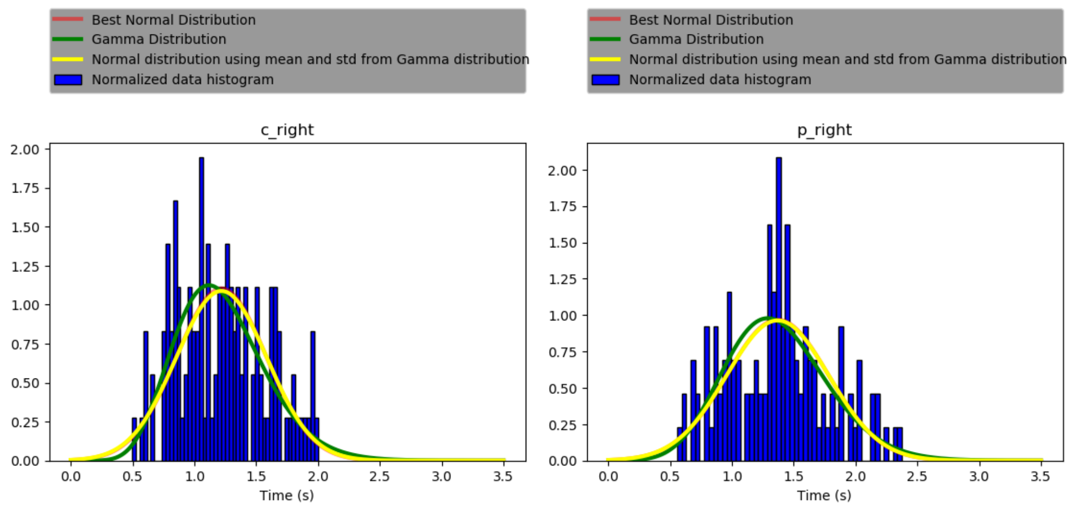

Figure 4.3: Grabbing the arm plots

and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

After performing unpaired t-test our p-value was less than 0.0001 (a=0.05, t = 9.9260, df = 214, standard error of difference = 0.060) and therefore, based on our results, in this part of the task, the system with proxy haptics (using right hand) is slower than the VR Wand system (controller with right hand).

Returning the Arm

For experiment1_time_to_return_arm, the best distribution found for all the settings was Gamma distributed. The results are shown in Table 4.4. In this case, the best p-value for all of them is above 0.5 and therefore we will do the t-test for both the left and the right hands. Figure 4.5 shows the

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Gamma	0.3615	0.8217	0.2630	0.7704	3.0295	0.1611	115
c_right	Normal	0.6550	0.8002	0.2148	0.5979	2.4679	0.1488	107
p_left	Gamma	0.1374	1.4245	0.6611	0.4425	1.8480	0.5086	113
p_right	Gamma	0.1853	1.4003	0.5709	0.9563	3.4553	0.3164	109

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.3: Experiment 1 Moving the Arm

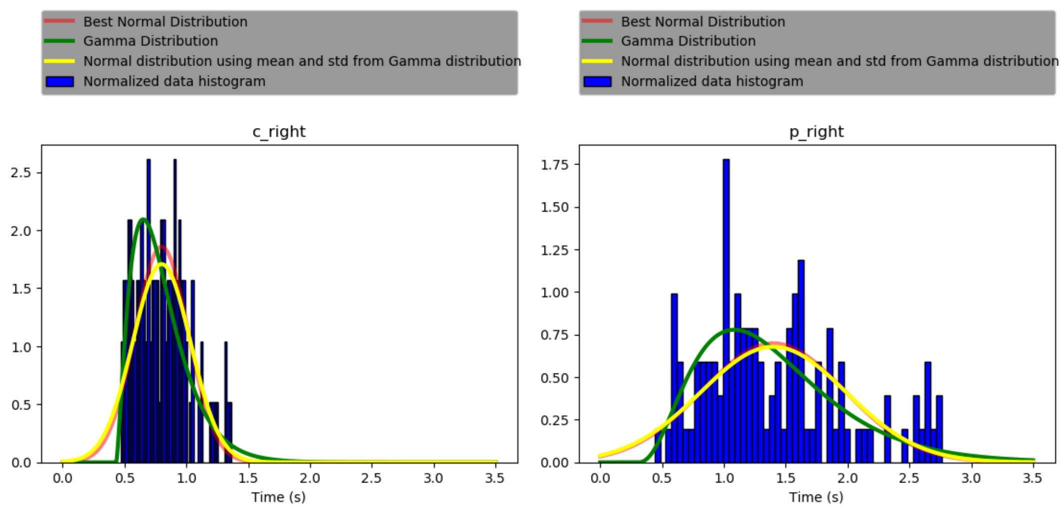

Figure 4.4: Moving the arm plots

histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

After performing unpaired t-test for the left hand, our p-value was 0.0021 (a=0.05, t = 3.1141, df = 231, standard error of difference = 0.028) and therefore, based on our results, in this part of the task, the system with proxy haptics (using left hand) is slower than the VR Wand system (controller with left hand).

The p-value for the t-test for the right hand settings was 0.1413 (a=0.05, t = 1.4764, df = 210, standard error of difference = 0.026) and therefore our hypothesis gets rejected in this scenario.

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Gamma	0.1377	0.6502	0.1968	0.8170	5.1704	0.0877	118
c_right	Gamma	0.0314	0.6638	0.2104	0.5585	4.5355	0.0992	112
p_left	Gamma	0.1733	0.7369	0.2176	0.7451	3.1650	0.1264	115
p_right	Gamma	0.4760	0.7026	0.1650	0.5187	14.6265	0.0432	100

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.4: Experiment 1 Returning the arm

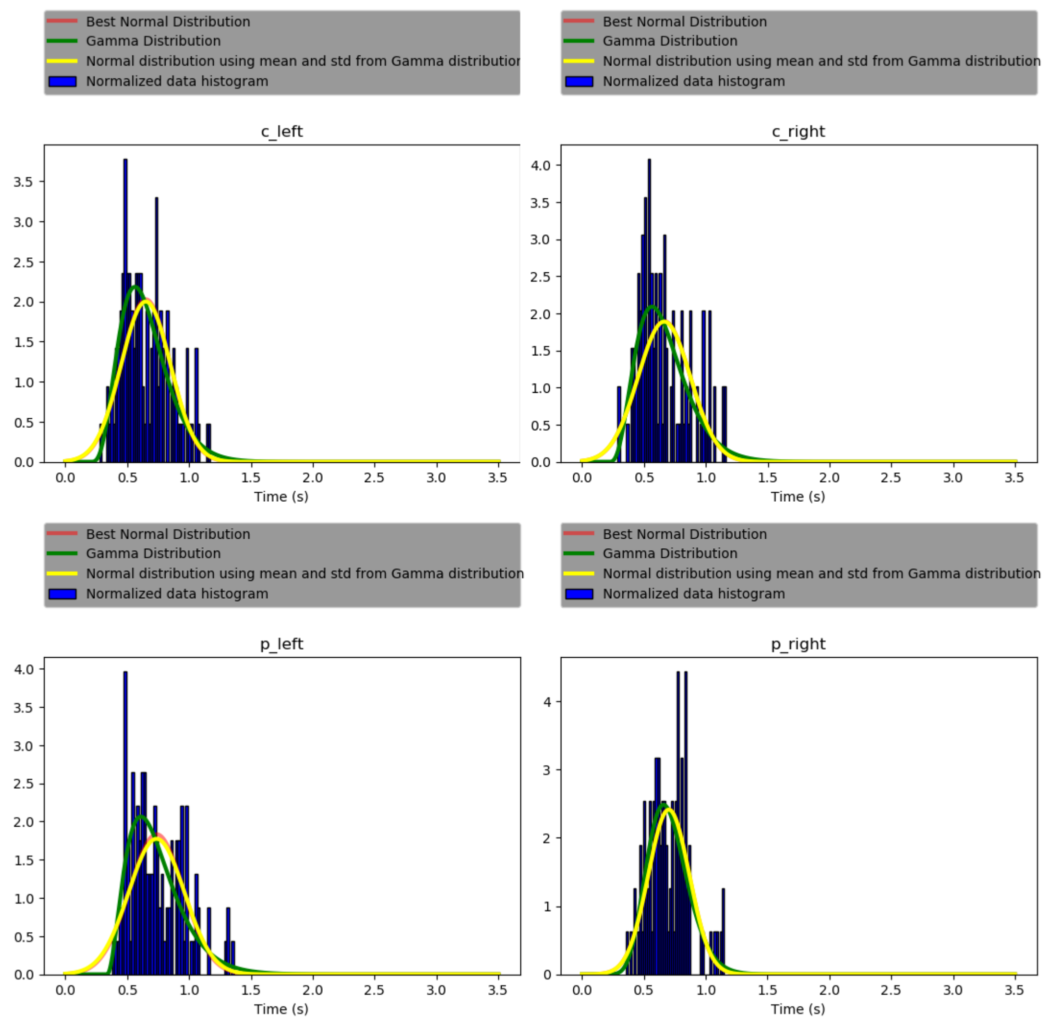

Figure 4.5: Returning the arm plots

ID	Description
experiment2_time_to_grab_syringe	The time between when trial starts (i.e. the time when the signal is given to the participants) and the time the participants touch the syringe
experiment2_time_to_move_syringe	The time between end of experiment2_time_to_grab_syringe and the time the tip of the syringe touches the target on the patient's right arm
experiment2_time_to_return_syringe	The time between the end of experiment2_time_to_move_syringe and the time the syringe is placed on the bed

Table 4.5: Experiment 2 measured times

4.2 Task 2: Surgical tool manipulations with a fixed arm location

In each trial of this task, we asked the participants to stand at a certain starting location shown in the virtual world. Then we gave them a signal and started the timer and the experiment. Upon hearing the signal, they were asked to move towards the syringe on the bed and grab it. Next, they were asked to make the tip of the syringe touch a certain target on the patient's right arm. The position of the target was different for each trial. Upon contact with the tip of the syringe and the target, the target disappeared. The participants were told to put the syringe back to its original place, shown in the virtual world. In the end, the participants were told to move back to the starting position and get ready for the start of the next trial. In this task, we measured the time between different parts of the experiment shown in Table 4.5. All times were measured automatically in Unity. Figure 4.6 shows the physical environment and the virtual environment for both controllers-only and proxy haptics settings.

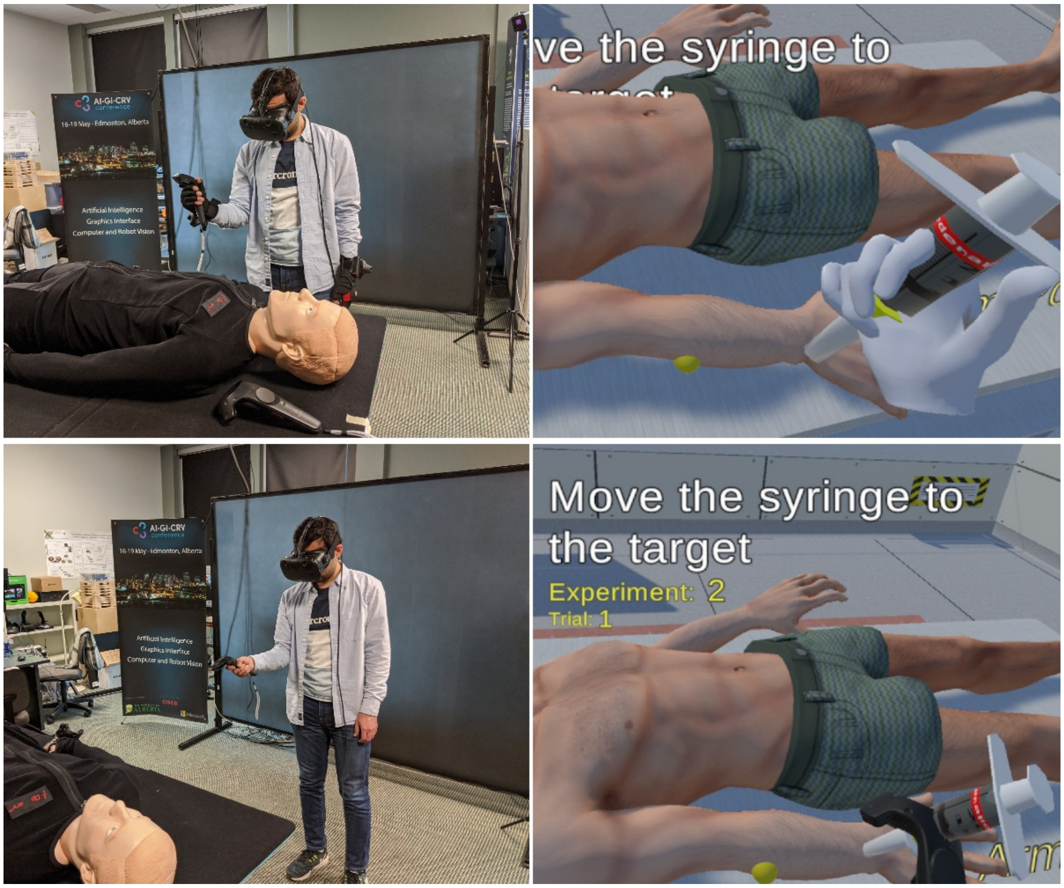

Figure 4.6: Experiment 2 physical and virtual environments
Top left is the participant doing the task using proxy haptics. Top right is what the participant sees when using proxy haptics. Bottom left is the participant doing the task using controllers. Bottom right is what the participant sees when using only controllers

4.2.1 Results

Grabbing the Syringe

For experiment2_time_to_grab_syringe, the best distribution found for c_left was Normally distributed with p-value 0.4181 . For c_right, p_left, and p_right the best distribution found was Gamma distributed with p-value 0.8982, 0.6206 and 0.9595 respectively. The results are shown in Table 4.6. since the p-value for c_left is below 0.5 we only do the comparison using unpaired t-test for the right hands. Figure 4.7 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Normal	0.4181	1.2258	0.4001	0.3705	1871.9184	0.0093	119
c_right	Gamma	0.5145	1.2240	0.3465	0.8982	24.7096	0.0700	119
p_left	Gamma	0.0762	1.3523	0.4289	0.6206	8.0061	0.1537	120
p_right	Gamma	0.6240	1.4208	0.4237	0.9595	29.9926	0.0775	120

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.6: Experiment 2 Grabbing the syringe

distribution.

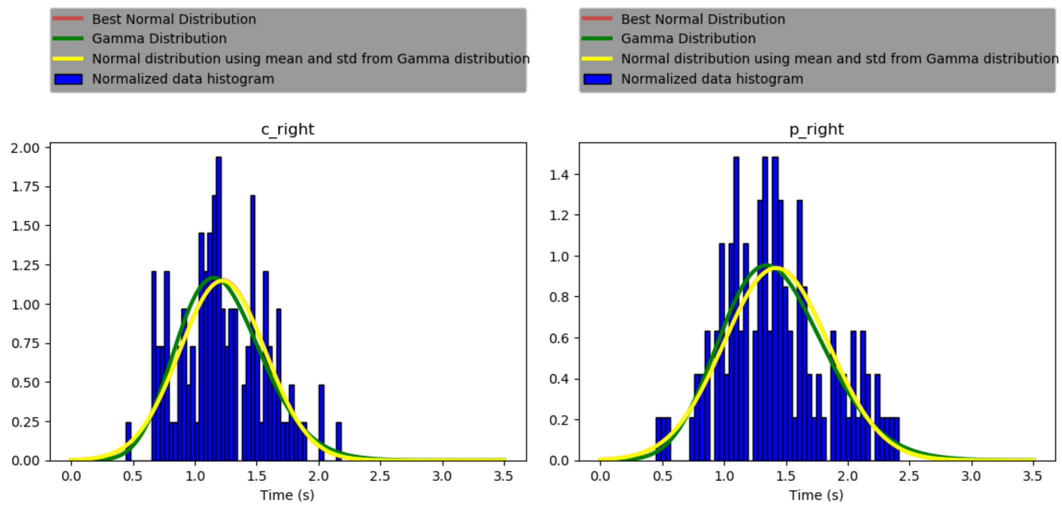

Figure 4.7: Grabbing the syringe plots

After running upaired t-test for the right hand setting, our p-value was 0.0001 (a=0.05, t = 3.9172, df = 237, standard error of difference = 0.050) and therefore proxy haptics system using right hand is slower than using the controller with right hand for this part of the task.

Moving the Syringe

The best distribution found for experiment2_move_syringe for c_left was Normally distributed with p-value 0.8067 . For c_right, p_left, and p_right the best distribution found was found to be Gamma distributed with p-value 0.9965, 0.9971 and 0.9114 respectively. The results are shown in Table 4.7. Figure 4.8 shows the histogram of the data, PDF of the best Normal distribution, PDF

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Normal	0.8067	0.9474	0.2802	0.4893	6.1178	0.1169	118
c_right	Gamma	0.4364	0.9610	0.2913	0.9965	7.2530	0.1090	118
p_left	Gamma	0.2494	1.0616	0.3391	0.9971	4.5444	0.1608	117
p_right	Gamma	0.0861	1.1505	0.3777	0.9114	2.0299	0.2851	115

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.7: Experiment 2 Moving the syringe

of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

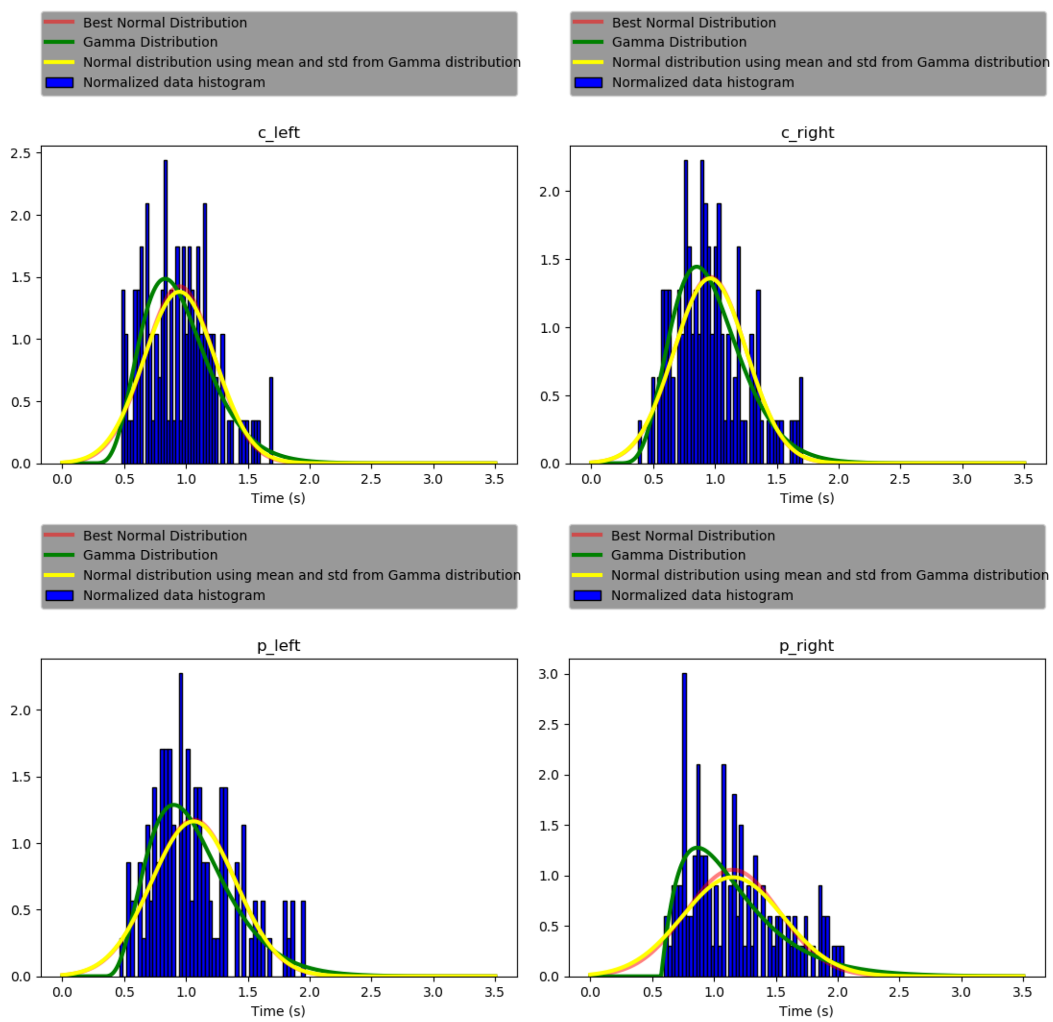

Figure 4.8: Moving syringe plots

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_left	Gamma	0.5736	0.7716	0.2658	0.8960	52.3348	0.0368	120
c_right	Gamma	0.0022	0.8241	0.2478	0.0632	5.3362	0.1042	112
p_left	Gamma	0.2952	0.8736	0.3285	0.7418	11.3005	0.0974	117
p_right	Gamma	0.0818	0.8123	0.2495	0.2683	18.1847	0.0575	106

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.8: Experiment 2 Returning the syringe

After performing unpaired t-test for the left hand our p-value was 0.0056 (a=0.05, t = 2.7968, df = 233, standard error of difference = 0.041) and therefore, based on our results, in this part of the task, the system with proxy haptics (using the left hand) is slower than the VR Wand system (controller with the left hand). For right hand setting p-value was 0.0001 (a=0.05, t = 4.0892, df = 231, standard error of difference = 0.046) and therefore for this part of the task proxy haptics system using the right hand is slower than virtual system using the right hand.

Returning the Syringe

For experiment2_time_to_return_syringe, the best distribution found for all the settings was Gamma distributed. The results are shown in Table 4.8. In this case the best p-value for c_right and p_right is lower than 0.5 therefore, we can only do the t-test for the left hand. Figure 4.9 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

After performing unpaired t-test for the left hand, our p-value was 0.0090 (a=0.05, t = 2.6334, df = 235, standard error of difference = 0.039) and therefore, based on our results, in this part of the task, the system with proxy haptics (using left hand) is slower than the VR Wand system (controller with left hand).

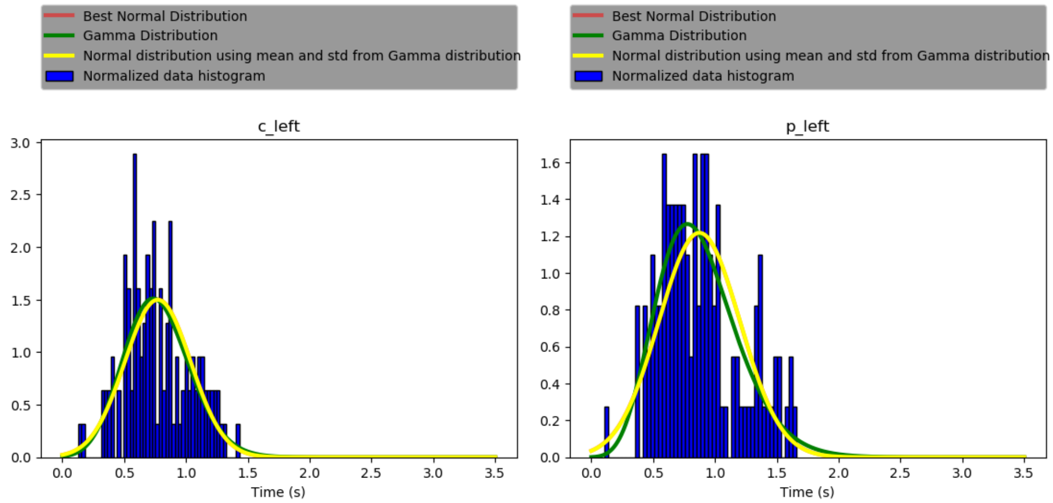

Figure 4.9: Returning the syringe plots

4.3 Task 3: Ambidextrous Surgical Tool Manipulation

In each trial, the participants were supposed to stand at a particular starting location shown in the virtual world. Then upon receiving a signal by the experimenter, a timer started, a target appeared the patient's right thigh, and the participants started moving towards the patient. Next, they grabbed the patient's arm and lifted it. After that, they were told to grab the syringe from the bed. Then they had to make the tip of the syringe touch the target on the patient's right arm. In this case, they had the freedom to move or orient the arm to be able to touch the syringe to the target more quickly. Moreover, some targets were on the other side of the arm meaning that they had to rotate the arm to be able to access those targets. Upon contact of the tip of the syringe with the target, the target disappeared and they had to place the syringe back to its original position on the bed and then they were supposed to put the patient's arm to its original place on the bed. In the end, they were asked to move back to the starting position for the next trial. For this task, since both hands were working there was no right hand vs. left-hand distinction. In this scenario, what we mean by the right hand (e.g. p_right) is taking the arm with the right hand and the syringe with the left hand. Since the opposite scenario (i.e., taking the patient's hand with the left hand and taking the syringe with right hand) required the participants to be in a cross-hand position which was difficult and not necessarily used in the real world, we only did this task with only one setting. In this task, we measured the time between different parts of the experiment shown in Table 4.9. All times were measured automatically in Unity. Figure 4.6 shows the physical environment and the virtual environment for both controllers-only and proxy haptics settings.

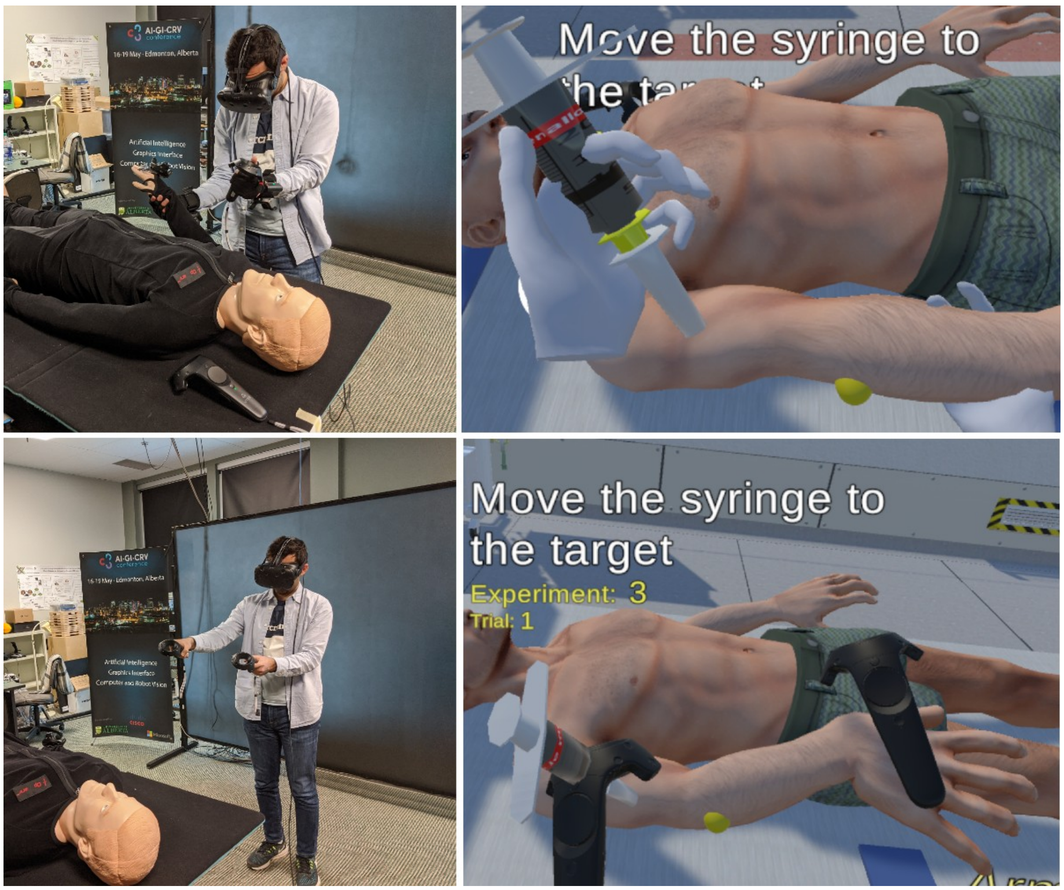

Figure 4.10: Experiment 3 physical and virtual environments
Top left is the participant doing the task using proxy haptics. Top right is what the participant sees when using proxy haptics. Bottom left is the participant doing the task using controllers. Bottom right is what the participant sees when using only controllers

ID	Description
experiment3_time_to_grab_arm	The time between when the trial starts (i.e. the time when the signal is given to the participants) and the time the participants touch the patient's arm
experiment3_time_to_grab_syringe	The time between end of experiment3_time_to_grab_arm and the time the participants touch the syringe
experiment3_time_to_move_syringe	The time between the end of experiment3_time_to_grab_syringe and the time the the tip of the syringe touches the target on the patient's right arm
experiment3_time_to_return_syringe	The time between the end of experiment3_time_to_move_syringe and the time the syringe is placed on its original position
experiment3_time_to_return_arm	The time between the end of experiment3_time_to_return_syringe and the time the patient's arm is placed on the bed on its original position

Table 4.9: Experiment 3 measured times

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_right	Normal	0.4546	1.1989	0.4063	0.2478	4.1734	0.2104	118
p_right	Gamma	0.4801	1.3885	0.4122	0.5591	16.4605	0.1027	118

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.10: Experiment 3 Grabbing the arm

4.3.1 Results

Grabbing the Arm

For experiment3_time_to_grab_arm, the best distribution found for c_right was Normally distributed with p-value 0.4546. For p_right the best distribution found was Gamma distributed with p-value 0.5591. The results are shown in Table 4.10. Figure 4.11 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

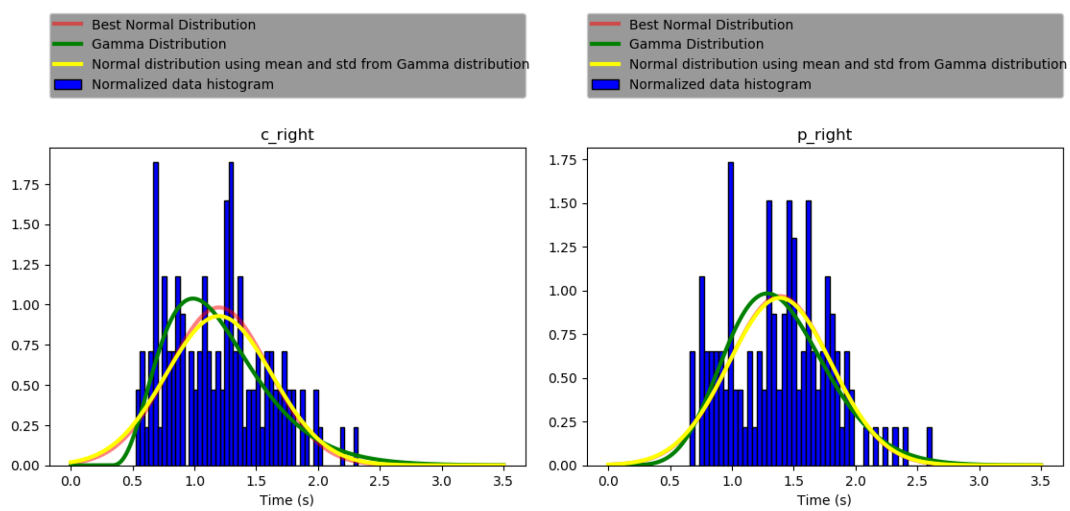

Figure 4.11: Grabbing the arm plots

Since the p-value for c_right is less than 0.5 one cannot assign a distribution to c_right and therefore we cannot perform the t-test in this case.

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_right	Gamma	0.3066	0.9155	0.3062	0.9636	6.4065	0.1225	115
p_right	Gamma	0.2467	0.9089	0.5400	0.5860	2.4630	0.3606	116

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.11: Experiment 3 Grabbing the syringe

Grabbing the Syringe

For experiment3_time_to_grab_syringe, the best distribution found for both of the settings was Gamma distributed. The results are shown in Table 4.11. Figure 4.12 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

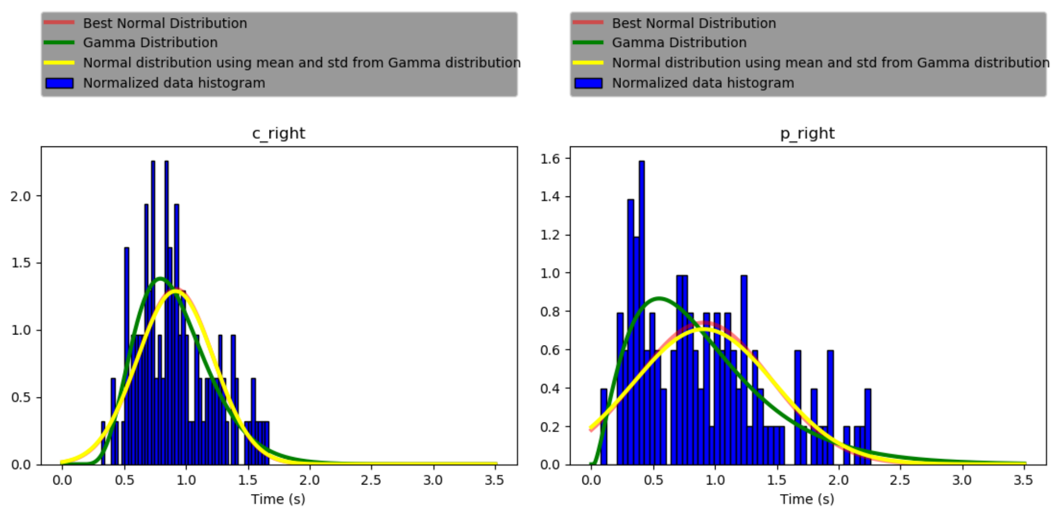

Figure 4.12: Grabbing the syringe plots

For the right hand setting, the result of running upaired t-test was p-value=0.9129 (a=0.05, t = 0.1095, df = 229, standard error of difference = 0.060) and therefore We cannot say anything about the controller being faster than the proxy haptics in this scenario.

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_right	Gamma	0.5682	0.8692	0.2202	0.8399	20.6269	0.0486	108
p_right	Gamma	0.0473	1.0468	0.3568	0.8466	3.4521	0.1960	112

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.12: Experiment 3 Moving the syringe

Moving the Syringe

The best distribution found for all the settings in experiment3_move_syringe was Gamma distributed. The results are shown in Table 4.12. Figure 4.13 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

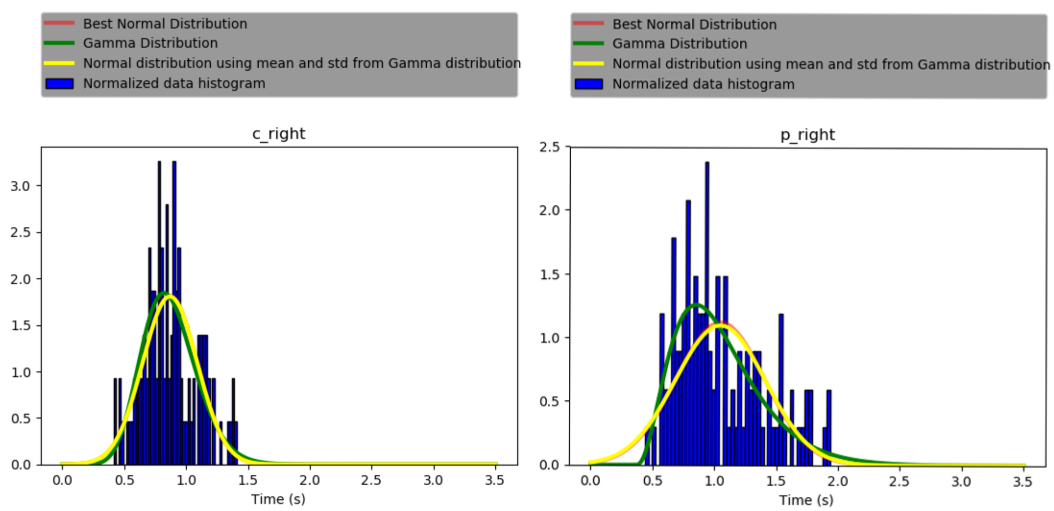

Figure 4.13: Moving the syringe plots

After performing unpaired t-test for the right hand our p-value was less than 0.0001 (a=0.05, t = 4.3542, df = 218, standard error of difference = 0.041) and therefore, based on our results, in this part of the task, the system with proxy haptics (using the right hand) is slower than the VR Wand system (controller with the right hand).

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_right	Gamma	0.0120	0.7598	0.2598	0.3787	4.3089	0.1246	114
p_right	Gamma	0.0599	0.9282	0.3909	0.9879	1.9579	0.2920	117

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.13: Experiment 3 Returning the syringe

Returning the Syringe

For experiment3_time_to_return_syringe, the best distribution found for all the settings was Gamma distributed. The results are shown in Table 4.13. Figure 4.14 shows the histogram of the data, PDF of the best Normal distribution, PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

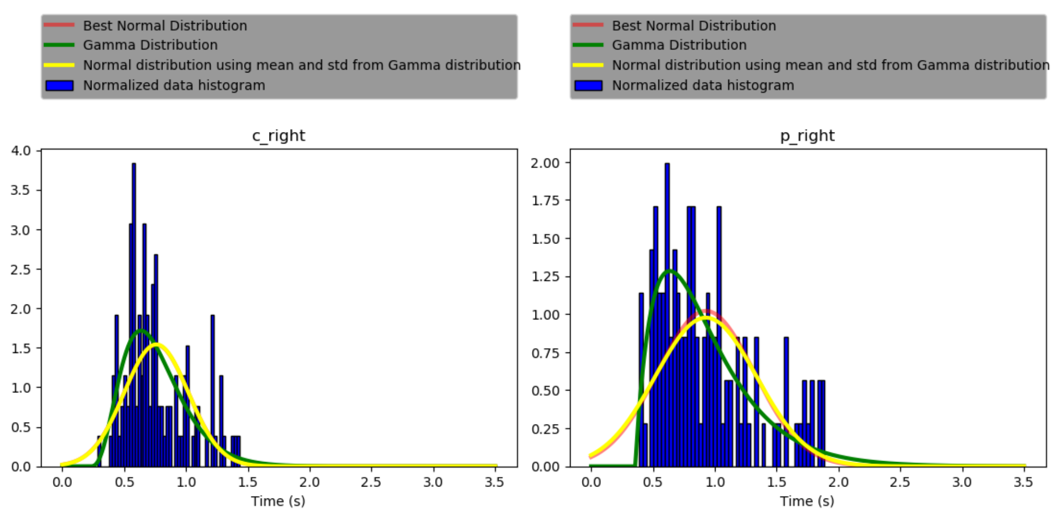

Figure 4.14: Returning the syringe plots

Since the p-value for c_right is less than 0.5 we cannot assign a distribution to c_right and therefore we cannot perform the t-test in this case.

Returning the Arm

For experiment3_time_to_return_arm, the best distribution found for all the settings was Normally distributed. The results are shown in Table 4.14. Figure 4.15 shows the histogram of the data, PDF of the best Normal distribution,

Setting	Dist.	Normal			Gamma			N
		P	Mean	STD	P	α	β	
c_right	Gamma	0.2226	0.9712	0.3666	0.2031	29.2145	0.0682	116
p_right	Gamma	0.4484	0.9189	0.4692	0.2364	7.9018	0.1713	115

Dist. is the best distribution found based on the p-values, N is the number of samples after the outliers were removed, and P is the p-value calculated from the Kolmogorov-Smirnov test

Table 4.14: Experiment 3 Returning the arm

PDF of the best Gamma distribution, and PDF of the Normal distribution using mean and STD calculated from the Gamma distribution.

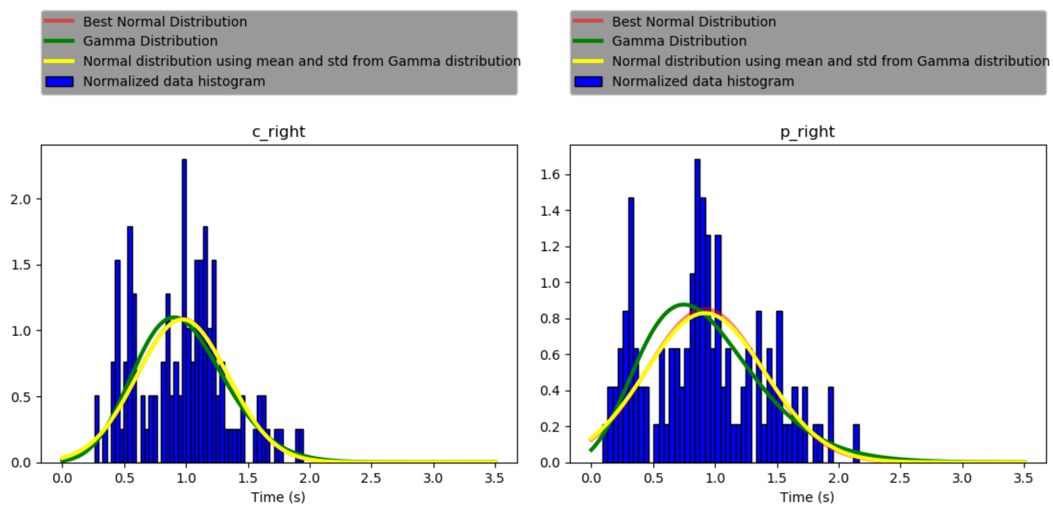

Figure 4.15: Returning the arm plots

Since the p-value for c_right and p_right is less than 0.5 we cannot assign a distribution to c_right and therefore we cannot perform the t-test in this case.

4.4 Questionnaire

4.4.1 Description

Our questionnaire consisted of 7 sections; 1 section asking general questions about their characteristics such as their hand dominance and if they wear glasses and 6 sections asking questions about the system. We had 3 tasks (discussed above) and 2 different settings (controller or proxy haptics), and we had one questionnaire for each of those. Generally, the questions for each of those

6 sections were the same with some minor differences based on the section. Each section consisted of 3 groups of questions; **1) Perceived competence scale** asking questions about how confident and comfortable the users were in working with the system. **2) System Usability Scale** asking questions about how usable the system was in the participant's view **3) Believability** asking how close the system was to the real world. A full version of the questionnaire can be found in the Appendix.

Each group of questions consisted of some questions or statements related to that group. The users had to choose, on a scale of 1 to 7, with seven meaning the completely agree and 1 meaning they disagree entirely, how much they agreed or disagreed with each statement. Some statements were negative (e.g. I found the system very cumbersome to use) and others were positive. In the end, we applied a function to all those responses for each group to get a score for each group between 1 - 100. The details about the scores are shown in Table 4.15. However, we could not merge all the questions in the believability section because of their different nature. For instance, one question asked about how much they believed they were dealing with a real-world problem and one question asked if they saw any difference between right hand and left-hand manipulation. We denoted, "I felt like I am dealing with a real-world arm' as the question directly asking about the believability of the system and we mapped the values of the responses to a number between 1 - 100 as a believability score. We will discuss other questions in the believability section later. At the end of the questionnaire, we also asked the participants to write their opinion about the system.

We next preformed unpaired t-test with a = 0.075 for all the experiments to compare the system with only controller with the system with proxy haptics. The results are shown in Table 4.16.

The results show that our hypothesis H2 is true for all the experiments meaning the participants view the system with proxy haptics more believable and closer to the real world than the pure VR version. Also based on Figure 4.16 The users seemed to feel less difference between right hand and left hand manipulation using the proxy haptics

Section	System Competence		System Usability		Believabitiy	
	Mean	STD	Mean	STD	Mean	STD
Experiment1 with controller	83.3333	14.7939	80.3819	12.0976	41.6667	27.9791
Experiment1 with proxy haptics	75.9259	16.1247	80.5556	15.0581	76.3889	18.0604
Experiment2 with controller	81.9444	13.0020	78.6458	16.1893	54.1667	31.0791
Experiment2 with proxy haptics	86.5741	9.6103	86.8055	7.5552	76.3889	24.0562
Experiment3 with controller	71.2963	12.7202	73.9583	13.6902	50	32.5669
Experiment3 with proxy haptics	84.2593	12.7202	81.2500	17.0644	76.3889	20.6685

SED stands for standard error of differences. The responses are from our 12 participants.

Table 4.15: Questionnaire scores

Experiments	Result			
	P	t	df	SED
Experiment 1	0.0015	3.6119	22	9.613
Experiment 2	0.0629	1.9587	22	11.345
Experiment 3	0.0270	2.3700	22	11.135

Table 4.16: Unpaired t-test results from 12 participants

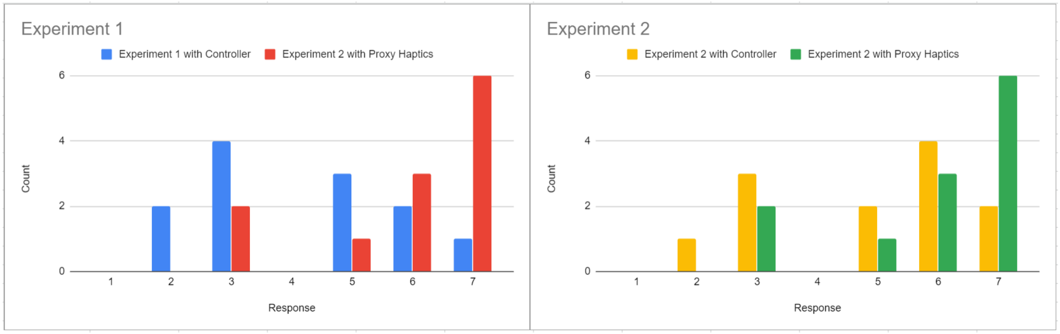

Figure 4.16: Responses for the question "I feel no difference between the right- and left-hand manipulations"

4.5 Discussion

By analyzing the data, we realized that in most cases, the proxy haptics is slower than the controller-only system. In fact, in 8 out 10 different situations for which we could find a distribution, the proxy haptics was slower, in 2 of them our hypothesis got rejected and in 7 of our situations, we could not run the experiment because we could not find a distribution good enough on our data. The table 4.17 summarizes the results of our first hypothesis.

This is to be expected since by adding a proxy, we are limiting the movement of the user and this can only slow them down. The difference between these two systems is like the difference between teleporting to some other place without being hindered by objects or walking to that place. By holding the patient's hand, the user is carrying the weight and he/she cannot move the hand wherever they want in the world. On the other hand, in a controller-only system, the users have no restriction of movement and can move the patient's hand, which is completely virtual in this case, to any place they want. In fact, in many cases, we observed users taking the syringe from inside the body of the patient to the target because that was a shorter path, while this is not possible using our proxy haptics system. Being able to move freely and not having the limitations we have in the real world makes the system less real and therefore, it may be less useful especially in surgical training cases. Imagine someone practicing some task while ignoring the boundaries of the patient's body. Therefore, we do not think being slower in the proxy haptics is a bad thing. What's interesting here is that in experiment 3, grabbing the syringe was not slower in the proxy haptics case. We think the reason for this might be that in this experiment, participants were holding the patient's arm with their right hand, and they had to grab the syringe with their left hand. What we observed was that using proxy haptics, in most cases, the participants were not looking at where the syringe was, and they were using their haptics feedback to grab the syringe.

Based on the questionnaire all of the tasks were more believable in the virtual world and therefore, our H2 gets validated as well. Moreover, when asked participants about their opinion, out of the 9 who responded to this question, 6 preferred proxy haptics over controller-only system saying things like it "Glove with proxy haptic because it feels more natural", "Glove with Proxy Haptic. I could feel the weight of the objects", or "Glove because it involved less clicks!". In addition, when asked about how much they liked the HTC Vive controller as a proxy to the syringe, out of 9 who answered to this question, 5 had positive feedback about it. One participant even said "Great. Didn't even notice the first time". However, there were some negative feedbacks relating to not being stable all the time. We do not believe that this was because of the controller as a proxy haptics. In our opinion, this issue was caused by occlusion and may have happened with HTC Vive trackers as well.

Exp.	Task	Hand	Result		
			Dist. found	H1 accepted	H1 rejected
1	Grab arm	right	✓	✓	-
		left	-	-	-
	Move arm	right	✓	✓	-
		left	-	-	-
	Return arm	right	✓	-	✓
		left	✓	✓	-
2	Grab syringe	right	✓	✓	-
		left	-	-	-
	Move syringe	right	✓	✓	-
		left	✓	✓	-
	Return Syringe	right	-	-	-
		left	✓	✓	-
3	Grab arm	right	-	-	-
	Grab syringe	right	✓	-	✓
	Move syringe	right	✓	✓	-
	Return syringe	right	-	-	-
	Return arm	right	-	-	-

Exp. is the experiment number

Table 4.17: H1 results

Chapter 5

Conclusion

In our work, we tried to introduce a new way of making VR more immersive. We decided to achieve this by mapping real-world objects as a proxy to some virtual objects. We used a mannequin as a proxy for a patient, an HTC Vive controller as a proxy to a syringe, and a table as a proxy to a surgery bed. We believe this approach while being affordable, gives users more freedom than approaches that require users to grab the end-effector of a robotic arm.

Our results show that our system is closer to the real world and, therefore more immersive. However, in most cases, our system is slower when compared to manipulations in the virtual world using wands. This is to be expected since, as in the virtual world, there are no limitations, while for example, for moving the hand of the mannequin, the users are limited by the movement of the mannequin in the proxy system while they do not have such restrictions in a completely virtual world. We think this illusion of speed comes at the cost of inaccuracy and lower quality surgical training. Because without having the limitations of the real world, VR surgical training might not be as good as the real-world surgical training. As we mentioned before, in our observations, many times users touched the body with the syringe or moved the syringe through the body. Not only some of them did it to be faster, and it may have been unintentional since, without the haptic feedback, they may not have known if they have touched the body or not. In addition, our results only indicate that participants did the tasks faster when they used our system compared to when they used the VR system. This, however, does not say anything about their performance when they move to the real-world task (e.g. real surgery). In order to test this more research needs to be done. One can devise a research in which one group of trainees train using a proxy haptic system and the other group train using the VR system. Then both groups can be tested on the same real-world task to see the effects of learning for each system.

While we tried our best to create an affordable system that would make the process or surgical training more immersive, it does not mean that there is nothing to improve on our system. Our study was a pilot study and there are definitely room for more research and improvement. We did not have enough data to do our hypothesis testing for some of the tasks. We believe by doing the same experiments with more people, the results would be more reliable. Also, our tasks were simple grabbing and moving tasks. In the future, it might be a good idea to devise some more complex surgical tasks and study the results on those. We also believe our system can be a basis to improvement surgical training. We sometimes had issues with occlusion and it had an impact on the experience of our system. It might be a good idea to use more reliable methods with less chance of occlusion either by having the system in a bigger room and with more optical cameras or by using other methods like magnetic tracking instead of optical tracking. Another thing that requires further investigation is grabbing multiple objects at the same time. As we indicated before, in the task where participants were supposed to grab a syringe while lifting the arm, our system was not slower and we think the reason for that might be that when people are grabbing multiple objects they are relying more on their sense of haptic since they cannot look at both objects at the same time.

Moreover, since it is a virtual world, one can add instructions, text, and videos on demand for the user. For example, if the users do not remember a part of the surgery, the first part of the procedure can be to show them by highlight the starting position. Also, it might be an excellent platform to do collaborative surgery or surgical planning. The students and surgeons can be in the same or different locations and all they need is our system. Using the fact that they can see each other in the virtual world and collaborate.

However, in the case that they are in different locations, they would need a more sophisticated version of this system to be able to hand each other tools and objects. Lastly, we think this system might also be beneficial both in laparoscopic surgery and open surgical training in particular because an issue with this type of surgery is that the surgeons have to look at a screen in another direction which is, as Dr. James Clarence Rosser Jr. mentioned, like "tying your shoelaces with three-foot-long chopsticks while watching it all on television" [22]. By wearing the HMD display, the surgeons can see the inside of the patient by directly looking at the patient which is more natural than looking at a television. In general, by adding the discussed features to the system and making the system more and more complete, it might be a way to provide affordable, accessible, and immersive surgical training experience to replace the traditional surgical training.

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Appendix A

Questionnaire

- Test ID
- Sex
  - Male
  - Female
  - Other
- Hand Dominance
  - Right
  - Left
- Age
- Wear Glasses
  - Yes
  - No
- Do you see in Stereo
  - Yes
  - No
- Do You Play Video Games
  - Often
  - Sometimes
  - Never

Experiment I with VR Wand

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to move the patient's hand towards the target	1	2	3	4	5	6	7
I can control the patient's hand well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the patient's hand to a specific region	1	2	3	4	5	6	7

System Usability Scale

	Not at all True			Somewhat True			Very True
I think that I would like to use this system frequently	1	2	3	4	5	6	7
I found the system unnecessarily complex	1	2	3	4	5	6	7
I thought the system was easy to use	1	2	3	4	5	6	7
I found the various functions in this system were well-integrated	1	2	3	4	5	6	7
I would imagine that most people would learn to use this system very quickly	1	2	3	4	5	6	7
I found the system very cumbersome to use	1	2	3	4	5	6	7
I felt very confident using the system	1	2	3	4	5	6	7
I needed to learn a lot of things before I could get going with this system	1	2	3	4	5	6	7

Believability

	Not at all True			Some-what True			Very True
I felt like I am dealing with a real-world arm	1	2	3	4	5	6	7
I felt strange using the system	1	2	3	4	5	6	7
I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

Experiment II with VR Wand

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to grab the syringe	1	2	3	4	5	6	7
I can control the syringe well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the syringe to the arm target	1	2	3	4	5	6	7

System Usability Scale

	Not at all True			Some-what True			Very True
I think that I would like to use this system frequently	1	2	3	4	5	6	7
I found the system unnecessarily complex	1	2	3	4	5	6	7
I thought the system was easy to use	1	2	3	4	5	6	7
I found the various functions in this system were well-integrated	1	2	3	4	5	6	7
I would imagine that most people would learn to use this system very quickly	1	2	3	4	5	6	7
I found the system very cumbersome to use	1	2	3	4	5	6	7
I felt very confident using the system	1	2	3	4	5	6	7
I needed to learn a lot of things before I could get going with this system	1	2	3	4	5	6	7

Believability

	Not at all True			Some-what True			Very True
I felt like I am dealing with a real-world arm	1	2	3	4	5	6	7
I felt strange using the system	1	2	3	4	5	6	7
I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

Experiment III with VR Wand

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to move to grab the syringe and the arm	1	2	3	4	5	6	7
I can control the syringe well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the syringe to the arm target	1	2	3	4	5	6	7

System Usability Scale

	Not at all True			Some-what True			Very True
I think that I would like to use this system frequently	1	2	3	4	5	6	7
I found the system unnecessarily complex	1	2	3	4	5	6	7
I thought the system was easy to use	1	2	3	4	5	6	7
I found the various functions in this system were well-integrated	1	2	3	4	5	6	7
I would imagine that most people would learn to use this system very quickly	1	2	3	4	5	6	7
I found the system very cumbersome to use	1	2	3	4	5	6	7
I felt very confident using the system	1	2	3	4	5	6	7
I needed to learn a lot of things before I could get going with this system	1	2	3	4	5	6	7

Believability

	Not at all True			Some-what True			Very True
I felt like I am dealing with a real-world arm	1	2	3	4	5	6	7
I felt strange using the system	1	2	3	4	5	6	7
I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

Experiment I with Proxy Haptic

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to move the patient's hand towards the target	1	2	3	4	5	6	7
can control the patient's hand well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the patient's hand to a specific region	1	2	3	4	5	6	7

System Usability Scale

	Not at all True			Some-what True			Very True
I think that I would like to use this system frequently	1	2	3	4	5	6	7
I found the system unnecessarily complex	1	2	3	4	5	6	7
I thought the system was easy to use	1	2	3	4	5	6	7
I found the various functions in this system were well-integrated	1	2	3	4	5	6	7
I would imagine that most people would learn to use this system very quickly	1	2	3	4	5	6	7
I found the system very cumbersome to use	1	2	3	4	5	6	7
I felt very confident using the system	1	2	3	4	5	6	7
I needed to learn a lot of things before I could get going with this system	1	2	3	4	5	6	7

Believability

	Not at all True			Some-what True			Very True
I felt like I am dealing with a real-world arm	1	2	3	4	5	6	7
I felt strange using the system	1	2	3	4	5	6	7
I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

Experiment II with Proxy Haptic

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to grab the syringe	1	2	3	4	5	6	7
I can control the syringe well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the syringe to the arm target	1	2	3	4	5	6	7

System Usability Scale

	Not at all True			Some-what True			Very True
I think that I would like to use this system frequently	1	2	3	4	5	6	7
I found the system unnecessarily complex	1	2	3	4	5	6	7
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Believability

	Not at all True			Some-what True			Very True
I felt like I am dealing with a real-world arm	1	2	3	4	5	6	7
I felt strange using the system	1	2	3	4	5	6	7
I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

Experiment III with Proxy Haptic

Perceived Competence Scales

	Not at all True			Some-what True			Very True
I feel confident in my ability to move to grab the syringe and the arm	1	2	3	4	5	6	7
I can control the syringe well	1	2	3	4	5	6	7
I feel able to meet the challenge of moving the syringe to the arm target	1	2	3	4	5	6	7

System Usability Scale

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I feel no difference between the right- and left-hand manipulations	1	2	3	4	5	6	7

General Questions

Which setting do you prefer (Controller Only vs Glove with Proxy Haptic)? why?

How did you like the controller as a proxy for the syringe?