A Body-Grounded Kinesthetic Haptic Device
For Virtual Reality

by
Andres Calvo

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
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Abstract

Kinesthetic haptic devices can make us feel that we are touching or holding objects that are not actually there by applying a force directly onto a user’s body. As a corollary of Newton’s third law, these devices are typically attached to the ground or else they would not be able to apply a net force onto a user. Thus, kinesthetic haptic devices typically have small workspaces—the area in which they can be used—or are overly cumbersome and expensive. Consequently, they are incompatible with room-scale virtual reality, which allows users to move and walk within a room. The portable haptics interface overcomes this limitation because its wearable form factor means it’s “grounded” directly to a user’s back, making it portable. In other words, this device approximates the sensations of a kinesthetic haptic device while also being portable. The haptic device consists of a robotic arm that is mounted on a user’s back, and its end-effector is attached to an HTC Vive controller, enabling use with virtual reality. A first example application uses the portable haptics interface to simulate the elasticity of a bow and arrow as a user pulls on the bowstring of a virtual bow. A second application renders haptic feedback for impacts by applying an impulse in the appropriate direction when a user hits a tennis ball with a racket in virtual reality. In an evaluation, we asked users to shoot targets in virtual reality with and without haptic feedback. Our results suggest that haptic feedback increases spatial presence with a large effect size but does not affect involvement and experienced realism. Our results also suggest several improvements to the ergonomics of the system such as using thicker straps to better distribute the load. In summary, portable kinesthetic haptic devices such as the portable haptics interface provide room-scale virtual reality applications with the sense of touch without constraining users to a chair.

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In this experience by Insko et al., a participant views a 20 foot virtual pit while standing on the edge of a 1.5 inch step. (left) An image of a user standing on the edge of the step while wearing a virtual reality display. (right) A rendering of the 20 foot virtual pit. Image from [32].

The TurkDeck uses passive haptic props that are moved by a group of human workers to within a user’s reach. In their paper, Cheng et al. demonstrated the implementation of a $300m^2$ virtual space within a $25m^2$ room in which props are used to provide feedback for walls, doors, ledges, and more. Image from [20].

Haptic regargeting leverages the dominance of vision when there is conflicting sensory information to provide passive haptic feedback for multiple virtual objects with a single physical prop. Image from [14].

Lopes et al. uses electrical muscle stimulation to activate muscles that pull a user’s arm backwards when he or she pushes on an object in virtual reality. (left) a user holds a box in virtual reality and feels haptic feedback from his arms resisting the motion as a result of muscle stimulation. (right) a screen capture of the virtual environment. Images from [36].

A sketch of the proposed design of a body-grounded kinesthetic haptic device. The device is mounted on a user’s back and contains a robotic arm with its end-effector attached to a user’s hand.

The robotic arm of the proposed design is an RRR manipulator with the configuration shown here.

The distance denoted by $lb$ is known as the forward functional reach from the acromial process to the pinch. The acromial process is a bony protuberance at the top of the shoulder located on the scapula. Image from [24].

The maximum reach of the robot arm is equal to the sum of the lengths of both links.

The portable haptics interface has a robotic arm mounted on a shoulderplate that is secured to a backpack. The mechanism is secured with straps and is similar to a backpack.

To attach an HTC Vive controller to the end effector of the portable haptics interface, a gopro hinge was fastened to a 3D printed coupler that was secured around the controller. The other end of the hinge was screwed onto another 3D printed block that was secured to the end effector.

A render of the robot arm used in the portable haptics interface. An HTC Vive controller is attached to the end effector and the base of the robot arm serves as the shoulder plate that is mounted onto a user.

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Chapter 1

Introduction

While haptics can lead to increased levels of immersion in virtual reality (VR) [29], the sense of touch in modern VR systems such as the HTC Vive is limited to vibration feedback, which lacks realism. In contrast, kinesthetic haptic devices can make us feel that we are touching or holding objects that are not actually there by applying a force directly onto a user’s body. As a corollary of Newton’s third law, these devices are typically grounded—that is, attached to the ground—or else they would not be able to apply a net force onto a user. Thus, kinesthetic haptic devices typically have small workspaces—the area in which they can be used. Moreover, they are typically overly cumbersome and expensive since they require large actuators [42].

Modern VR systems can track users over room-sized areas, allowing people to walk and move in a natural manner, and are therefore incompatible with kinesthetic haptic devices with small workspaces. To overcome this issue, I developed the portable haptics interface, a wearable kinesthetic haptic device that is grounded by being attached to a user’s torso with a mechanism similar to a backpack. A 3-DOF robotic arm with two links is attached to the backpack and contains a handle at its end-effector. When a user holds the handle, the robotic arm is able to apply kinesthetic feedback according to the current state of the virtual environment.

I hypothesize that 1) this device can approximate the sensations of a kinesthetic haptic device while also being portable and 2) large body parts such as the hips and the torso can absorb the reaction
forces exerted on the arms, hands, or fingers without disrupting the user. This device allows room-scale VR to leverage the sense of touch, increasing immersion and enabling the development of unprecedented user experiences.

1.1 Contributions

This research has four main contributions:

1. the development of a body-grounded haptic device that is portable and can exert continuous and controlled forces onto a user

2. the implementation of two example applications of this device in the context of virtual reality

3. an evaluation of the sense of presence and ergonomics that the haptic device provides

4. a discussion of design insights for wearable haptic devices

The design insights attempt to outline a series of guidelines for the design of wearable haptic devices that address considerations such as workspace, weight, and ergonomics.

1.2 Related Work

This section situates this work within the space of existing haptic feedback devices. Haptic devices are typically divided into two categories: tactile and kinesthetic. Tactile devices, which are also known as cutaneous devices, stimulate receptors located on the skin. In contrast, kinesthetic devices typically display forces through a tool and stimulate receptors in the muscles, joints, and ligaments.

Alternatively, haptic devices can be classified by the way in which they absorb reaction forces. First, *grounded devices* transmit reaction forces to a surface that is connected to the ground such as a table. Second, *ungrounded devices* utilize properties such as the gyroscopic effect to generate momentary forces without having to be grounded. Third, *body grounded devices* transmit reaction forces through a user’s body and are typically wearable and/or portable.
1.2.1 Tactile Feedback Devices

Vibration motors have been used to stimulate the sense of touch and emulate the vibrations of a given sensation [39], and they are typically small and portable. However, unlike kinesthetic devices, vibration motors cannot apply a net force onto a user and, as a result, they lack realism. Skin deformation feedback devices emulate the tangential (e.g., [42]), normal (e.g., [38]) or rotational (e.g., [15]) skin deformation that is caused by a manipulation task. These devices display direction and magnitude more accurately than vibration motors. However, kinesthetic feedback results in skin deformation and, consequently, has more cues than skin deformation feedback [42].

1.2.2 Kinesthetic Haptic Devices

The PHANToM haptic interface applies a controlled force to a users finger, allowing users to feel virtual objects, and its workspace is comparable to the size of a computer keyboard (see Figure 1-1) [37].

The CyberForce [2], shown in Figure 1-2, consists of a CyberGrasp system (that is, a hand-worn exoskeleton that applies forces to a user’s individual fingers) attached to a robotic armature. It can exert forces on each finger and on the hand while being grounded through the armature’s base. Its workspace is equal to $12 \times 12$ in swept through $133^\circ$ with a radius of 20 in. The DLR bimanual haptic device uses two KUKA robotic arms mounted to a fixed structure behind a user to provide haptic feedback and attempts to maximize the intersecting workspace of the robot and human arms [31]. Although these devices have large workspaces, they are bulky and expensive.

Ungrounded kinesthetic devices can apply net forces onto a user without being grounded by leveraging the gyro effect [29, 46], dynamically changing the center-of-mass of a handheld device [43], or rotating flywheels to change a system’s angular momentum [45]. The GyroVR system, shown in the top of Figure 1-4, uses a headworn flywheel to render inertia in virtual reality and, for example, increase the inertia of a virtual reality head-mounted display when a user’s character in a game is wounded and moving more slowly [29]. Yano et al. used a flywheel that can be rotated by motors to exert a momentary force due to conservation of angular momentum (see bottom left of Figure 1-4) [29]. TorqueBar, which stimulates the awareness of dynamic inertia, is a system held by both of
a user’s hands that changes its center of gravity by moving a servo motor throughout its length (see bottom right of Figure 1-4). Although ungrounded kinesthetic devices are portable, the forces they exert on a user are difficult to control and of limited duration.

1.2.3 Body-Grounded Devices

Exoskeletons such as the Dexmo [28] apply forces to a user’s fingers while being grounded to the wrist (see Figure 1-5). Larger exoskeletons such as the ones built by Frisoli et al. and Carignan et al. (see Figure 1-6) [18, 27] have been used to provide force feedback in virtual reality but are typically grounded. Exoskeletons that take into account the shoulder joint are bulky and complex as they require complex mechanisms for a ball-and-socket joint because the shoulder has multiple degrees of freedom. Furthermore, they are difficult to fit to individuals and difficult to wear and remove [42].

The haptic edge display contains an array of piezoelectric actuators on the side of a smartphone that stimulate a user’s fingers [34], as shown in the left of Figure 1-7. The Wolverine is a wearable haptic hand that applies brakes in between every finger and the thumb to emulate the sensations of grasping [21] (see the right of Figure 1-7). NormalTouch renders surfaces by providing force feedback onto a user’s index finger using a tiltable and extrudable platform that while TextureTouch renders detailed surface structure by independently moving every pin in a 4x4 matrix (see Figure 1-8) [16]. While these devices render force onto a user’s fingers, the portable haptics interface exerts force onto a user’s hand and, and its reaction forces are felt throughout the arm.

Achibet et al. attached elastic bands to users and synchronized the position of buttons within a virtual environment to the length of the bands [12, 13], as shown in Figure 1-9. As a result, the elastic bands provided passive haptic feedback as a user pressed a virtual button. Though this setup is portable, it can only be used in limited scenarios since it only provides feedback for a single button at a fixed distance. Kamuro et al. developed a pen that provides kinesthetic feedback by shrinking or growing in length [35]. This pen is a body-grounded kinesthetic device since it applies a force on the fingers and is effectively grounded against the part of a user’s hand on which it rests. Consequently, the force that this device exerts is limited to the fingers and does not reach the forearm. Furthermore,
Figure 1-1: Massie and Salisbury’s PHANTom haptic interface exerts a controlled force onto a user’s finger tip to provide haptic feedback. Image from [37].
Figure 1-2: The CyberForce consists of a CyberGrasp system (a hand-worn exoskeleton that applies forces to a user’s individual fingers) attached to a robotic armature. It can exert forces on each finger and on the hand while being grounded through the armature’s base.

Figure 1-3: The DLR bimanual haptic device utilizes two DLR/KUKA robot arms mounted to a fixed structure to provide 6DOF haptic feedback to both of a user’s hands. Image from [31].
the device cannot accurately control the direction of the force.

No existing device applies forces to a user’s fingers or hands while being grounded to a large body part such as a user’s torso or hips. In contrast, the portable haptics interface exerts continuous and controlled forces on a user while being portable due to its wearable form factor.

1.2.4 Room-scale Virtual Reality

Tracking systems that can measure the position and orientation of a user have enabled room-scale virtual reality applications. Optical tracking systems such as Optitrack [6] estimate the position and orientation of one or more motion capture markers by using multiple cameras mounted at known locations. The HTC Vive [9] is a virtual reality system that can track the position and orientation of its components (such as a head mounted display) by using photodiodes to track a reference laser that a base station projects throughout the room. Google’s Tango [7] uses specialized hardware and computer vision techniques such as Simultaneous Location and Mapping (SLAM) to allow smartphones and tablets to estimate their position relative to the world without relying on GPS.

Room-scale VR experiences allow a user to move within a virtual environment by moving within a physical space. In a first person shooter game called Hover Junkers, for example, users are able to walk and duck within a room-sized hovercraft by moving throughout the physical room. Users can thus shoot at players in other ships while also being able to take cover. Another example is Google’s Tiltbrush [3], which uses virtual reality to allow user’s to paint on a room-sized 3D canvas by using the HTC Vive’s controller as a brush. A last example is Real Virtuality [19], illustrated in Figure 1-10, which allows two users to walk in a virtual environment similar to a dungeon. Both users are able to and manipulate a physical rod and see a corresponding torch move the same way in virtual reality. Participants of Real Virtuality have been able to throw and catch the rod between two people based on only the feedback from virtual reality.

VR experiences can even take place in areas larger than a single room. For example, Sra et al. [41] used a Tango tablet to generate a virtual environment of the same dimension as a hallway. Participants were then able to walk throughout the virtual environment by walking on the hallway.
1.2.5 Haptic Feedback in Virtual Reality

Virtual reality is typically limited to the visual and auditory modalities. Haptic devices are able to create new experiences in virtual reality by leveraging the modality of touch. Improving a user’s sense of presence is a common theme within the research of haptic devices applied to virtual reality. Although there are multiple definitions of presence, we will use the definition of Schubert, Friedmann, and Regenbrecht [40]: presence is a user’s psychological sense of being within virtual environment even though a user is physically located elsewhere.

Surround haptics uses a low-resolution grid of vibrotactile actuators to generate continuous moving tactile strokes on skin. In their work, Israr et al. presented an application of Surround haptics that consists of a driving simulation game in which a user receives tactile feedback on a chair with embedded vibrotactile actuators (see Figure 1-11) [33]. The vibrotactile sensations provide feedback for events such as collision, skidding, tire traction, and acceleration.

Insko et al. used passive haptics to create an experience in which participants viewed a 20 foot virtual pit while standing on the edge of a 1.5 inch step, as shown in Figure 1-12 [32]. They found that augmenting a virtual environment with passive haptics increases participants’ sense of presence as evaluated with a standardized questionnaire.

The TurkDeck uses passive haptic props that are moved by having a group of human workers move the props to within a user’s reach [20]. In this article, Cheng et al. demonstrated the implementation of a 300 m² virtual space within a 25 m² room in which props are were used to provide feedback for walls, doors, ledges, and more (see Figure 1-13). They conducted an evaluation that showed passive haptic props moved by human workers increased subjective ratings of realism.

Azmandian et al. created a framework for using a single physical prop for providing passive haptic feedback for multiple virtual objects by leveraging the dominance of vision when there is conflicting sensory information (see Figure 1-14) [14]. In their evaluation, they asked participants to use each of their retargeting implementations and measured their sense of presence using a standardized questionnaire.

Lopes et al. used electrical muscle stimulation to activate muscles that pull a user’s arm backwards...
when he or she pushes on an object in virtual reality (see Figure 1-15). This system can provide haptic feedback for large, heavy objects in virtual reality systems that allow users to walk freely. They used open ended questions to evaluate the realism of several variations of haptic feedback based on electrical muscle stimulation using open ended questions and found that some of these variations were more realistic than a vibration-only baseline.

The next chapter discusses the mechanical design of the portable haptics interface.
Figure 1-4: (top) A head worn flywheel that renders inertia in virtual reality resulting from the gyroscopic effect. Image from [29]. (bottom left) A flywheel tilted by motor controlled gimbals to exert a momentary force resulting conservation of momentum. Image from [46]. (bottom right) TorqueBar is a bar that is held by both of a user’s hands and changes its center-of-mass in real time to exploit the awareness of dynamic inertia. Image from [43].
Figure 1-5: Dexmo is a mechanical exoskeleton for the hand that tracks a user’s fingers and provides force feedback to by using a micro servo to firmly lock a ratchet wheel and prevent a finger’s motion. Image from [28].

Figure 1-6: The Maryland-Georgetown-Army (MGA) exoskeleton has 6DOF and is designed for shoulder rehabilitation, namely functional training in virtual environments. Image from [18].
Figure 1-7: (left) The Wolverine is a wearable haptic device that uses brake-based locking sliders between the thumb and three fingers to simulate grasping rigid objects. Image from [21]. (right) The haptic edge display is a device with the form factor of a mobile phone that contains an array of piezoelectric actuators to stimulate a user’s fingers. Image from [34].

Figure 1-8: (a) NormalTouch renders surfaces by providing force feedback onto a user’s index finger using a tiltable and extrudable platform. (b) TextureTouch renders detailed surface structure by independently moving every pin in a 4x4 matrix. Images from [16].

Figure 1-9: Elastic arm uses elastic bands to provide passive haptic feedback for a user pressing a button in virtual reality. Image from [12]
Figure 1-10: Real virtuality allows one or more users to manipulate objects in virtual reality by manipulating physical objects with synchronized positions. Image from [19].

Figure 1-11: A driving simulation game demonstrates an application of Surround Haptics, a grid of vibrotactile actuators that can generate continuous moving tactile strokes. A user receives tactile feedback on a chair with embedded vibrotactile actuators and the vibrotactile sensations provide feedback for events such as collision, skidding, tire traction, and acceleration. Image from [33].
Figure 1-12: In this experience by Insko et al., a participant views a 20 foot virtual pit while standing on the edge of a 1.5 inch step. (left) An image of a user standing on the edge of the step while wearing a virtual reality display. (right) A rendering of the 20 foot virtual pit. Image from [32].
Figure 1-13: The TurkDeck uses passive haptic props that are moved by a group of human workers to within a user’s reach. In their paper, Cheng et al. demonstrated the implementation of a $300m^2$ virtual space within a $25m^2$ room in which props are used to provide feedback for walls, doors, ledges, and more. Image from [20].
Figure 1-14: Haptic regargeting leverages the dominance of vision when there is conflicting sensory information to provide passive haptic feedback for multiple virtual objects with a single physical prop. Image from [14].

Figure 1-15: Lopes et al. uses electrical muscle stimulation to activate muscles that pull a user’s arm backwards when he or she pushes on an object in virtual reality. (left) a user holds a box in virtual reality and feels haptic feedback from his arms resisting the motion as a result of muscle stimulation. (right) a screen capture of the virtual environment. Images from [36].
Chapter 2

Mechanical Design

This chapter discusses the requirements of the mechanical design of the portable haptics interface and a proposed concept and describes its implementation.

To exert force feedback, the device needs actuators and is thus effectively a robot. While there are many different types of actuators such as pneumatics and hydraulics capable of exerting forces, I chose to use DC motors because of their fast response times.

2.0.1 Design Requirements

The mechanical design of the haptic device should meet the following goals:

- the device should be capable of applying a controlled force of 15 lb onto a user’s hand,
- the refresh rate of the motors should be at least 300 Hz,
- the workspace of the device should be designed for the range of motion of a typical human arm,
- the device should have minimal weight while being able to exert a reasonable amount of torque,
• the device should be comfortable to wear and relatively quick to don and doff,

• the device should be grounded to a user’s back, torso, or hips, and

• the torque the device’s motors exert when turned off should be reasonably small, and

• the end effector of the device should be securely attached to a user’s wrist/palm or to an accessory that a user can hold such as a pen.

While stronger motors with larger bandwidths are able to provide crisper force feedback, they come at the expense of increased weight and size, which is undesirable for wearable devices. Finding a suitable tradeoff between strong/fast motors and a reasonable weight will be an important aspect of the design. In a survey of haptic devices for medical training simulators, [Coles et al.] listed 25 haptic devices from nine different companies and found that the maximum force they can exert ranges from 0.07 lb to 56 lb. Two of the devices are outliers and have maximum forces off 22 lb and 56 lb. The remaining devices have an average maximum force is 3 lb with a standard deviation of 2.2 lb. In our case, we chose a requirement of 15 lb based on an example application of the portable haptics interface (Section 4.0.3) in which it provides force feedback as a user pulls on the bowstring of a bow and arrow. A typical bow and arrow for a beginner has 15 lb of draw weight (that is, it exerts 15 lb tension at a full draw).

[Burdea] argues that the minimum refresh rate to ensure correct force feedback perception is 300 Hz, which is why we selected this value as a design requirement.

The point at which the device is grounded is a design decision with many considerations. First, I am only considering grounding points that are large body parts (that is, the back, torso, or hips) since they need to absorb the reaction forces of the force feedback. Second, the grounding point determines the range of a user’s body through which reaction forces are felt. For instance, if a device is grounded about the hips, a user feels reaction forces throughout his torso and arm. In contrast, if a device is grounded about a user’s upper arm, the reaction forces are only felt through the forearm and hand. Since a user’s hips are closer to the ground and more steady, they would provide the most stable grounding point. However, grounding a device about a user’s back may be easier to don and doff as well as easier to build since it can be incorporated into a backpack.
The mechanism through which the end-effector of the device exerts forces onto a user’s hand is another design decision. Including a pen or a handle for a user to hold is the simplest solution, but it has the disadvantage of precluding applications that require a user to open his or her hands. On the other hand, attaching the end-effector to a user’s wrist has the disadvantage of exerting forces at an unnatural location. A third alternative is to attach the end-effector to the palm of a user through a glove, and this solution would address the issues with the previous ones though the lack of rigidity of the glove may cause problems if the fabric shifts around.

When the motors of the haptic device are turned off, a user’s arm should ideally be able to move freely without exerting any forces. In practice, however, all motors exert a torque even when no current is applied. The inability of a haptic device to exert zero force is a problem that is known as transparency. This consideration will be taken into account while selecting the actuators of the haptic device.

2.0.2 Design Concept

Although a 6DOF robot can exert both torque and force feedback, there is evidence that, at least for certain tasks such as drawing, a 3DOF device with force feedback alone can approximate the performance of a 6DOF device with both torque and force feedback [44]. Verner and Okamura note that, when forces and torques are presented to user are coupled through the environment, force feedback alone may be sufficient to complete the task. As discussed below, the portable haptics interface has an HTC Vive controller at its end effector, and the lever arm created by the controller results in torque being applied to the user. However, this torque cannot be controlled. Lacking torque feedback is a limitation for more complex tasks where force and torque should be decoupled such as rotating a doorknob [44]. There is a tradeoff between this limitation and the reduced cost and complexity of a haptic device that only uses force feedback. Out of the 25 haptic devices surveyed by Coles et al., 11 have 3DOF and three more devices come in 3DOF and 6DOF versions. Based on this evidence and on the desire to keep the design as simple as possible, the portable haptic device was designed to be a 3DOF robotic arm.

The above design requirements suggest mounting the haptic device to a user’s back, torso, or hips.
After considering all options, I decided to mount the robotic arm on a user’s back with a backpack (see Figure 2-1) for simplicity, as mounting a device to the torso or hips would require more complex and less intuitive mechanisms. More specifically, the robotic arm is an RRR manipulator as illustrated by Figure 2-2 where its base is mounted on top of a user’s shoulder.

![Figure 2-1: A sketch of the proposed design of a body-grounded kinesthetic haptic device. The device is mounted on a user’s back and contains a robotic arm with its end-effector attached to a user’s hand.](image)

The advantage of a manipulator that goes over the shoulder as opposed to an exoskeleton is that it bypasses the shoulder and, consequently, does not require a ball-and-socket joint, resulting in a
Figure 2-2: The robotic arm of the proposed design is an RRR manipulator with the configuration shown here.
simpler design that requires less weight and size. The workspace of the manipulator is determined by the placement of the base and by the lengths of each link.

### 2.0.3 Design Choices

To encompass the range of motion of a person’s arm, the combined length of both of the robot arm’s links should be greater than the person’s forward functional reach, which is the distance from the acromial process to the pinch as illustrated by Figure 2-3.

A forward functional reach of 25.1 in is average while a reach of 27.9 in is at the 95th percentile [24]. Designing the reach of the arm to be greater than or equal to 27.9 in therefore ensures that the robot arm encompasses the range of motion of at least 95% of people.

The maximum reach of the robot arm is equal to the sum of the lengths of both links, as shown in Figure 2-4. The portable haptics interface’s links are 32 in (15 and 17 in, respectively). Since this value is larger than 27.9 in, it exceeds the requirement and adds buffer space so that the robot arm is always bent even when a user stretches his or her arm all the way.

Since the portable haptics interface was designed with a primary focus on virtual reality, the end-effector of the robot was attached to an HTC Vive controller.

To exert the 15 lb of force from the requirements given the dimensions above, the actuator with the highest load needs to exert 4.2 N-m of torque to result in a 15 lb force when the end effector is near its base.

Based on the requirements above, the portable haptics interface uses three dynamixel MX-64T servos [5]. These servos contain maxon motors, 12-bit 360 degree absolute encoders, and an integrated microprocessor that supports half duplex asynchronous communication. They weigh 126 g and have a stall torque of 6 N-m and a no load speed of 63 rpm at 12 V.

For simplicity, the prototype is powered using USB comms and a DC power jack, though a full-fledged system would use a battery and wireless or bluetooth communication.
Figure 2-3: The distance denoted by $1b$ is known as the forward functional reach from the acromial process to the pinch. The acromial process is a bony protuberance at the top of the shoulder located on the scapula. Image from [24]
Figure 2-4: The maximum reach of the robot arm is equal to the sum of the lengths of both links

2.0.4 Making it Wearable

The portable haptics interface attaches its robot arm to a user’s shoulder using a shoulderplate that is attached to a rigid backplate (see Figure 2-5). This mechanism is relatively quick to don & doff and is similar to a backpack.

To don the portable haptics interface, a user should 1) place both arms in the shoulder straps just as with a regular backpack, 2) tighten both shoulder straps as much as possible while still remaining comfortable, 3) buckle & tighten the waist belt, and 4) buckle & tighten the cross strap. The waist belt ensures that the backplate remains securely attached to the back and the cross strap secures the shoulder plate onto a user’s shoulder. The shoulder plate has a layer of foam padding at the bottom to conform to the shape of the shoulder.

2.0.5 Attaching the HTC Vive Controller

To attach an HTC Vive controller to the end effector of the robot arm, we used a hinge from a gopro mount and screwed it onto a 3D printed coupler that was secured around the end of the robot arm’s...
Figure 2-5: The portable haptics interface has a robotic arm mounted on a shoulderplate that is secured to a backplate. The mechanism is secured with straps and is similar to a backpack.

second link. The other end of the hinge was fastened to a 3D printed block that was secured to the end effector. This setup is illustrated in Figure [2-6]

2.0.6 Mechanical Prototype

A render of the robot arm used in the portable haptics interface is shown in Figure [2-7]. The backplate was lasercut out of 0.25 in acrylic while the shoulder plate and robot links were waterjet cut out of 0.07 in, 6061 aluminum.

In an early prototype, the robot arm lacked robustness because its links would deflect under regular load. In this prototype, the cross section of each link was a rectangle (see Figure 2-8).

Equation (2.1) is the maximum deflection for a beam of length L, Young’s modulus E, and moment of inertia I subject to an applied force F.

\[
\delta_y = \frac{FL^3}{3EI}
\]  

(2.1)
Figure 2-6: To attach an HTC Vive controller to the end effector of the portable haptics interface, a gopro hinge was fastened to a 3D printed coupler that was secured around the controller. The other end of the hinge was screwed onto another 3D printed block that was secured to the end effector.
Figure 2-7: A render of the robot arm used in the portable haptics interface. An HTC Vive controller is attached to the end effector and the base of the robot arm serves as the shoulder plate that is mounted onto a user.

Figure 2-8: An early prototype used flat sheets of waterjet cut aluminum to build each link. The cross section of each sheet is a rectangle.
Although the values of $L$, and $E$ are constrained by the dimensions of the link, increasing the moment of inertia decreases the maximum deflection. The moment of inertia of a rectangular cross section is given by Equation (2.2).

$$I = \frac{bh^3}{12}$$

(2.2)

By changing the shape of the cross section to the one shown in Figure 2-9, its moment of inertia increases, which reduces its maximum deflection. Calculated using superposition and the parallel axis theorem, this moment of inertia is given by Equation (2.3).

$$I = \frac{bh^3}{12} + \frac{2hh_2^3}{12} + 2hh_2\left[\frac{h_2 + h}{2}\right]^2$$

(2.3)

With this change, the moment of inertia increases by two orders of magnitude and the resulting links no longer deflect under regular loads. To fabricate links from aluminum sheets that have ‘c’ shaped cross sections, a waterjet cutter was used to cut each sheet with extra flanges to the side (see Figure 2-10) that were then bent using a sheet metal bender.

The final result Figure 2-11 shows a user wearing the portable haptics interface.
Figure 2-9: Using a ‘c’ shaped cross section increases a links moment of inertia and reduces its maximum deflection.
Figure 2-10: To fabricate the side of each link, a sheet of aluminum was waterjet cut with extra flanges on its side, and these flanges were then bent sideways using a sheet metal bender.
Figure 2-11: A user wearing the portable haptics interface.
Chapter 3

Mathematical Modeling

The portable haptics interface is effectively a 3DOF manipulator with three joints. This section defines the coordinate system of each joint, derives the kinematics of the manipulator, and presents a model for gravity compensation.

3.0.1 Coordinate Systems

The generalized coordinates of the manipulator, $\vec{\theta} = (\theta_1, \theta_2, \theta_3)$, are defined as shown in Figure 3-1. The coordinate system of each joint and manipulator as well as its end effector are defined with respect to the base as shown in Figure 3-2.

We now show the homogeneous transformation matrices between adjacent joints. In the following notation, $^a_b{T}$ is the transformation from frame B to frame A, and $^a\vec{r}$ is the coordinate of point $\vec{r}$ relative to frame $a$.

\[
^\text{base}_1{T} = \begin{bmatrix}
\cos(\theta_1) & -\sin(\theta_1) & 0 & 0 \\
\sin(\theta_1) & \cos(\theta_1) & 0 & 0 \\
0 & 0 & 1 & M \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (3.1)
Figure 3-1: The generalized coordinates of the portable haptics interface.

\[
\frac{1}{2}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & 0 \\ \sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}
\]

\[
\frac{2}{3}T = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & l_1 \\ \sin(\theta_3) & \cos(\theta_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}
\]

\[
\frac{3}{t}T = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.4}
\]
Figure 3-2: Coordinate system definitions for the portable haptics interface, which is effectively a 3DOF manipulator with three joints.
3.0.2 Forward Kinematics

The forward kinematics calculate the position of the end effector relative to the base given a set of generalized coordinates.

\[ b_{\text{base}}^t T = b_{\text{base}}^1 T \times 1_2 T \times 2_3 T \times 3_t T \]

The forward kinematics are equal to the translation that results from \( b_{\text{base}}^t T \):

\[
\begin{align*}
  x &= l_1 \cos(\theta_1) \cos(\theta_2) - l_2 \cos(\theta_1) \cos(\theta_2 + \theta_3) \\
  y &= l_1 \sin(\theta_1) \cos(\theta_2) + l_2 \sin(\theta_1) \cos(\theta_2 + \theta_3) \\
  z &= l_1 \sin(\theta_2) + l_2 \sin(\theta_2 + \theta_3)
\end{align*}
\]

3.0.3 Inverse Kinematics

The inverse kinematics calculate the manipulator’s generalized coordinates given the position of the end effector relative to the base. Here, we derive the inverse kinematics algebraically.

First, we calculate \( \theta_1 \) by noting that it only depends on \( x \) and \( y \) (see Figure 3-1):

\[ \theta_1 = \arctan2(y, x) \]

Then, we reduce the calculation of \( \theta_2 \) and \( \theta_3 \) to a two-dimensional problem by representing the problem with respect to \( \tilde{x} \) (see Figure 3-3). Figure 3-4 shows a plot of this reduction.

Applying the law of cosine to Figure 3-4
Figure 3-3: Reducing the inverse kinematics problem to a plane.

Figure 3-4: The generalized coordinates of the portable haptics interface.
\[
\tilde{x}^2 + z^2 = l_1^2 + l_2^2 - 2l_1l_2 \cos(\pi - \theta_2)
\]
\[
= l_1^2 + l_2^2 + 2l_1l_2 \cos \theta_2
\]
\[
\cos \theta_2 = \frac{\tilde{x}^2 + z^2 - l_1^2 - l_2^2}{2l_1l_2}
\]

(3.8)

While we could calculate \(\theta_2\) by applying an arccosine to Equation (3.8), expressing this equation in terms of a tangent results in more numerical precision. To do so, we use the identity from Equation (3.9).

\[
\tan \frac{\theta_2}{2} = \frac{\sqrt{1 - \cos \theta_2}}{\sqrt{1 + \cos \theta_2}}
\]

(3.9)

The result is shown in Equation (3.10).

\[
\tan \frac{\theta_2}{2} = \pm \sqrt{\frac{2l_1l_2 - \tilde{x}^2 - z^2 + l_1^2 + l_2^2}{-(l_1 - l_2)^2 + \tilde{x}^2 + z^2}}
\]

(3.10)

Applying arctan to Equation (3.10) and noting that arctan is an odd function leads to Equation (3.11).

\[
\theta_2 = \pm 2 \arctan \sqrt{\frac{(l_1 + l_2)^2 - \tilde{x}^2 - z^2}{\tilde{x}^2 + z^2 - (l_1 + l_2)^2}}
\]

(3.11)

Equation (3.12) expresses \(\theta_1\) in terms of \(\beta\), which is defined in Figure 3-4.

\[
\theta_1 = \arctan\left(\frac{z}{\tilde{x}}\right) - \beta
\]

(3.12)

From Figure 3-4, the value of \(\beta\) can be calculated as shown in Equation (3.13).

\[
\beta = \arctan\left(\frac{l_2 \sin \theta_2}{l_1 + l_2 \cos \theta_2}\right)
\]

(3.13)
Combining Equation (3.12) and Equation (3.13) results in Equation (3.14).

\[ \theta_1 = \arctan \frac{z}{x} - \arctan \left( \frac{l_2 \sin \theta_2}{l_1 + l_2 \cos \theta_2} \right) \]  

(3.14)

Note that there are two possible solutions for \((\theta_1, \theta_2)\). This multiplicity of results means that the robot arm can typically reach the same position in two different manners. To disambiguate between both solutions, the portable haptics interface chooses the one that has a non-positive value of \(\theta_2\).

### 3.0.4 Jacobian

The Jacobian of the manipulator is calculated from the forward kinematics (that is, Equations (3.5), (3.6), and (3.7)).

\[
J = \begin{bmatrix}
J_{0,0} & J_{0,1} & J_{0,2} \\
J_{1,0} & J_{1,1} & J_{1,2} \\
J_{2,0} & J_{2,1} & J_{2,2}
\end{bmatrix}
\]  

(3.15)

Where
The jacobian is used to calculate the torque that each motor should apply at a given state to exert a desired force at desired direction (see Equation (3.16)), though this equation does not take into account gravity or friction.

\[ \vec{\tau} = J^T \vec{F} \] (3.16)

### 3.0.5 Gravity Compensation

We can compensate for the effects of gravity by adding a compensation term that we derive using Lagrangian mechanics. Figure 3-5 illustrates the variables used in this section.

First, we calculate the potential energy of each link:
Figure 3-5: The first and second links have masses $m_1$ and $m_2$, respectively, and their center of gravities are at a distance of $r_1$ and $r_2$ from their joints, respectively.

\[ U_1 = m_1 g r_1 \sin \theta_2 \]
\[ U_2 = m_2 g (l_1 \sin \theta_2 + r_2 \sin (\theta_2 + \theta_3)) \]
\[ U = U_1 + U_2 \]

Next, we calculate the partial derivatives of the potential energy with respect to $\theta_2$ and $\theta_3$:

\[ \frac{\partial U}{\partial \theta_2} = m_1 g r_1 \cos \theta_2 + m_2 g (l_1 \cos \theta_2 + r_2 \cos (\theta_2 + \theta_3)) \]
\[ \frac{\partial U}{\partial \theta_3} = m_2 g r_2 \cos (\theta_2 + \theta_3) \]

The Lagrangian is equal to the torque:

\[ Q_1 = \tau_1 \]
\[ Q_2 = \tau_2 \]

The Lagrangian Equations for mechanics are contained in Equation (3.17).
\[
\tau = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) - \frac{\partial L}{\partial \theta}
\]

(3.17)

For simplicity, this derivation makes the quasi-static assumption, in which velocities and accelerations are negligibly small.

\[\dot{\theta} = \ddot{\theta} = 0\]

The result is given by Equation 3.18:

\[
\tau = \begin{bmatrix}
    m_1 g r_1 \cos \theta_2 + m_2 g (l_1 \cos \theta_2 + r_2 \cos(\theta_2 + \theta_3)) \\
    m_2 g r_2 \cos(\theta_2 + \theta_3)
\end{bmatrix}
\]

(3.18)

Note that the gravity compensation term is independent of \(\theta_1\) and that the two torque values given in Equation 3.18 are for the second and third motors. Also note that the torque for gravity compensation of the first motor is zero and is not included in this equation. Adding this term to the motor torques theoretically compensates for the effects of gravity under quasi-static conditions.

Experimentally, the gravity compensation model was able to lift the weight of the motor, but the end-effector was only able to move slowly when enabled. As a result, gravity compensation impeded transparency and was unsuitable for haptic feedback. Having faster motors would overcome this limitation.
Chapter 4

Implementation and Applications

This section describes the simulation environment used to test the mathematical model for the robot’s arm, the system used to control the motors, and two example applications that demonstrate the capabilities of the portable haptics interface.

4.0.1 Simulation Environment

We used Robot Operating System (ROS) to develop a simulation environment to quickly test algorithms and validate our models. We wrote a Unified Robot Description Format (URDF) file that describes all of the elements of a robot including its links and joints. Rviz uses an URDF file to render a visualization of the robot given a set of generalized coordinates.

To test the inverse kinematic model, we developed a script for Rviz that uses inverse kinematics to set the generalized coordinates of the robot so that its end effector touches an interactive marker (see Figure 4-1). A user can move the marker by dragging it to a different position. By moving the marker throughout the workspace of the robot and visually checking that the robot tracks its position, we informally validated the inverse kinematic model.
Figure 4-1: Validating our inverse kinematic model using a simulation. The inverse kinematic model is used to set the position of the robot to match the position of an interactive marker, which can be moved around by clicking and dragging.
4.0.2 Electronics and Communication

The portable haptics interface uses dynamixel MX-64T servos [5], which are controlled using serial communication at a baud rate of 250000. Our setup uses a USB2Dynamixel, a USB device that connects to a computer’s USB port and allows communication with one or more dynamixels while drawing power from an external power supply.

Each servo has a built-in encoder with 4096 ticks per second. To control the position of a servo, a serial command must enable torque (that is, register 24) and then specify a goal position (that is, registers 30 and 31). To control the torque of a servo, a serial command must enable torque control mode (that is, register 70) and specify a goal torque (that is, registers 70 and 71).

The serial communication for the simulation environment utilized a ROS library called dynamixel_motor (see [3]). ROS is, however, directly incompatible with virtual reality applications that are implemented and executed on Windows computers. On Windows, I used the Dynamixel SDK, which contains helper functions that read from and write to the registers of each dynamixel servo.

Two example applications demonstrate the design space of body-grounded kinesthetic haptic devices: first, the portable haptics interface was used to provide force feedback while shooting a bow and arrow in virtual reality, and second, to provide force feedback for impacts such as hitting a ball with a paddle.

4.0.3 Shooting a Bow & Arrow

This section describes the design and implementation of an example application that allows a user to shoot a bow and arrow in virtual reality while receiving force feedback from the portable haptics interface in a way that simulates the tension of the bowstring.

When a person pulls on a bowstring while shooting a real bow and arrow, the tension of the bowstring exerts a force onto the person’s fingers, but when shooting a bow and arrow in virtual reality, this force feedback is not available. With the HTC Vive, for example, each controller has an embedded vibrotactile actuator, and a game called The Lab utilizes vibration feedback as a user pulls on a virtual bow and arrow [10].
This example application extends the haptic feedback of a virtual bow and arrow to include force feedback, which adds a new dimension to the experience.

**Bow & Arrow Terminology**

To shoot a real bow and arrow, a person must pull on the bowstring, aim, and release the bowstring to fire. The draw length is the distance between the nocking point of the bowstring (that is, the point of contact of the arrow and the bowstring) and the grip of the bow handle at full draw [30]. A “standard” draw length is 28 inches, and bow manufacturers typically specify its draw weight, which is the force that the bowstring exerts at this standard draw length.

**Mathematical Model**

Our model assumes that 1) the elasticity of the bow is linear and 2) the bow and arrow aims away from the base of the portable haptics interface (and thus, all forces are exerted towards its base).

Since we assume the elasticity of the bow is linear, we can use Hooke’s law to model it as a “virtual wall” with enough compliance to resemble pulling on a bowstring (see Figure 4-2). After placing an arrow on the bow’s arrow rest, when a user pulls on the bowstring, his or her hand reaches inside the virtual wall, and the portable haptics interface begins exerting a force that is proportional to the distance from a user’s hand to the virtual wall (that is, the draw length, \(d_L\)) as shown in Equation (4.1).

\[ F = -kd_L \]  

(4.1)

The virtual wall is modeled as a plane with normal \(\hat{n}\) that intersects point \(p\) (see Figure 4-3). The value of \(\hat{n}\) is determined by the position of the bow as it runs along the same direction as an arrow while the value of \(p\) is calibrated for each user. For calibration, a user fires an arrow while pulling back as far as possible, and the minimum and maximum distances to the base throughout this shot...
Figure 4-2: Using a virtual wall to implement the tension of a bow and arrow. When a user places the arrow on the bow’s arrow rest, a user feels the tension of the bowstring increase in proportion to the draw length. The draw length is calculated relative to a virtual wall that is placed at the bowstring’s position. Pulling on the arrow is analogous to pulling an object inside a virtual wall of high compliance.

are recorded as the range of motion of the arrow. The value of $p$ is set to be at this maximum distance from the base along the direction of $\hat{n}$.

The draw length, which is equivalent to the distance from the bowstring to the virtual plane, is calculated using Equation (4.2), which follows form Figure 4-4.

$$d_L = \text{Proj}_{\hat{n}}(x - p) = (x - p) \bullet \hat{n}$$

Once the desired force is calculated using the model above, our system uses the jacobian transpose method to find the torques that each motor should apply. This process is periodically repeated so that the system constantly updates its model.
Figure 4-3: The virtual wall is defined by a plane with normal \( \hat{n} \) that intersects point \( p \). The tension of the bowstring is applied along the direction of \( \hat{n} \) and its magnitude is proportional to \( |p - r_a| \).
Figure 4-4: The draw length of a bow and arrow is equivalent to the distance from the bowstring to the virtual plane and can be calculated by projecting $x - p$ onto $\hat{n}$. 
Virtual Reality

The virtual reality environment, shown in Figure 4-5, was implemented using Unity3d and VRTK [11], which is a library of scripts and prefabs. The bow is attached to an HTC Vive’s left controller, and when a user presses-and-holds the trigger on the right controller, an arrow appears and is automatically attached to the controller’s position. To shoot an arrow, a user must move it close to the handle of the bow, pull back, and release the trigger.

Our demo virtual environment consists of an open terrain with a vertical wall behind which the user is able to take cover from a turret that periodically tries to shoot at the user. The turret and the wall are designed to encourage a user to move, which highlights the portability of our system. Behind the wall, there are bulls-eye targets that a user is able to shoot. The targets are positioned in a way that they cannot be seen unless a user steps out into the range of the turret.

Figure 4-5: A screen capture of the virtual environment that demonstrates the bow and arrow application.
4.0.4 Simulating Impacts

This section describes the implementation of an example application that uses the portable haptics interface to simulate impacts such as hitting a ball with a tennis racket. While the bow and arrow example demonstrates impedance control, where the force exerted by the haptic device is determined as a function of its position, the force resulting from an impact is a function of time.

Mathematical Model

An impact is modelled as an impulse of force. An impulse of force is implemented by calculating the desired torque of each motor using jacobian transpose force control with a relatively large force value and then setting these desired torques for 50 consecutive samples, which corresponds to approximately 250 ms. This process generates a force in the same as the direction of the impact (see Figure 4-6).

Virtual Reality

The virtual reality environment was implemented using Unity3d and has a virtual tennis racket attached to an HTC Vive controller (see Figure 4-7). Balls are intermittently launched at a user from a canon, and a user is able to hit them with the racket. When a user hits a ball, the portable haptics interface generates an impulse of force to provide haptic feedback for the impact.

Informal Testing

We conducted an informal evaluation of this application by having three users wear the portable haptics interface to receive haptic feedback when hitting a ball with the racket. One user noted that he was focused on looking at the ball rather than on looking at the racket, so the haptic device provided quick feedback on whether the ball was hit. Another user noted that the haptic feedback increases the realism of the game.
Figure 4-6: The direction of the impulse of force is the same as the direction of impact.
During testing, we observe a limitation of the current prototype. Users were not able to freely and comfortable position and rotate the tennis racket because the HTC Vive controller has a constrained axis of rotation. Users are able to freely pan and tilt the controller, but the attachment to the end effector of the robot arm fully constrains roll. This constraint was not a limitation for the bow & arrow application discussed above, but in the case of a tennis racket, users cannot rotate the handle to adjust the angle of the face of the racket. Even if the prototype allowed the HTC Vive controller to freely rotate about the roll axis, the shape of the controller is designed so that it’s only comfortable to hold at a single position. In other words, holding the controller after rotating it about the roll axis is uncomfortable. The shape of the controller would have to be extended or modified to be uniform and more inline with a racket.

4.0.5 Other Applications

In addition to the applications demonstrated above, the portable haptics interface could also be used for the following applications.
Representing weight of virtual objects. For example, while a bucket full of water and an empty bucket only differ in appearance slightly, haptic feedback can make the difference in their weights apparent. Moreover, the portable haptics interface can represent negative weights such as that of a collection of helium balloons.

Representing viscosity or drag. When moving a paddle through the water or a large piece of cardboard through the air, a resistance that is proportional to velocity is created. The portable haptics interface can be used to emulate these properties and enable a user to, for example, feel the resistance of water while rowing on a boat or while moving a hand in the water while swimming.

Sculpting and painting. Google’s Tiltbrush [8] uses the HTC Vive’s controller to create 3D paintings on a virtual canvas. The portable haptics interface could be used to allow a user to sculpt or paint on a wall or surface while being subject to its properties and compliance.

A game of pinball. Not only can one pull on the plunger to shoot the ball at the beginning of a game, but one could also push on the side of the pinball machine to tilt and shake the table.

Teleporting or moving objects. The portable haptics interface is capable of moving the HTC Vive controller. If, for instance, a user is in a virtual environment with zero gravity, the device can move the controller as if it were floating when a user lets go. A user could then see the controller float away and grab it before it gets too far away. Similarly, the controller or the object attached to it could teleport to a different location in virtual reality as the haptic device moves the controller to its new position.
Chapter 5

Evaluation

The evaluation will be divided into two sections. First, a technical evaluation will measure the maximum force the haptic device can apply. Second, a subjective evaluation will measure the sense of presence and the comfort of a small group of participants while completing a task in a virtual environment both with and without the prototype haptic device.

5.0.1 Technical Evaluation

*Maximum force.* The maximum force near the base was measured experimentally by pulling on the robot arm with a manual scale. The portable haptics interface was instructed to apply a force in the forward direction. The magnitude of the force was controlled by software. Theoretically, the maximum force it can apply is 21 lb, but this is when one of the motors is at stall torque. When the end effector applied 14 lb, one of the motors made a loud noise because two of its internal gears were overdriven and had worn. Although the motor is capable of exerting more torque, its gearing is not robust enough to support this load for continuous periods. We have tested applying 5 lb and 10 lb of force for a minute after replacing the motor and did not encounter any failures.

*Update rate.* In a typical program, a main loop reads each motor’s position and outputs desired torque values. In these circumstances, we measured the update rate of each motor to be 200 Hz. Although this update rate is lower than our target of 300 Hz, we note that it may be sufficient for our
Table 5.1: A summary of the design requirements and the achieved results for the maximum force and refresh rate of the portable haptics interface.

<table>
<thead>
<tr>
<th>property</th>
<th>requirement</th>
<th>achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>max force</td>
<td>15 lb</td>
<td>14 lb</td>
</tr>
<tr>
<td>refresh rate</td>
<td>300 Hz</td>
<td>200 Hz</td>
</tr>
</tbody>
</table>

purposes. [Coles et al.] found that the required update rate depends on the stiffness of the surfaces that are simulated [23]. In other words, lower refresh rates are sufficient for providing feedback for softer objects. In particular, both the bow & arrow application and the impact simulation application require a coarse resolution and relatively low stiffness.

Table 5.1 summarizes the requirements and the results for the design goals relevant to the technical evaluation.

5.0.2 Subjective Evaluation

The objective of the subjective evaluation is to assess the ergonomics of the prototype haptic device and to test the following two hypotheses:

- use of haptics increases a user’s sense of presence in virtual reality
- large body parts such as the hips and torso can absorb the reaction forces exerted on the arms, hands, or fingers without disrupting the user

We evaluated the first hypothesis by measuring if the prototype device is able to increase the sense of presence of a user while completing a task in virtual reality, which would suggest that there is a degree of realism to the sensations it produces. The second hypothesis was evaluated by measuring the comfort of a user since unwieldy reaction forces would manifest themselves as discomfort.

A bow and arrow task was chosen to evaluate the use of the portable haptics interface for the following reasons: 1) the HTC Vive already has a bow and arrow game that is widely considered to be captivating [10], 2) shooting targets yields many objective metrics such as accuracy rate and time.
between shots, 3) demonstrates compliance control, which is a core application of the portable haptics interface, and 4) it fully leverages a first person perspective, making it suitable for evaluating presence.

Methods

Participants. Twelve right-handed members of the MIT community took part in this study. Eleven of them had previous experience with virtual reality and six of them had experience shooting a bow and arrow. They were not paid and eight participants were female.

Task. The task, which takes place entirely in virtual reality, consists of shooting arrows at bulls-eye targets while taking cover behind a virtual wall and avoiding arrows from a computer controlled character who is at a fixed location. If a user is hit by an arrow, a red overlay flashes on the screen and an audio file of an arrow hitting an object is played. Having to avoid the arrows encourages a participant to move, highlighting the portability of the system. If a user dodges the arrow, an audio file of an object rushing through the air, which is informally described as whooshing, is played.

A participant must step into the range of fire of the computer controlled characters to see a target. After a participant hits a target, a text overlay indicates whether the target was hit and the next target appears at a different location. The objective is to shoot thirty targets while avoiding the computer controlled character’s arrows as much as possible.

The direction at which a user is aiming with the bow and arrow is indicated with a line projected on the ground. This line does not provide any distance cues. The virtual environment contains distance markers at 10, 20, and 30 yards to help people get a sense of its scale.

Design. This experiment has a within-subjects design with two conditions: 1) with haptics and 2) without haptics. Although a user wears the portable haptics interface in both conditions, its force feedback is disabled in the latter. The purpose of having a user wear an unpowered and disactivated haptic device for the without haptics condition is to isolate the effect of the haptic feedback in and of itself while avoiding confounds related to its wearability and ergonomics. The order of the conditions was counterbalanced.
Apparatus. An HTC Vive running a custom application built with Unity3d displays the virtual environment and records data. Additionally, a prototype of the portable haptics interface is used for the with haptics condition and provides force feedback and emulates the elasticity that one would feel while pulling on a bow string. The force needed to pull the robot arm to a standard draw length was measured to be 4.6 lb. Although this value is small compared to the draw weight of a real bow and arrow, pilot tests revealed that this force was sufficient.

Metrics. For each condition, we recorded a participant’s performance shooting targets, and we measured a user’s sense of presence and discomfort using standardized and validated questionnaires. In particular, we recorded the time it took a user to shoot a target, whether each target was hit, the number of times a user was hit by the computer controlled opponent, and the draw length of the arrow as a user shot.

Schubert, Friedmann, and Regenbrecht [40] define presence as a user’s psychological sense of being within virtual environment even though a user is physically located elsewhere. We measured presence using the ‘iGroup Presence Questionnaire (IPQ)’ [4], which divides presence into three factors: spatial presence (the sense of being physically within the virtual environment), involvement (how much attention a user devotes to the virtual environment), and experienced realism (the subjective experience of realism) [4]. These subscales are fairly independent factors and were developed from a principal components analysis. Presence has been used as a metric to evaluate the effectiveness of haptic devices in virtual environments, especially when the haptic feedback is trying to emulate sensations that occur in the real world [14, 20, 22, 33, 36].

We appended two questions to the IPQ that are specific to the bow & arrow scenario: 1) “pulling on the bowstring has a realistic feeling” and 2) “the position of my hand when pulling on the bowstring is realistic.’ These questions have a scale from -3 to 3 ranging from “fully disagree” to “fully agree.”

To measure comfort, we will use a modified version of the Cornell Musculoskeletal Discomfort Questionnaires (CMDQ) [1]. The CMDQ asks participants if they experienced pain or discomfort in specific body parts throughout the last work week, but in our case, a participant will only experience the haptic device once. The questionnaire will be modified to take this into account while leaving everything else as is. The CMDQ will also be used to assess the ergonomics of the prototype and
evaluate if its size and weight cause any discomfort.

Procedure. We first introduce the purpose of the evaluation and present an overview of the task. Second, we fit the headset of the HTC Vive to the user and ensure that it’s comfortable. Third, we explain how to shoot a bow and arrow in virtual reality and have a user shoot ten targets without haptic feedback as training. Fourth, for the first condition, we start by having the user shoot 30 targets, the first 10 of which are considered training data. Fifth, we ask the participant to fill out the presence questionnaire (that is, the IPQ). Sixth, we ask the user to repeat steps four and five for the second condition. Seventh, we ask a user to fill out the comfort questionnaire (that is, the CMDQ) while still wearing the portable haptics interface. Finally, after a user doffs the portable haptics interface, we conduct a brief interview to obtain open-ended feedback. Figure 5-1 shows an overview of the procedure.
Results

Participants completed a total of 720 trials (12 participants \( \times \) 30 trials per condition \( \times \) 2 conditions). It took each participant 35 to 45 minutes to complete the entire evaluation.

*Objective data.* A paired-samples t-test was conducted to compare the time it took a user to shoot a target with and without haptics. There was a significant difference in the scores for the haptics (M=4317 ms, SD=1279 ms) and without-haptics (M=3421 ms, SD=875 ms) conditions; \( t(10)=-2.382, p=0.038 \) (see Figure 5-2). The remaining metrics recorded by the virtual reality software revealed no significant differences. These metrics include the percentage of times a target was hit, the number of times a user was hit by the computer controlled opponent, and the draw length of the bow as a user shot an arrow.

![Figure 5-2: With haptic feedback, participants take a longer time to shoot arrows than without haptic feedback.](image)

*Presence.* Although all questions in the iGroup Presence Questionnaire (IPQ) were anchored with -3 to +3, they were transformed to a score from 0 to 6 for analysis. Reliability analyses on the results of the IPQ found the Cronbach’s alphas for spatial presence, involvement, and realness summarized in Table 5.2.

The IPQ measures spatial presence, involvement, and experience realism with six, four, and five questions, respectively. The results of the IPQ were used to calculate metrics for spatial presence,
Table 5.2: The results of a reliability analysis on the data collected using the iGroup Presence Questionnaire.

<table>
<thead>
<tr>
<th></th>
<th>spatial presence</th>
<th>involvement</th>
<th>experienced realism</th>
</tr>
</thead>
<tbody>
<tr>
<td>with haptics</td>
<td>0.506</td>
<td>0.786</td>
<td>0.664</td>
</tr>
<tr>
<td>without haptics</td>
<td>0.700</td>
<td>0.225</td>
<td>0.457</td>
</tr>
</tbody>
</table>

involvement, and experienced realism by taking the means of each group of questions after reversing items with reversed scales [4].

Three dependent variables (spatial presence, involvement, and experienced realism) were considered through a two level (haptic and without-haptic) repeated measures multiple analysis of variance (MANOVA). Within subjects contrasts revealed a significant effect of haptic feedback upon spatial presence $F(1, 11) = 6.828, p = .024, \eta^2_p = .383$ (see Figure 5-3). No significant effects of haptic feedback were seen for involvement $F(1, 11) = 1.042, p = .101, \eta^2_p = .225$ or experienced realism $F(1, 11) = 2.570, p = .137, \eta^2_p = .189$. The large effect size ($\eta^2_p = .383$) seen in the spatial presence effect was submitted, along with the experimental design, to a power calculator, G*Power [25, 26], which suggested that a sample size of 10 participants would be ideal to detect significant effects.

![Figure 5-3: With haptic feedback, participants have an increased sense of spatial presence.](image)

**Bow & arrow specific questions.** The two questions we appended to the IPQ are 1) “pulling on the bowstring has a realistic feeling” and 2) “the position of my hand when pulling on the bowstring is realistic.” There was a significant difference in the results of the first question for the haptics
Table 5.3: A summary of the results of the CMDQ shows how many participants out of 12 chose answers different than “not uncomfortable.” No participant chose “very uncomfortable” for any body part. Body parts not listed on this Table only had answers of “not uncomfortable.”

<table>
<thead>
<tr>
<th>body part</th>
<th># slightly uncomfortable</th>
<th># moderately uncomfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>shoulder (right)</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>shoulder (left)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>upper back</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>upper arm (right)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>upper arm (left)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>lower back</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>forearm (right)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>forearm (left)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>wrist (right)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>wrist (left)</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

(M=5.00, SD=1.13) and without-haptics (M=2.25, SD=2.18) conditions; t(11)=3.667, p=0.004 (see Figure 5-4). The results of the second question did not reveal any significant differences between conditions.

Figure 5-4: Results suggest that pulling on the bowstring has a more realistic feeling in the with-haptics than the without-haptics condition.

Discomfort. Table 5.3 summarizes the results of the CMDQ questionnaire.
Chapter 6

Discussion and Conclusion

On types of haptic feedback. The bow & arrow application demonstrated the use of compliance control (that is, the desired force is a function of the deviation from a resting position) whereas the impact simulation application showed the use of time based control (that is, the desired force is a function of time). The portable haptics interface can also implement impedance control, which is more general than compliance control and supports more complex functions such as dashpots. For instance, impedance control could be used to render a magnetic field that attracts a virtual reality controller. Alternatively, impedance control can use dampeners so that it resists motion as if one were underwater. A limitation of the current prototype is that it cannot be used to render textures because its bandwidth is too low. Rendering perceptually stable textures requires 5-10 kHz of bandwidth [22], which is significantly more than the 200 Hz our current motors are able to output.

On performance. The results of the subjective evaluation suggest that participants take more time to shoot arrows with haptic feedback than without. The extra time needed to shoot arrows may be explained by the users having to exert more force to pull the bowstring to a given length. The other objective metrics recorded did not differ between conditions, including the percentage of times a target was hit, the rate at which a user was hit by computer controlled opponent, and the draw length of a bow. During the interviews after the evaluation, three participants noted the haptic feedback helped them feel how far back they were pulling. For instance, P12 stated "I had more control because I felt how much I was pulling back." However, this effect did not lead to a performance
gain. These results, overall, suggest that the performance of users while shooting targets does not differ between the with- and without-haptics conditions.

On presence. Spatial presence increased in the with-haptics condition, which suggest that haptic feedback increases a user’s sense of being physically present within the virtual environment. P3 noted that, unlike with her previous VR experience, she wasn’t self-conscious about waving her arms around due to the haptic feedback. P1 noted the virtual reality world was more believable when there was haptic feedback.

There were no significant differences in the involvement between the with- and without-haptics conditions. This result suggests that, while shooting targets with a bow and arrow, haptic feedback does not increase how much attention a user devotes to the virtual environment. A user’s focus is typically on trying to hit the targets and on avoiding the computer controlled opponent’s fire, and these aspects are both present regardless of whether haptic feedback is enabled.

There were no significant differences in the experienced realism between the with- and without-haptics conditions. On the other hand, there was a significant difference in the responses to the “Pulling on the bowstring has a realistic feeling” question, which suggests that haptic feedback increased the perceived realism of pulling on the bowstring. The subjective data corroborates this point. When asked what pulling on the virtual bow and arrow felt like in an open ended manner, all users with previous bow and arrow experience (that is, seven out of 12 participants) stated it felt very similar to pulling on a real bowstring. P8 emphasized that the sudden drop in force the moment he shoots an arrow felt realistic and adds value to the game. These results suggest that, although pulling on the bow and arrow is perceived as realistic, the visual and auditory aspects of the virtual environment are not realistic.

On mental models. The 3D model of the bow used in the virtual environment was in the form of a recurve bow, and its force increased proportionally to draw length. P5 stated that the increase in force while pulling on the bowstring is clear, but that the recurve bows that he used have more sudden increases in force towards the beginning of a draw (see Figure 6-1). Since this participant had significant experience using recurve bows, his mental model of the force exerted by a bow and arrow was slightly different than the Hooke’s law model used by the haptic device. This observation
highlights the importance of ensuring that the visuals and the haptic feedback go hand in hand. If the mental model that the visuals evoke differ from the haptic feedback, a user may be confused when feeling the haptic feedback for the first time.

Figure 6-1: A recurve bow’s draw force increases more rapidly during the beginning of a draw; it increases at a decreasing rate until it straightens out and begins to increase at an increasing rate.

Realism vs. Gaming Some participants found the increased force they needed to exert with haptic feedback to be tiring. In particular, P10 noted that “shooting arrows is not something you can do for long periods of time because it’s tiring”, and P11 noted that “pulling on the bowstring is difficult with haptic feedback.” The force exerted by the portable haptics interface is significantly lower than the draw weight of any bow and arrow, so more realistic haptic feedback would exert higher forces and make people more tired more quickly. If the intent is to maximize realness, becoming tired is an expected side effect for novice shooters. If, on the other hand, the intent is to build a game that users can play for longer periods of time, then smaller forces are desirable.

On discomfort. Most participants experienced discomfort in right wrist and right forearm from the weight of robot arm. This weight may have also decreased realism. In particular, P9 stated that, due to the weight of the robotic arm, the arrow seemed to weigh more than the bow, which was
Table 6.1: A summary of the hypotheses tested in the evaluation of the portable haptics interface and their results.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>use of haptics increases presence</td>
<td>Partially supported. Haptics increases spatial presence but has no effect on involvement or experienced realism</td>
</tr>
<tr>
<td>large body parts absorb the reaction forces</td>
<td>Supported. Few participants reported discomfort in their shoulder or back.</td>
</tr>
<tr>
<td>without disrupting the user</td>
<td></td>
</tr>
</tbody>
</table>

not realistic. Furthermore, both P8 and P9 also noted that the weight of the robotic arm caused the arrow to seem too heavy. A potential solution for this problem is to introduce gravity compensation so the robot’s motors are able to compensate for the weight of the robot arm.

No users experienced moderate or higher discomfort in their back and only one reported moderate discomfort on the right shoulder, which suggests that the back and the shoulder are able to absorb the reaction forces exerted on the arms, hands, or fingers without disrupting the user.

Table 6.1 summarizes the hypotheses of this evaluation and the results we obtained.

6.1 Limitations and Future Work

The weight of the robot arm is non-negligible and contributes to people’s arm getting tired. Although the motors we selected were compact, lightweight, and capable of exerting sufficient torque, they were too slow to allow a user to move normally when gravity compensation was enabled. Using faster motors could allow the gravity compensation model developed in Chapter 3 to reduce the weight of the robot arm.

Seven users experienced slight discomfort on right shoulder and one experienced moderate discomfort. This discomfort was caused by the shoulderplate, which transmits the reaction forces from the base of the robot arm to the shoulder and backplate. P4 suggested making the padding underneath the shoulder plate softer. An improved prototype can use medical foam to make the padding softer while maintaining its shape.

Five participants experienced slight discomfort on the upper back. This discomfort may have been
caused by not having enough padding on the backplate and by overtightening straps. This issue can be ameliorated by adding medical foam to the backplate and by using straps that are slightly elastic. Additionally, P3 and P12 found the straps to be uncomfortable because they exerted too much pressure. A future prototype would use thicker, padded straps.

When P5 fully extended his arm, the robot arm reached the outer portion of its workspace, where it has a singularity because its links are parallel and are only able to move up or down. This position prevented horizontal movement until the links were unlocked. Although the length of the robot arm was designed to accommodate users with large arms, the base of the robot arm did not rest over his shoulder. A future prototype would make the position of the shoulderplate relative to the backplate adjustable. Similarly, when P9 moved the HTC Vive controller too far back, the first link of the robot arm reached an angle greater than 90 degrees, which caused it to move all the way back due to gravity. Gravity compensation would solve this problem.

The experimenter observed all participants accidentally move the robot arm into the HTC Vive’s head mounted display while starting the evaluation. The large size of the head mounted display contributes to this problem. A potential solution to this limitation would be to tilt the base of the robot arm by 45 degrees so the first link is further away from a user’s head.

A limitation of the current prototype is that it uses a USB cable and an external power supply. A future prototype would use wireless communication and a battery worn on the backpack.

Another limitation of the device is that it does not allow users to, for instance, lean against a wall since body-grounding cannot exert net forces onto the user even though it can exert net forces onto a user’s hand and arm. Additionally, the device can only exert forces onto a single hand. An avenue of future work is to use two symmetric mechanisms to explore the design space of two handed haptic devices.

Another avenue of future work is to explore applications of the portable haptics interface outside of virtual reality. In this case, the device would be thought of as an extra limb as opposed to a haptic device. For example, the device could be used to pass a user tools as one solders or performs an activity that occupies both hands.
6.2 Insights for Wearable Haptic Design

The following design guidelines derive from the design, implementation, and evaluation of the portable haptics interface.

- When designing the dimensions and workspace of a manipulator, use anthropometric research to ensure that it fits on the majority of people. For example, design for a user in the 95% percentile of arm length, shoulder width, or any other relevant dimension.

- Design the manipulator so that its links do not collide with a user’s body and are far from singularities throughout the relevant portion of a user’s range of motion.

- Use gravity compensation to avoid taxing the users with carrying unnecessary weight.

- Calibrate the magnitude of applied forces for each individual user to avoid making them too tired too quickly.

- Ensure that the 3D models used in virtual reality evoke mental models that are associated with the way the haptic feedback feels.

- Minimize the weight on the robot arm and shift bulkier components to a user’s back.

- Use thick straps with some elasticity to secure a device to a user’s back.

6.3 Conclusion

We developed the portable haptics interface, a wearable kinesthetic haptic device for providing haptic feedback in virtual reality. We demonstrated two example applications of this device: 1) simulating the elasticity that one feels while pulling on a bowstring when shooting a bow and arrow, and 2) simulating a sudden impact such as hitting a ball with a paddle by rendering an impulse of force. Moreover, we evaluated our system by having 12 users shoot targets with a bow and arrow in virtual reality both with and without haptics and measuring their performance, sense of presence, and discomfort. The results of this evaluation revealed that haptics increased spatial presence with
a large effect size while there was no statistically significant effect on involvement and experienced realism. Additionally, results suggested several improvements to the ergonomics of the system such as using thicker straps to better distribute the load. Wearable kinesthetic haptic devices are suitable for room-scale virtual reality applications because of their portability. Force feedback provides an opportunity to create new experiences and increase a user’s sense that he or she is within the virtual environment, and making them portable gives users these benefits without constraining them to a chair.
Bibliography


[28] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in vr. In


