The Touch Thimble: Providing Fingertip Contact Feedback During Point-Force Haptic Interaction

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ABSTRACT

Touching a real object with your fingertip provides simultaneous tactile and force feedback, yet most haptic interfaces for virtual environments can convey only one of these two essential modalities. To address this opportunity, we designed, prototyped, and evaluated the Touch Thimble, a new fingertip device that provides the user with the cutaneous sensation of making and breaking contact with virtual surfaces. Designed to attach to the endpoint of an impedance-type haptic interface like a SensAble Phantom, the Touch Thimble includes a slightly oversize cup that is suspended around the fingertip by passive springs. When the haptic interface applies contact forces from the virtual environment, the springs deflect to allow contact between the user's fingertip and the inner surface of the cup. We evaluated a prototype Touch Thimble against a standard thimble in a formal user study and found that it did not improve nor degrade subjects' ability to recognize smoothly curving surfaces. Although four of the eight subjects preferred it to the standard interface, overall the Touch Thimble made subjects slightly slower at recognizing the presented shapes. Detailed subject comments point out strengths and weaknesses of the current design and suggest avenues for future development of the device.

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human Information Processing; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O;

1 INTRODUCTION

Almost all living organisms have a sense of touch, the capacity to detect contact between self and environment [1]. Haptic (touch-based) feedback includes two primary channels: tactile sensation from the skin and force sensation from the muscles. Researchers have developed a wide variety of systems that enable haptic interaction with virtual environments, extending touch beyond the physical realm. The objective that unifies almost all haptic interfaces is a goal of stimulating the user's sense of touch in a manner that resembles real interactions. For example, such systems can allow a user to explore the contours of a computer-aided design (CAD) model or practice medical procedures on a virtual patient.

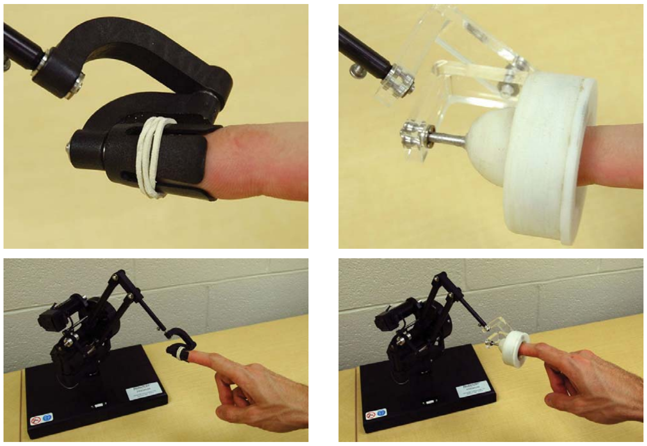

Figure 1: The standard thimble (left) and our new Touch Thimble (right) can both attach to a SensAble Phantom Premium 1.0 (bottom) to allow a user to feel virtual surfaces with a fingertip.

Some haptic interfaces focus on tactile sensation, attempting to recreate intricate textures and pressure distributions over an area of skin. But most haptic interfaces, like the SensAble Phantom shown in the lower panels of Figure 1, portray only forces. Typical three-dimensional point-force haptic interfaces measure the motion of the user's finger and map it into a computer-simulated world. An appropriate reaction force vector is computed in real time from a model and displayed to the user using the device's actuators. The connection between the device and the hand is usually accomplished via a pen-like stylus or a thimble, as pictured.

Though it is used on almost every point-force haptic interface that seeks to simulate fingertip contact with real surfaces, a standard thimble interface like that shown on the left side of Figure 1 does not capture the full sensation of touching real objects. Humans sense the making and breaking of fingertip contact through the sudden stimulation of sensitive mechanoreceptors in the skin [22]. Wearing a thimble floods these receptors with constant tactile information and prevents the skin from making fresh contacts. The human ability to discriminate softness by fingertip probing was extensively studied by Chen and Srinivasan [2]. These researchers found that the just-noticeable difference (JND) in softness is approximately 5% for the bare finger and for a finger wearing a thin latex glove. Interestingly, JND performance decreases to approximately 50% when the finger operates from inside a rigid thimble. We expect that a similar diminishing of tactile sensation exists between bare finger touching and touching through the standard thimble on the Phantom; thus, we conjecture that the addition of contact feedback could drastically improve the feel of virtual environments.

This work develops and evaluates the new Touch Thimble device shown on the right side of Figure 1. The Touch Thimble allows the

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[*] This work was supported by the University of Pennsylvania, the Johns Hopkins University, and the National Science Foundation via grant #IIS-0347464 and an REU fellowship. K. J. Kuchenbecker is with the General Robotics, Automation, Sensing, and Perception (GRASP) Lab, Mechanical Engineering and Applied Mechanics Department, University of Pennsylvania. D. Ferguson, M. Kutzer, M. Moses, and A. M. Okamura are with the Laboratory for Computational Sensing and Robotics (LCSR), Mechanical Engineering Department, Johns Hopkins University. M. Kutzer is also with the Applied Physics Laboratory, Johns Hopkins University.

user of a point-force haptic interface to feel the natural sensation of making and breaking contact with virtual or remote objects. As overviewed in Section 2, this research builds on many previous efforts in haptic device development. Section 3 details the design of our system, which centers on a new passive mechanical attachment device for the fingertip. This new interface suspends a larger thimble around the fingertip with carefully selected springs that deflect to allow contact when the haptic interface applies forces to the fingertip. We evaluated the performance of the Touch Thimble relative to a standard thimble through the human-subject study on shape recognition described in Section 4. Results in Section 5 indicate that the Touch Thimble design did not improve nor degrade shape recognition accuracy, but it was found to make subjects slightly more slow in responding. Section 6 discusses these findings, along with the qualitative comments of users comparing the two thimbles. We conclude by making recommendations for future design improvements that may be able to better combine the distinct modalities of force and tactile feedback in a simple fingertip mechanism.

2 BACKGROUND

Many researchers have sought to enhance the user's experience of fingertip contact with virtual objects by developing new hardware interfaces. Some work has focused on creating novel finger attachment devices for devices such as the SensAble Phantom to enable the user to experience a variety of additional sensations. Other researchers have turned to alternative system paradigms to provide a more compelling feel.

2.1 Fingertip Attachment Devices for Impedance-Type Haptic Interfaces

The widely used SensAble Phantom Premium haptic interface [14] is a computer-controlled desktop device that allows the user to touch virtual objects and receive haptic, graphic, and auditory feedback from the interaction. The Phantom's mechanism is a backdrivable spatial linkage with low inertia, low friction, high-resolution position sensing, and high-fidelity actuation. The computer uses a fast digital servo loop to measure the position of the Phantom, determine the current state of the virtual interaction, and apply a three-dimensional force vector at the Phantom's endpoint for the user to feel. The connection between the user's finger and the device has a strong influence on the experience but has received relatively little attention in research and commercial development to date. The two user/device interfaces that are commonly used with a Phantom are the stylus and thimble. Haptic software designers who want to simulate fingertip interactions almost exclusively employ the thimble shipped with the Phantom, as shown on the left side of Figure 1.

The earliest example of a non-standard finger-device interface may be the Tactile Feedback Thimble designed and constructed by Hasser and Daniels to provide both steady-state and vibratory forces at the user's fingertip [5]. This thimble design centers on a solenoid that can press up into the fingerpad, and it includes a load cell in series with the solenoid plunger to enable closed-loop control of the tactile stimulus. The thimble was mounted to a Phantom device via custom gimbals equipped with optical encoders for orientation sensing. Notably, the researchers sought to minimize the mass of the device so that it would not overly degrade the dynamic performance of the Phantom, since the user must accelerate this mass to move around in the virtual environment. In addition to the Phantom's standard effective end-effector inertia of 50 to 100 g, the Tactile Feedback Thimble has a mass of 39.5 g, and its custom gimbal set has a mass of 55.0 g [5]. The researchers found this additional tip-mounted inertia to significantly limit dynamic performance and recommended at least a 30% mass reduction for future thimble designs [6]. Unfortunately, formal user testing of the Tactile Feedback Thimble cannot be found in the literature.

Another effort to add tactile sensation to the endpoint of a point-force haptic interface is the TextureExplorer by Ikei and Shiratori [7]. This system places a two-by-five array of 0.5 mm diameter pins against the skin of the user's distal fingerpad. The pins are controlled to vibrate at 250 Hz with a range of intensities in coordination with the macroscopic movement of the user's finger over a virtual texture. The tactile stimulation unit has a mass of 30 g, but the mass of the entire device, including its handle and gimbals, was not available. Subjects displayed a significant increase in their ability to discriminate textures in timed trials when receiving both tactile and force feedback than when receiving force feedback alone, supporting the promise of such combined feedback strategies.

Wagner et al. also developed a pin display that could attach to the end of a force feedback device [20]. Their system mounted a six-by-six array of 1.0 mm pins covered by a thin sheet of rubber on a WAM robot arm to allow users to simultaneously feel contact forces and local shape. Human subjects were able to discriminate stiffnesses more accurately when they received tactile feedback along with force; force feedback alone yielded success rates that did not statistically differ from chance. This result indicates that tactile feedback can significantly improve a user's ability to interact with and perceive properties from a virtual environment.

Another successful example of a thimble attachment device for the Phantom is the Tactile Slip Display designed and constructed by Webster, Murphy, Verner, and Okamura [21]. This device locates a motor-driven ball under the fingertip in order to display the sensations of sliding contact and incipient slip as the user travels over virtual surfaces. The designers sought to minimize the size and mass of the device to facilitate integration with the Phantom, and the final version has a mass of 192 g. Human subject testing in a virtual paper-sliding task demonstrated that the addition of slip feedback through the device helped individuals modulate the forces they applied to the virtual piece of paper more accurately. Another recent device that portrays fingertip slip is that of Provancher, Erickson, Barbagli, and Tan [18]: their system focused on rendering rotational slip, rather than sliding contact, and user tests have not yet been reported.

A final example of an attachment device for enhancing haptic sensation from virtual surfaces is the Contact Location Display by Provancher, Kuchenbecker, Niemeyer, and Cutkosky [17, 19]. This system uses a forearm-mounted motor and sheathed push-pull wires to drive a roller forward and backward along the bottom of the user's distal fingerpad. The contact element is attached to the distal link of a Phantom, and the push-pull wires connect the cylinder to an open-bottomed thimble worn by the user. The system moves the cylinder to the centroid of contact with objects in a planar virtual environment, and it was found to improve subject discrimination of both curvature and object motion. In another human-subject study [12], the Contact Location Display enabled subjects to complete a contour-following task approximately twice as quickly and four times as accurately as the standard Phantom thimble. One of the most compelling features of this device is that the contact element is sprung away from the fingertip to allow the sensation of making and breaking contact. Because the motor that drives the contact element is positioned on the forearm, this system's effective tip mass is almost identical to that of the standard Phantom thimble. It should be noted, though, that the Contact Location Display is susceptible to inadvertent fingertip contact during high accelerations in free space, and it cannot function in three-dimensional virtual environments.

2.2 Alternative System Paradigms

Researchers seeking to enable more compelling haptic interactions have also developed new system paradigms that do not center on an impedance-type device like the Phantom. First, the Encountered Object Approach naturally includes the sensation of making and breaking contact [15]. Rather than attaching the user's finger to the endpoint of a backdrivable robot arm, an encountered-type system tracks the movement of the user's hand in free space, often via optical sensors. It then anticipates contact and aims to place a physical object at the location in space where a virtual object will next be contacted; the physical object can be anything from a button or a switch to a small, flat surface patch. The object to be encountered is typically moved by a non-backdrivable robot arm, so contact can feel very stiff, in contrast to the softness of traditional impedance-type displays [11]. Most notably, the mechanoreceptors on the user's fingertip receive no stimulation until contact with something in the virtual environment, which is represented authentically by a physical object.

The Encountered Object Approach can be applied to a ring, thimble, or hand exoskeleton that surrounds the user's fingertip. Yoshikawa and Nagura created such a device in order to portray both touch and force feedback to the operator's fingertip in two dimensions [23]. In this design, the user places his or her fingertip inside an oversized ring attached to a robotic arm. An array of optical sensors on the ring tracks fingertip movement and controls ring position such that the ring and fingertip touch only when contact with a virtual object occurs. An improved system that could track three-dimensional motion was described in [24]. This second Encountered Object system has a thimble that is equipped with optical tracking sensors; it is driven through a mechanism by two three-degree-of-freedom force-feedback robots, one controlling position and the other orientation. An encounter-type hand exoskeleton is showcased in [16], using photo reflectors to adeptly track the fingertips. These systems enable unencumbered free-space motion and an authentic transition to contact, but they require significant new hardware development.

In this same approach to haptic rendering, Cini, Frisoli, Marchesci, Salsedo, and Bergamasco designed and constructed a finger-mounted thimble that can move a flat contact plate with five active degrees of freedom around the fingertip [3]. Their Active Haptic Thimble combines the characteristics of an encountered-object system with a focus on contact patch orientation. Furthermore, they state that the device could be attached to the endpoint of a force-feedback robot in order to combine encountered contact sensation with grounded forces. Though the design and control of the device are well documented, user tests of the system are not yet available.

2.3 Summary

Researchers have invented many new methods of conveying contact between the user's fingertip and a virtual surface since the development of the SensAble Phantom. The technique of designing and constructing a device that can attach to the Phantom has yielded many successful systems, though one must carefully negotiate the trade-off between increased functionality and added mass. Standalone devices can shed the constraints of traditional impedance-type rendering and successfully enable new types of haptic interaction, but their size and complexity make the development task more daunting. With the goal of improving the realism of virtual surfaces, we observe than no one has yet provided a simple system for giving authentic feedback on the making and breaking of contact. The Contact Location Display by Provancher et al. included this functionality among its feature set [17, 19, 12], but it was limited to planar motion and could convey contact only along the fingerpad. The present work thus seeks to meet the following challenge: design, build, and test a lightweight, passive thimble for the SensAble Phantom to enable authentic haptic portrayal of the presence and absence of fingertip contact in three dimensions.

3 TOUCH THIMBLE SYSTEM

We developed a system that allows the user of an impedance-type haptic interface to experience the sensation of making and breaking fingertip contact with virtual objects. Our approach combines a custom thimble attachment device constructed from passive mechanical elements with a minimally modified version of the traditional proxy-based haptic rendering algorithm.

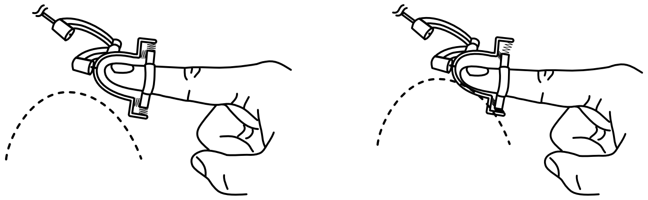

Figure 2: Cut-away diagram of a finger in the Touch Thimble near a virtual object (dashed line). The finger is inserted into a padded ring, which connects to the shell through a set of springs. The Touch Thimble shell does not contact the user's fingertip until forces from the haptic interface deflect the springs.

3.1 Touch Thimble Concept

The Touch Thimble design suspends an oversized rigid shell around the fingertip via a set of springs, as illustrated in Figure 2. The tip of the thimble attaches to the endpoint of a Phantom or a similar haptic interface through concentric gimbals, and the springs attach to the finger through a padded ring located at the wearer's distal interphalangeal (DIP) joint. The objective of the design is for the springs to maintain a separation between the sensitive fingertip and the thimble's inner surface during all free-space motion. When the user's finger enters a virtual obstacle, the haptic interface displays a repelling force proportional to penetration, which deflects the springs and brings the shell into contact with the fingertip. This design gives the user the freedom to interact with the haptic environment with any part of his or her distal index finger phalanx, including the top, sides, front, and bottom of the fingertip.

The Touch Thimble concept is designed around ideal, quasi-static motions that do not include significant accelerations. Clearly, these assumptions could be violated by humans using such an interface in practical applications, so the feasibility of the design hinges on the stiffness selected for the springs. Qualitatively, it can be observed that stiff springs maintain a good separation between the fingertip during changing free-space motions, but they require the user to exert a larger force against a virtual surface before fingertip contact occurs. Conversely, soft springs readily allow contact with virtual surfaces, but they also allow inadvertent fingertip stimulation during changing free-space motion; a quantitative analysis of this trade-off is presented in the Appendix.

In theory, the appended analysis is sufficient to select a spring constant given geometrical properties of the thimble and the desired dynamic response of the haptic interface. Practically, however, the formulation's strong nonlinearities, the large range of possible joint positions, velocities, and accelerations to consider, and the significant assumptions make quantitative optimization cumbersome, if not impossible. Because only two parameters need to be selected (k, the stiffness of the springs, and d_c, the resting distance between the finger and the thimble), we opted for an empirical testing method in which candidate springs were added to a prototype and quickly tested by the researchers in a virtual environment to qualitatively determine whether the force required to deflect them was too large or too small, testing both fast motions and slow contacts.

3.2 Mechanical Design

The Touch Thimble concept has been realized in a series of physical prototypes to enable evaluation of its potential for improving haptic interactions with virtual environments. Figure 3 provides two views of the CAD model of our final design, and the right side of Figure 1 shows the final prototype. The asymmetric shape of the finger cup, which is visible in profile in the top view of the CAD model, was derived from measurements of a real fingertip of roughly average

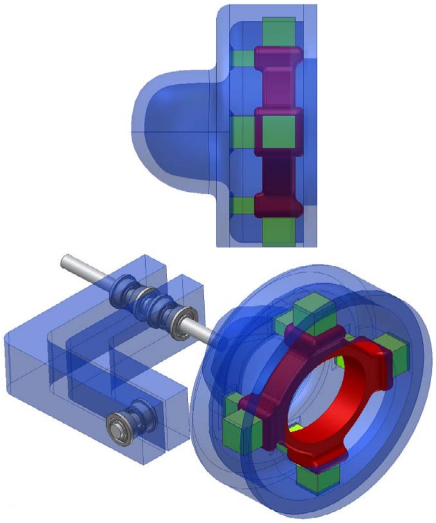

Figure 3: Views of the CAD model of the Touch Thimble assembly (top) and the Touch Thimble with custom gimbals (bottom).

size and proportion. The inner surface of the thimble was made to be 3 mm larger than the measured fingertip in all directions, thereby fixing d_c. Because the design constraints are concerned with the total force required to deflect the springs to fingertip contact, we were free to select either k or d_c based on other concerns. The distance was fixed at 3 mm to keep the size of the device to a minimum without precluding use by individuals with slightly larger fingers. The length of the contact area was also selected based on measurements of the stereotypical fingertip, seeking to locate the padded ring just in front of the DIP joint while maintaining approximately 3 mm of clearance at the fingertip.

The thin-walled shell that encloses the fingertip is connected to a larger thin-walled cylinder that houses the springs and the padded finger ring. Rather than being circular, the cylinder has an oval cross section to better match the shape measured from the stereotypical finger. The Touch Thimble prototype has three sets of springs inside this housing, one set for each Cartesian direction of movement. The left-right and up-down directions include two springs each, and the insertion direction has four, which can all be seen in the lower angled view of Figure 3. Rectangular blocks of open cell foam are used as the springs, and they are connected to the ring and the thimble with glue at slightly recessed locations to help maintain their orientation and position. When installed, each spring has approximately 5 mm of travel so that it never prevents the user from contacting the inner thimble surface. Furthermore, the springs are pre-compressed by approximately 3 mm to help prevent the ruptures and disattachments that can stem from excessive spring tension. As mentioned above, this particular type of foam was chosen via empirical testing of a variety of potential materials; it was selected because it provided a good qualitative compromise between resistance to inadvertent contact and the amount of force necessary for initial deflection during virtual surface contact. The effective spring constant for the spring set in each direction is 200 N/m.

The finger-attachment ring was designed for the size and shape of the reference finger's DIP joint. The ring's inner surface is approximately 2.5 mm larger than the measured shape of the finger to leave room for foam cushioning, which makes the system more comfortable to wear for individuals with a range of finger sizes. Lastly, an oval plate with a central hole was placed on the back of the thimble both to protect the parts inside and to help keep the ring aligned with the thimble cup. The three main parts of the thimble (shell, ring, plate) were printed in white ABS plastic on a fused deposition modeling (FDM) machine. The plate and the rod at the thimble's tip were glued in place after the ring and springs had been assembled. The gimbals were modeled after those of the traditional Phantom haptic interface, and they include bearings at all pivots.

3.3 Rendering Algorithm

The Touch Thimble is compatible with the traditional proxy-based rendering algorithm for virtual environments, but its naturalness can be improved by a simple calibration procedure. Synchronizing the timing of actual fingertip contact with the occurrence of contact in the graphical rendering seems to help the user mentally connect these events. Because a small force is required to deflect the springs through the offset d_c, the spherical haptic proxy (used for collision detection and force computation) needs to be larger than the graphical proxy (shown on the screen).

The size of the haptic proxy can be calibrated by testing the force required for the user to feel contact. The procedure we developed asks the user to press slowly into a haptic surface that has very low stiffness. The user indicates the force level at which he or she just barely detects the contact, and the size of the haptic proxy is updated accordingly. This simple adjustment causes the haptic interface to output a small force when the graphical proxy is close to making contact with a surface in the virtual environment. The force becomes large enough to cause the user to feel contact when the graphical proxy actually makes contact. Calibration was chosen over a universal haptic proxy diameter to better account for individuals with different sized fingers and different levels of sensitivity to contact stimulation.

4 USER STUDY

We conducted a human-subject experiment to help evaluate the usefulness of the Touch Thimble system for point-force interaction with a virtual environment. The study was framed as a comparison between the Touch Thimble and a standard thimble for the SensAble Phantom Premium (both illustrated in Figure 1). The two thimbles were called the *white thimble* and the *black thimble* in all study materials to avoid biasing the subjects toward our own design. We sought to determine how these two finger attachment devices affect interactions between the human user and a computer-controlled virtual environment.

Following the haptic mode taxonomy of Kirkpatrick and Douglas [9], goal-oriented haptic interactions can be divided into the two primary areas of motor control and perception, though sophisticated applications often blend elements from both of these categories. Continuing to the lowest level of this taxonomy, we argue that the haptic modes most relevant to thimble design are target acquisition (moving to a desired location in free space), geometric perception (being able to identify shapes by feel), and material perception (being able to feel surface properties such as texture and temperature). For this initial study, we chose to focus on geometric perception, and future studies will analyze the effects of thimble design on target acquisition performance. We do not plan to study material perception tasks because they generally include sustained contact with a small part of the object [13], which we do not expect to differ significantly between the two studied thimbles.

A thimble-based point-force haptic interface generally models the fingertip as a sphere, so orientation control is not critical. Instead, the user attempts to move the spherical proxy to desired locations in the virtual environment to enable interaction with interesting geometric features. This process is analogous to the bare-handed exploratory procedure of contour following, useful for determining the volume and exact shape of an object [13]. Thus, we decided to evaluate the two thimbles through a shape recognition task. The specific hypotheses for this study were as follows:

1. The white thimble enables users to identify surface shapes more accurately and more quickly than the black thimble.

2. Users prefer the white thimble over the black thimble.

4.1 Experimental Setup

Each subject tested both thimbles on the same desktop haptic interface. The design of the white thimble was described in Section 3.2, and the black thimble is commercially available from SensAble Technologies; it holds the tip of the user's index finger firmly in a plastic cup. The fit of the black thimble was tightened by wrapping a rubber band circumferentially around its four leaves to prevent it from slipping off the finger of the subject. Each thimble includes gimbals that allow arbitrary orientation of the fingertip, though these three rotation angles are not sensed.

The point-force haptic interface employed in the study was the SensAble Phantom Premium 1.0 shown in Figure 1. Its distal link has a hollow cylindrical tip, into which the attachment rod of either thimble's outermost gimbal can be inserted. The chosen rod is held in place by a set screw threaded through the Phantom's distal link. When the thimbles are installed on the Phantom, the distance from the tip of the distal link to the center of the gimbals' rotation is identical, so that swapping thimbles does not alter the kinematics of the system.

The haptic interface was controlled by a personal computer running Fedora Core Linux, the SensAble OpenHaptics toolkit, and CHAI 3D [4]. At a rate of 2500 Hz, the servo loop reads the Phantom encoders, computes the position of the center of the gimbals, determines whether the spherical proxy is colliding with a virtual surface, and applies the resulting contact force. Leveraging the .obj file-loading capabilities of CHAI, the shapes were haptically rendered as meshes with a planar point resolution of 0.5 mm. To isolate the subject's sense of touch, no graphical feedback was presented, and the Phantom was hidden from view by a black cloth hung over an open-front box.

4.2 Shape Recognition Experiment

The chosen experiment was designed to determine how the white and black thimbles differentially affect the user's ability to recognize three-dimensional shapes in a haptic virtual environment. Building on the design of a study by Kirkpatrick and Douglas [9], we chose to test subject recognition of the five smoothly curving shapes defined by Koenderink and van Doorn: cap, ridge, saddle, rut, and cup [10]. These geometric shapes are defined by the equation

$$z = ax^2 + by^2, \tag{1}$$

where the z-direction is positive up and a and b take a different pair of values for each surface. Illustrations of the chosen shapes and their corresponding equations are provided in Figure 4. This type of surface patch can be used to assemble a second-order approximation of a generic surface [10], so recognition performance of these shapes should translate well to generic shape recognition.

Each study volunteer was first screened to ensure that both thimbles could achieve a comfortable, secure fit on the index finger of the individual's dominant hand. The goals and procedures of the study were then presented to the potential subject, and he or she was given the opportunity to sign an informed consent document in order to participate. Enrolled subjects completed a questionnaire recording their gender, age, handedness, and prior experience with haptic interfaces. All experimental methods and study documents were approved by the Institutional Review Board of the University of Pennsylvania under protocol #806862.

Shape Training: Subjects completed the shape recognition experiment first with one thimble and then with the other. Thimble presentation order was balanced across subjects. After the current thimble was attached to the haptic interface, the subject inserted his or her finger into it and lowered the black fabric curtain over the Phantom. Text prompts in a terminal window on the computer screen guided the subject through initial explorations of all five shapes in sequence, providing the name of the shape (cap, ridge, saddle, rut, or cup). When done exploring, subjects were required to press the corresponding labeled key on the computer keyboard to identify the shape and proceed to the next one. Between shapes, the subject's finger was gently pulled to a location several centimeters above the center of the workspace in order to prevent contact during the transition to the new shape. This training phase was not limited in duration, but subjects could not backtrack to previously explored shapes.

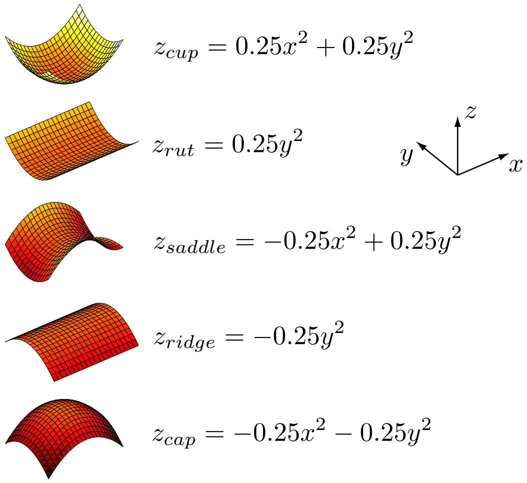

Figure 4: Five shapes with equations.

Recognition Practice: Subjects then practiced haptically recognizing the five shapes, which were presented twice each in random order. The subject was instructed to explore the surface until he or she could confidently judge which shape it was. The subject recorded the vote by pressing the chosen key on the keyboard and immediately received feedback on whether it was correct, including the name of the true shape. Between surface presentations, the finger was again pulled toward the location above the center of the shapes. The true shape, the subject's judgment, and the exploration duration were recorded for each practice trial, along with a time-stamped archive of the movement path taken by the subject.

Recognition Testing: The system then transitioned to the formal testing phase, in which each virtual surface was presented four times in fully random order. The subject was asked to identify each shape by feel alone, following the procedure of the recognition practice session. After the subject attempted to identify each shape four times, this activity concluded, and the other thimble was attached to the Phantom. The subject then performed the training, recognition practice, and recognition testing phases for the second thimble. Finally, the subject was asked to complete a short written questionnaire to provide qualitative opinions about the performance of the two thimbles during the shape discrimination task.

4.3 Subject Pool

Eight individuals participated in the shape recognition study described above. All were graduate students in engineering at the University of Pennsylvania. Their mean age was 25, and all were right handed. Seven of the subjects were male, and one was female. When asked to state their previous experience with haptic interfaces, three indicated that they had none, two said theirs was limited to less than three prior encounters, two said moderate, and one said extensive.

5 RESULTS

Subject recognition of the five shapes was almost perfect for both thimbles; only one surface was identified incorrectly during the entire testing period of the study, which included 320 trials.

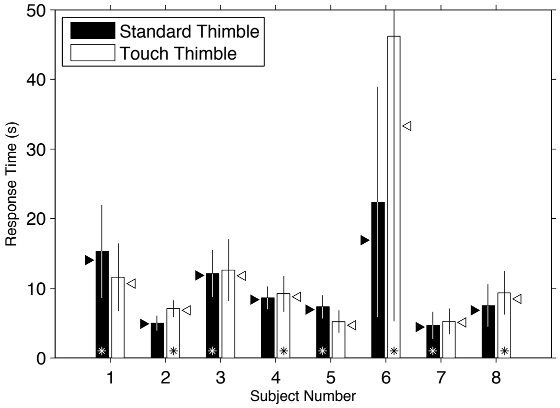

Figure 5: Shape recognition times, by subject. Bars indicate the average time taken by the subject for a shape recognition trial when using the indicated thimble. Triangles denote the medians, lines show standard deviation, and asterisks mark the thimble that was tested first by each subject.

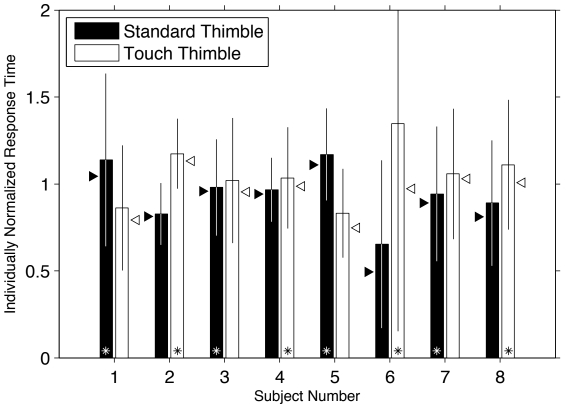

Figure 6: Individually normalized shape recognition times, by subject. Bars indicate the mean normalized time taken by the subject for a shape recognition trial when using the indicated thimble. Triangles mark the medians, lines show normalized standard deviation, and asterisks mark the thimble that was tested first by each subject.

In contrast to this consistently high shape-recognition accuracy, we observed wide variations in the time it took different subjects to recognize the rendered surface. As depicted in Figure 5, most individuals could usually identify the surface within about ten seconds, but subject 6 worked much more slowly than the others and had several outlier trials that were longer than 100 seconds. Identifying these substantial subject-to-subject variations is challenging when one has data from so few members of the population. Furthermore, individual performance variations are confounded with the cross-subject factor of presentation order: odd-numbered subjects were randomly assigned to test the standard thimble first and the Touch Thimble second, and even-numbered subjects the reverse. Because we did not seek to understand the way in which presentation order might affect overall mean task performance (rather, we were interested in understanding the difference in the effect of the two thimble designs on performance), response times were normalized for each subject. This normalization was achieved by dividing each response time measurement by the overall mean of the individual subject's response times, such that normalized time values greater than one are longer than average *for that subject*, and values less than one are shorter than average *for that subject*.

Figure 6 presents the mean, median, and standard deviation of individually normalized response time. We now observe more similar behavior across subjects and can focus on the differential effects of thimble design and presentation order. Table 1 gives the means ($\bar{\tau}_r$) and standard deviations (σ) of normalized response time for the four combinations of Touch Thimble or standard thimble and first or second set of the experiment.

Table 1: Normalized response time across subjects and trials.

		Set One	Set Two
Touch Thimble	$\bar{\tau}_r$ (σ)	1.166 (0.648)	0.943 (0.349)
Standard Thimble	$\bar{\tau}_r$ (σ)	1.058 (0.375)	0.834 (0.342)

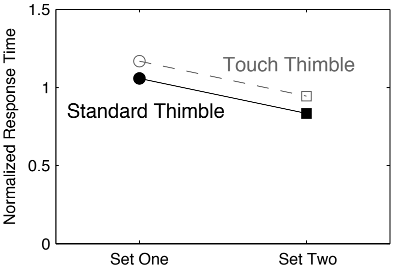

Figure 7: Normalized response time means. Subjects recognize shapes faster in set two of the study than in set one, and they do it more quickly with the black thimble than with the white.

A 2×2 analysis of variance was carried out on the transformed success rate data. There was a significant main effect of set number ($F(1,317) = 20.1, p = 0$), with the second set taking subjects approximately 20% less time than the first. There was also a significant main effect of thimble design ($F(1,317) = 4.76, p = 0.03$), with the standard thimble taking approximately 10% less time than the Touch Thimble. The size of each of these effects was calculated using the partial Eta squared method, giving $\eta_p^2 = 0.0596$ and $\eta_p^2 = 0.0148$ respectively. This statistical quantity gives the proportion of the effect plus error variance that is attributable to the effect: larger values of η_p^2 indicate stronger effects, so set number (i.e., presentation order) has a stronger effect on normalized response time than thimble design. Furthermore, these effect sizes are relatively small, indicating that set number and thimble design can account for only about 6% and 1.5% of the observed variance (effect plus error) of the normalized response time data. As seen by the parallel traces in Figure 7, which graphs $\bar{\tau}_r$ for each treatment, the interaction between set number and thimble design is perfectly insignificant because normalization unifies the mean of the measurements for each subject.

Subjects voted for their preferred thimble at the end of their session, and the total vote counts were matched at four to four. Subjects also provided copious written comments on the factors that influenced their vote, as well as their recommendations for improving the experimental procedure. These qualitative comments are presented and discussed in the following Section.

6 DISCUSSION

Subjects were surprisingly adept at recognizing the five gently curving shapes used in the study. In contrast to the 15% error rate found by Kirkpatrick and Douglas in a similar experiment [8], the error rate here was just 0.3%. Explanations for this difference may include the user/device interface (stylus vs. thimble) and the size of the shapes being presented; the shapes in our study covered the horizontal workspace of the device, while those in [8] spanned only

Table 2: Thimble preference and explanation for all subjects. Votes are tabulated by Touch Thimble vs. Standard Thimble, but the subjects call these devices the white and black thimbles, respectively.

Subject	Vote	Explanation
1	Touch	The white thimble allows the user to "feel" the shape due to the spherical encasing. This helps and enhances the experience, giving the user a sensation to identify as the "surface". But some focus is required as shapes can be sensed quite efficiently, even without this enhancement.
2	Standard	Greater detail of feedback, discrete edges on all the shapes. Cup on the white thimble might need to be bigger to ensure that the cup isn't touched by normal exertion on the suspended frame.
3	Standard	I liked the black thimble because it was less clunky. I felt like I was really using my own finger to feel around. The white thimble felt much less natural. It was a bit too big or something.
4	Touch	I was able to identify the shapes correctly in both instances. However I preferred using the white thimble. It made the recognition easier for me. I did not like the constant pressure on my finger that the black thimble produced. It gets in the way of feeling the shapes. The white thimble does not have this interference, which I believe is better.
5	Touch	More contact area felt like I could press better against the surface and get a feeling of the angle of the plane I was pushing against. [The white] thimble felt a little awkward when moving around and not in contact with surface. Had tendency to roll around, which made free space motion not feel smooth.
6	Touch	Preferred movement of white thimble gimbal. [Verbally indicated that white thimble ring was tight, which made contacting the thimble's front inner surface difficult.]
7	Standard	I felt like my finger twisted around too much in the white thimble. See drawing. [Accompanied by illustration of finger angled in thimble, touching inner surface.]
8	Standard	More constant contact with finger. The white one had a bit of a delayed reaction.

a few centimeters, though their curvature was higher. The shape recognition rate was thus not able to demonstrate any differences between the two thimbles; future studies of this type should make the surfaces more difficult to discriminate, either by reducing their overall curvature or presenting a smaller portion of each surface.

More interesting results were gleaned from the amount of time taken by each subject to recognize shapes under different experimental conditions. Focusing on differential effects within each subject, rather than on overall performance trends, we found two significant main effects. First, subjects continued to improve their recognition speed throughout the experiment, completing the second set of trials 20% more quickly, on average, than the first. This finding on its own is not problematic, because the effect can be isolated across subjects through ANOVA, but future studies might be able to eschew time normalization by having subjects perform more than one test set with each thimble design in pseudo-random balanced order.

The second main effect identified in the study was the slowing influence of the Touch Thimble. Though the size of this effect is small, the Touch Thimble was found to significantly diminish the speed with which subjects could recognize shapes. Improving this performance requires adjusting the design, a process that can be well guided by the written comments of the users, each of whom spent approximately fifteen minutes (training, practice, and experiment) interacting with virtual shapes through each of the interfaces. Table 2 lists the thimble preference and unabridged comments of the eight subjects.

The four subjects who voted for the Touch Thimble primarily praised its ability to let them feel the shape of the surface with their fingertip. These comments indicate that the prototype achieved the intention of the design, at least to some extent and/or for some subjects. Subject 4 even specifically complained about the constant pressure exerted on the finger by the standard thimble, a feature that we sought to improve on. It should be noted that the intended functionality of the Touch Thimble was not explained to the subjects, so their statements reflect their natural, unguided opinions of the system.

The criticisms of the Touch Thimble focus mostly on its behavior in free space, rather than in contact. Subjects 2 and 7 articulate experiencing inadvertent fingertip contact, and the comments from subjects 3 and 5 might also indicate a deficiency in this area. Clearly, the Touch Thimble needs to be made more resistant to the loads exerted by the subject's finger in free space, including both forces and moments, so that such contact can be prevented. The original system analysis overlooked the role of rotational stiffness, but it will be included in the next design iteration.

The stiffness of the connection between finger ring and thimble is also mentioned by Subject 8, who seems not to like the delay between surface force application and fingertip contact. Lastly, subjects 3 and 6 indicated that the white thimble did not adequately fit their fingertip. A loose fit might also cause comments like that of Subject 8. Subjects were screened for thimble fit by asking if the thimbles were comfortable at the start of the study, but no individuals opted to remove themselves from participation on these grounds. Future versions of the Touch Thimble will need to accommodate fingertips of a wider range of sizes in order to be a viable alternative to the traditional thimble.

Overall, the results of the study do not support our hypotheses about the value of the current Touch Thimble prototype. We are encouraged by the balanced subject vote and the slightness of the differences in performance between the two thimble designs. Our findings will be used to guide future development on this project, ensuring that the final version will be able to meet the expectations of its potential users. We look forward to eventually producing a simple, lightweight thimble attachment device that can provide colocated force and tactile feedback to the user's fingertip and thus enable more compelling interactions with virtual surfaces.

ACKNOWLEDGEMENTS

The authors thank Joe Romano for assisting with Linux and OpenHaptics and Dan Morris and Christopher Sewell from CHAI 3D for quickly and effectively answering technical support questions.

APPENDIX

The Touch Thimble's trade-off on spring stiffness can be quantified by analyzing the system dynamics in a manner following that of Yoshikawa and Nagura [24]. The force vector applied to the system by the user's finger, F, and the actuator torques, τ, both act on the interface's configuration-dependent dynamics. Specifically, we can use the Phantom's Jacobian matrix, J, to write

$$F = (J^T(q))^{-1}[M(q)\ddot{q} + \hat{h}(q,\dot{q}) - \tau] \quad (2)$$

$$\hat{h}(q,\dot{q}) = C(q,\dot{q})\dot{q} + G(q) + V(q,\dot{q}) \quad (3)$$

where the vector q contains the three Phantom joint angles, $M(q)$ is the configuration-dependent inertia matrix, and $\hat{h}(q,\dot{q})$ sums the Coriolis, gravitational, and viscous friction forces, denoted $C(q,\dot{q})$, $G(q)$, and $V(q,\dot{q})$ respectively. To calculate the Jacobian, we define the Cartesian position of the end effector, r, as the intersection point of the gimbal rotation axes. The analysis can neglect these passive joint angles because the end effector is at their intersection and cannot transmit torque. The operating range of the Phantom intentionally avoids singularities, so we can assume the Jacobian is always invertible.

In considering how forces are transferred from the user to the thimble, we make one further simplifying assumption. The torques τ applied by the Phantom actuators create a pure force at a central point of the thimble. The finger/ring interface is offset some distance from this point, and in general the equal and opposite force applied by the finger will not be co-linear with the force applied by the Phantom. In order to maintain balance of moments, the finger will usually have to apply a moment to the thimble in addition to the force. The offset distance, and hence the applied moment, is small. For this reason we neglect the effect of the moment and assume the spring mechanism is loaded by a pure force alone.

When the user's finger is in the no-contact mode, all forces F transferred to the thimble are a direct result of spring displacement. We further note that the applied spring force is maximized when the spring displacement is maximized, which occurs at thimble contact, d_c. With these definitions in place, we establish a no-contact distance $d_{nc} < d_c$; for finger displacements less than d_{nc}, the fingertip is far away from the thimble's inner surface and can be considered free floating. We use this information to bound the desired spring force by calculating a minimum force, F_{min}, and a maximum force, F_{max}, as follows. In order to avoid unintended contact during free-space motion, the force it takes to deflect the thimble springs into the fingertip must be greater than the maximum sum of inertial, Coriolis, gravitational, and viscous friction forces we expect the system to experience during use:

$$F_{min} = \max_{q,\dot{q},\ddot{q}} \left[(J^T(q))^{-1} [M(q)\ddot{q} + \hat{h}(q,\dot{q})] \right], \qquad (4)$$

Similarly, in order to ensure that the system can always cause fingertip contact, the force required to deflect the springs should be no more than the net force the actuators can impose on the system in any dynamic configuration:

$$F_{max} = \max_{\tau} \left[\min_{q,\dot{q},\ddot{q}} \left[(J^T(q))^{-1} [M(q)\ddot{q} + \hat{h}(q,\dot{q}) - \tau] \right] \right] \qquad (5)$$

In both (4) and (5), q is bounded by the motion envelope of the system, and τ by actuator limits. Limits on $\dot{q}$ and $\ddot{q}$ can be calculated via

$$\dot{q} = J(q)\dot{r} \qquad\qquad \ddot{q} = J^{-1}(q)[\ddot{r} - \dot{J}(q)\dot{q}] \qquad (6)$$

using estimates of comfortable finger velocity and acceleration for $\dot{r}$ and $\ddot{r}$. Together, these equations define two critical points on the force/displacement curve of the spring mechanism, F_{min} and d_{nc} during no-contact, and F_{max} and d_c during contact; this pair of points can be used to select an appropriate spring stiffness for the use of the Touch Thimble on a selected haptic interface.

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