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CONTACT FORCE PERCEPTION WITH AN UNGROUNDED HAPTIC INTERFACE

Christopher Richard
crichard@cdr.stanford.edu

Mark R. Cutkosky

Center for Design Research
Stanford University
Stanford, California 94305-2232

ABSTRACT

Two haptic interfaces, each able to provide either grounded or ungrounded haptic feedback, were constructed. Tests were conducted to compare a subject's ability to perform boundary detection and object size discrimination tasks with grounded or ungrounded haptic feedback, with or without vision. Not surprisingly, grounded feedback is better than ungrounded feedback in displaying forces that stem from grounded sources. However, ungrounded haptic feedback can give comparable results in boundary detection tests.

Subjects also reported that the application of forces to the fingertips by a moving paddle, as employed in the ungrounded tests and in some of the grounded tests, enhanced the realism of the virtual boundary contacts. Additional results concerning the synchronization of different feedback mechanisms and the use of a brake for grounded feedback are discussed in terms of their implications for the design of haptic interfaces.

1. INTRODUCTION

1.1 Background

Haptic interfaces can be classified according to how their forces are applied. As every action must have an equal and opposite reaction, the desired output force of a haptic interface must be balanced by an equal and opposite reaction force. In many interfaces this reaction force is applied to a massive object such as a desk, wall or ceiling. Such devices are called "earth grounded" or described as having a fixed ground (Burdea, 1996; Salisbury and Srinivasan, 1992; Hasser, 1995).

One example of an earth grounded device is SenseAble Device's PHANToM.[1] The PHANToM, when used with its thimble attachment, applies forces to the user's fingertips. The force imparted at the thimble is canceled by the reaction forces between the PHANToM and the table to which it is rigidly attached.

"Ungrounded," or user-grounded haptic interfaces apply their reaction force to a part of the user's body, away from the area of desired force feedback. Grigore Burdea's "Rutgers Master I and Master II" are both examples of ungrounded haptic displays. Like the PHANToM, the Rutgers Masters display kinesthetic information to their wearers at the fingertips (Gomez et al, 1995). They differ from the PHANToM in that their reaction forces are directed against the user's palm, so that the user only experiences forces internal to the hand.

1.2 Motivation

There are several advantages to using a grounded haptic interface to perform tasks in a virtual or remote environment. Grounded interfaces are able to display forces that come from grounded sources without ambiguity. As the literature shows, they are able to display an object's geometric characteristics such as size, shape and texture (Minsky et al, 1990), as well as a system's dynamic characteristics such as mass, stiffness and friction (MacLean, 1996; Richard et al, 1997).

The main advantage of ungrounded haptic interfaces is their portability, and correspondingly large workspace (Burdea, 1996). Unfortunately, little research has been done on the perceptual effects of displaying either geometric or dynamic characteristics of an environment using an ungrounded haptic interface. As Salisbury and Srinivasan (1992) note,

> *"The consequences of using an ungrounded display to simulate contact forces which really stem from grounded sources are not known and warrant investigation."*

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[1] SenSable Devices Inc, Cambridge MA. http://www.sensable.com

To illustrate the ambiguity involved in representing contact forces with an ungrounded device, consider two tasks: squeezing a virtual ball, and pressing a virtual button.

In the ball squeezing case, fingertip force is all that is needed to provide a realistic depiction of the virtual object's size, shape and stiffness. This is because all forces involved in a squeezing task are internal to the user's hand and the ball.

When a person presses a button, however, not only does he or she feel a force at the fingertips, but the reaction force from the button inhibits further motion of the hand. In this case, an ungrounded haptic display can reproduce the sensation of fingertip contact, but cannot provide a reaction force to prevent motion. The nature of ungrounded force representation raises an interesting question: "Are fingertip forces alone sufficient for a haptic exploration task?" Of particular interest are tasks for which an absolute reference would seem to be useful. For our investigation we have chosen tasks dealing with detecting an environment's boundaries, and discerning the distance to various object surfaces. In the next section we describe two devices that were used to compare the effects of grounded and ungrounded feedback for the aforementioned exploratory tasks.

1.3 Experimental Apparatus Description

Apparatus #1 is shown in Fig. 1. The user's finger is connected to the device with a harness as indicated. The force applicator, driven by a low friction DC motor, moves into and out of contact with the user's fingertip to provide the desired force feedback and cutaneous sensation of contact. The motor is controlled using a position servo running at 1kHz. At the base of the interface carriage is a low-friction linear bearing. The carriage is constructed of acrylic plastic and has a mass of approximately 0.3Kg.

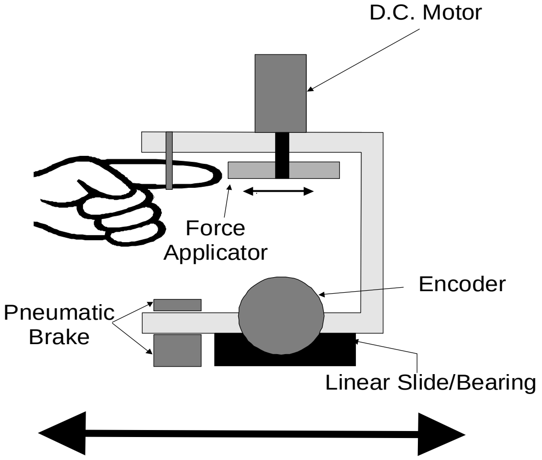

Fig. 1. Apparatus #1, Front View

In the ungrounded tests, the linear bearing slides freely so that the motion of the subject's hand is unimpeded, even as the force applicator applies contact forces to the fingertip. To enable comparisons between grounded and ungrounded feedback, a pneumatic brake, actuated by a solenoid valve, was added. The brake is used to lock the carriage in place thereby grounding it to the table. An encoder, attached to the carriage, is used to sense the fingertip position, providing signals to actuate the brake and/or force applicator. Apparatus #1 was used only for the first round of boundary detection experiments.

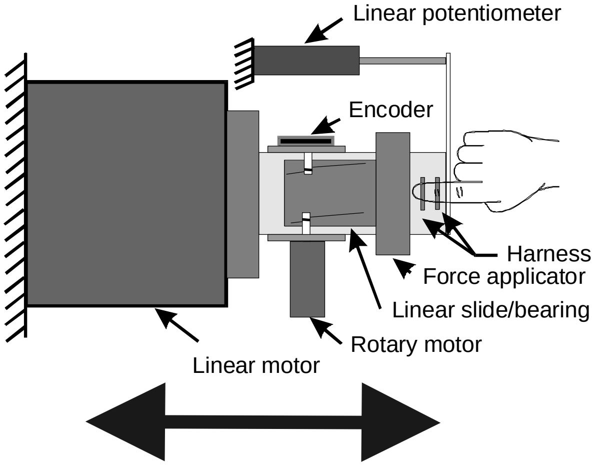

Fig. 2. Apparatus #2, top view

Initial experiments conducted with apparatus #1 inspired several design changes incorporated into a second device, shown in Fig. 2. In this device, a large linear voice coil motor moves a carriage that supports the finger harness and fingertip force applicator. As in apparatus #1, the carriage provides grounded force feedback through a finger harness. Grounded feedback can be used with or without the secondary fingertip force applicator. For ungrounded feedback the linear motor is turned off and the carriage rolls freely, propelled by the human subject. The fingertip force applicator consists of a linear slide driven by a low-friction DC servo motor.

The approximate total mass of the carriage assembly is 2.9Kg and the moving mass of the fingertip force applicator is approximately 0.27Kg. While moving toward the wall, subjects experienced typical friction "drag" forces of 0.49 N, as compared to average peak contact forces of 27 N. The servo rate was 2kHz, although the visual display was updated at a 30Hz rate.

2. BOUNDARY DETECTION EXPERIMENTS

2.1 Procedure

In the boundary detection experiments, we compared the effects of different types of feedback on the ability of nine subjects to determine when a virtual wall is encountered (Fig. 3). The subjects were asked to move toward the virtual wall and lightly touch it three or four times, returning to the starting position after each tap. On apparatus #1, subjects performed this experiment five times. Subjects using apparatus #2 performed this experiment seven times. For each experimental run different combinations of visual and haptic feedback were used. The different combinations of feedback used are listed in Table 1.

As discussed below, the results obtained with the first apparatus prompted some changes in the way we conducted experiments with the second apparatus. We eliminated the brake in favor of a large linear motor that could be controlled to provide a unidirectional elastic force, in proportion to the depth of penetration into the wall. To reduce time delays, we also anticipated the contact between the subject's fingertip and the virtual wall. Ideally, the momentum of the force applicator should be equal and opposite to that of the subject's hand so that, instantaneously, the collision of the fingertip with the force applicator is identical to a collision with a rigid wall. After experimenting with various estimation and prediction schemes we found that best results were obtained by simply servoing the force applicator so that its distance to the virtual wall was held equal and opposite to the measured distance between the subject's hand and the wall.

Prior to each run, the force applicator was calibrated by moving into contact with the subject's finger and then recording the finger distance from zero. Such a calibration routine is necessary to ensure that the applicator contacts the finger at the right time. Calibration also helps to reduce errors due to a subject's finger slipping in the harness between runs.

Table:1. Summary of Boundary Detection Experiments

Run#	Haptic Feedback Type	Visual Feedback?	Apparatus
1	None	Yes	#1 and #2
2	Ungrounded	No	#1 and #2
3	Ungrounded	Yes	#1 and #2
4	Grounded	No	#2 Only
5	Grounded	Yes	#2 Only
6	Ground+ Tactile	No	#1 and #2
7	Grounded+ Tactile	Yes	#1 and #2

2.2 Boundary detection results with apparatus #1

Burdea lists three criteria for evaluating a user's performance on a task: 1) task completion time, 2) task error rate, and 3) average contact force/torque (Burdea, 1996). For the boundary detection tests, task error rate and average contact force are synonymous. Because our virtual wall is modeled as a linear stiffness element, the average force experienced by a subject is directly proportional to subject's average wall penetration. Since users were asked to touch the wall gently, rather than striking it, the wall penetration is a measure of error.

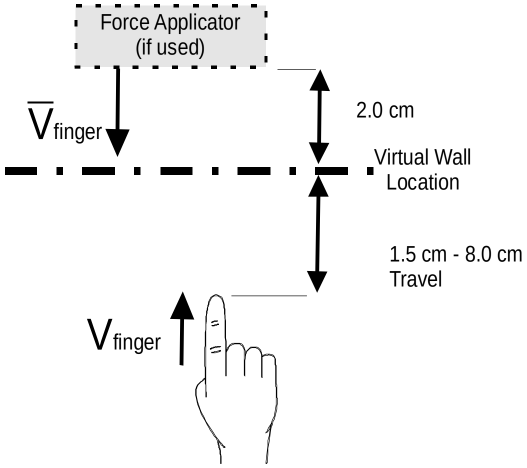

Fig. 3. Boundary Detection Experiments

Figure 4 shows typical wall penetrations for one of the subjects tested. The difference between ungrounded and grounded haptic feedback is significant when no visual feedback is provided. However, as seen in Fig. 5, the difference between grounded and ungrounded haptic feedback decreases significantly when visual feedback is added.

A couple of other interesting effects are revealed in Figs. 4 and 5. The reader will note that the curves representing grounded feedback have flat tops, rather than the rounded peaks seen for the ungrounded curves. These "plateaus" appear because the force that the brake applies is bi-directional. It not only impedes the user's progress as the wall is entered, it also briefly impedes the user's retreat. Furthermore, a small delay is introduced because of the actuation time of the pneumatic brake. This delay contributes to the wall penetration observed when grounded feedback is employed. A second observation is that users sometimes anticipate contact with the wall, and hesitate or reduce their approach velocity. This phenomenon is most common when visual feedback is added (as in the first approach in Fig. 5). The implications of these results are discussed further in section 4. As

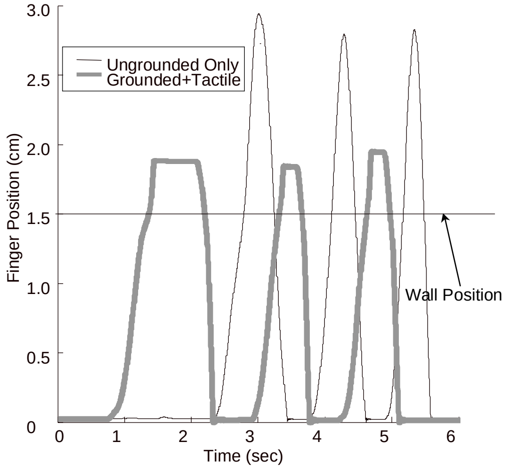

Fig. 4. Boundary detection for apparatus #1 (without visual feedback)

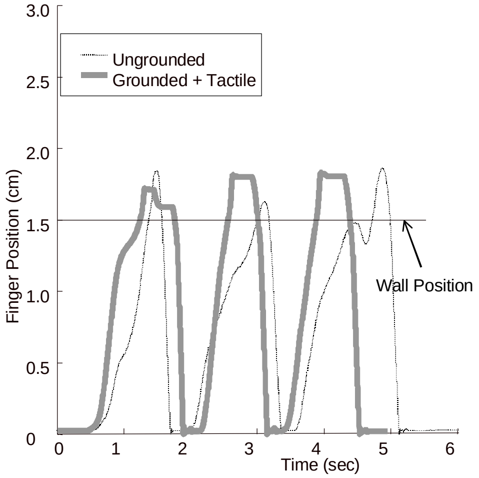

Fig. 5. Boundary detection for apparatus #1 (with visual feedback)

mentioned earlier, the experiments conducted with apparatus #2 sought to minimize some of these effects.

2.3 Boundary detection results with apparatus #2

Figures 6 and 7 show a typical user's penetration distance with and without visual feedback using apparatus #2. Tests were conducted with ungrounded (tactile) feedback and with grounded feedback, with or without the addition of tactile feedback. The data show that the new apparatus gives smaller penetration distances in general. This is due in part to reduced time delays.

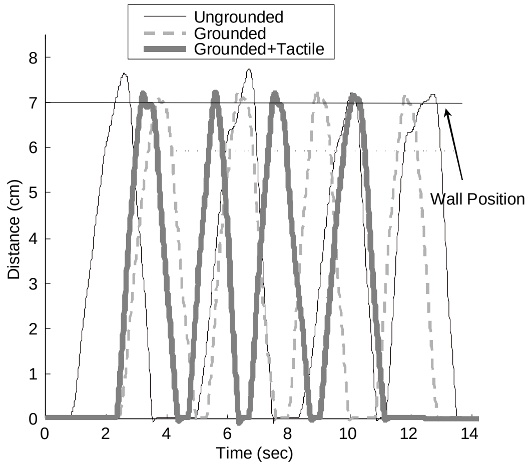

Fig. 7. Boundary detection for apparatus #2 (with visual feedback)

Figures 8 and 9 emphasize the equalizing effect of visual feedback. In general, apparatus #2 gives results similar to apparatus #1. The ungrounded case yields the largest penetration distances, but the difference between grounded and ungrounded feedback is reduced when vision is added. Figures 8 and 9 also reveal the large variation across subjects. One reason for the wide range of penetration distances has to do with the control law governing the force applicator. Rapid changes in a subject's velocity near the wall can cause the applicator to overshoot its desired position and strike the subject's finger before the finger has actually touched the virtual wall. This effect is seen in the third peak of the ungrounded run, and in the last peak of the grounded+tactile run in Fig. 6.

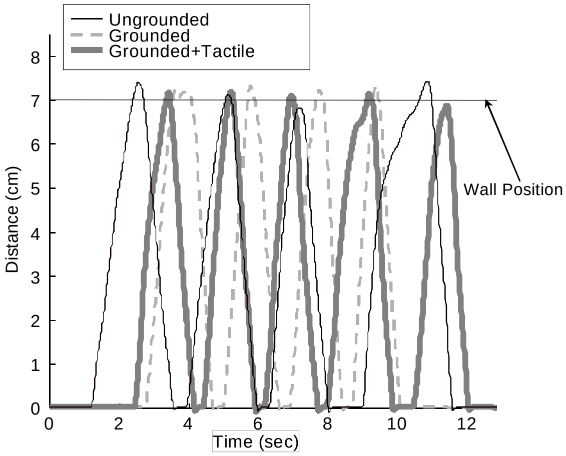

Fig. 6. Boundary detection for apparatus #2 (without visual feedback)

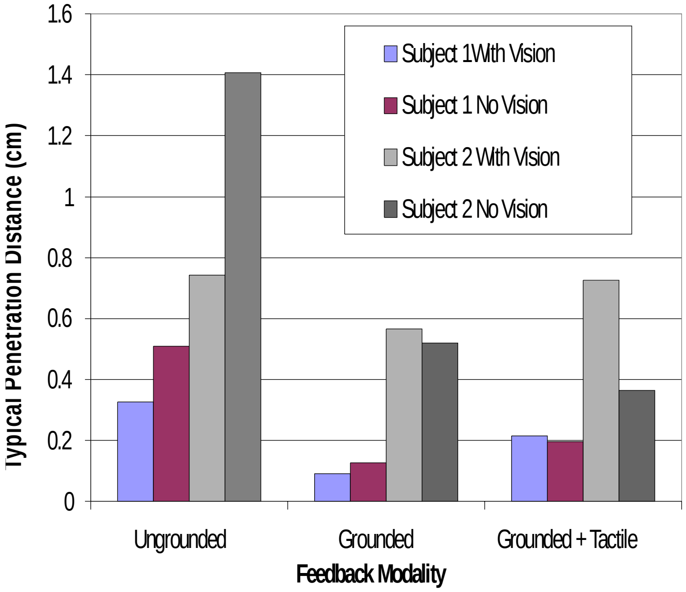

Fig. 8. Typical penetration distances for two subjects

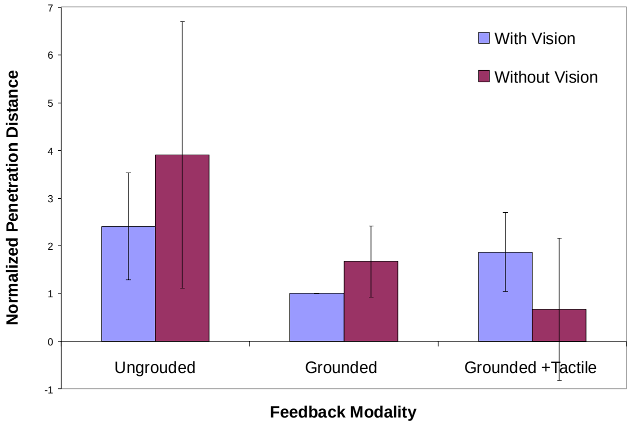

Fig. 9. Normalized average penetration distance for all subjects

There were significant variation in terms of how rapidly different subjects approached the wall and how strongly they contacted it, resulting in a large subject-to-subject differences in average wall penetration. To minimize this effect, the penetration distances for each subjects' data were normalized with respect to their grounded+vision case. Even with this normalization the averages have large standard deviations, especially for ungrounded and grounded+tactile modes, as Fig. 9 shows.

3. OBJECT SIZE DISCRIMINATION EXPERIMENTS

3.1 Procedure

Object size discrimination tests were performed exclusively on apparatus #2. No visual feedback was used. Subjects were asked to distinguish between pairs of virtual surfaces, located different distances from a starting position. In each pair-wise comparison, one of the two virtual surfaces was always a standard distance of 5.0 cm from the starting point. The other surface was located between 5.0 and 8.0 cm from the starting point (see Fig. 10). The surfaces were presented in random order and the haptic feedback was randomly chosen from among three possibilities: ungrounded (with touch), grounded without touch, or grounded with touch.

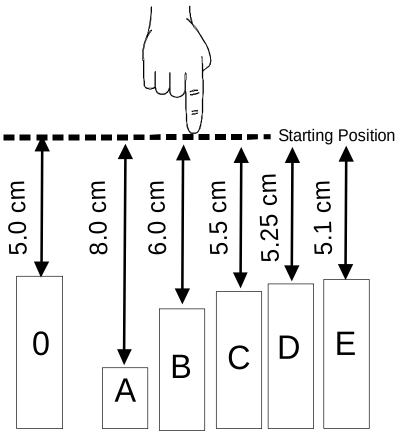

Fig. 10. Object discrimination experiment

During each comparison subjects could switch between the first and second surface at will. Subjects were told that there was no time limit for this task, but the testing sessions were sufficiently time consuming that subjects rarely spent more than 30 seconds on any single comparison (see Fig. 11). Our metrics for performance for this task are the percentage of closer/further surfaces correctly identified and the task completion time.

3.2 Objection Discrimination Results

Although it is difficult to find an absolute trend favoring a particular feedback mode in the object discrimination results, some interesting features in the task completion time data should be noted. One would expect that as the difference in height between the two blocks decreases, the time necessary to discern the difference increases. This effect is clearly seen in Fig. 11. The first case, "8/5" with ungrounded feedback was the "training case." It was the first case presented to all subjects, and as such its time is slightly higher than the trend would predict.

The fact that no single mode of feedback has a significantly superior task completion time or task error rate suggests that all three modes may be viable. However, this observation does not account for the large standard deviations present in the data for the ungrounded case. These deviations show that ungrounded feedback allowed some subjects to complete their task quickly, but caused others to take longer.

Most test subjects agreed that case E, or the "5.1/5" pair was quite difficult to discern, especially when ungrounded feedback was provided. Figure 12 shows an error rate for this case of over 40%. Such a rate is not much better than the 50% rate that pure guessing would have provided. In contrast, both grounded and

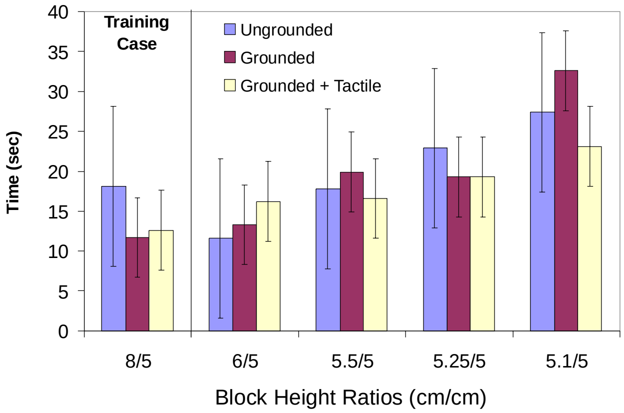

Fig. 11. Task completion times for object discrimination

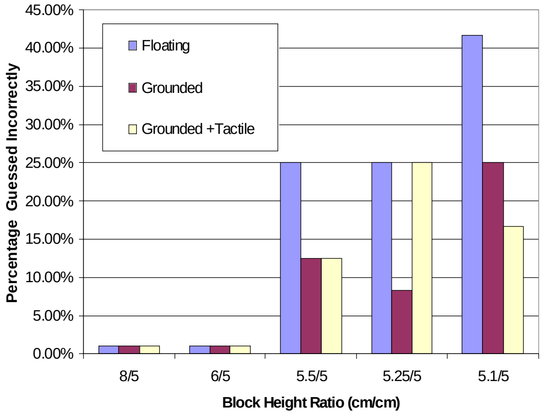

Fig. 12. Task error rates for object discrimination

grounded+tactile allowed users to correctly discern a 1mm surface height difference roughly 80% of the time.

Though the data show no clear victor in terms of feedback choice, subject comments indicated that grounded+tactile was the preferred mode of feedback for this test. They remarked that the grounded+tactile feedback gave them a better indication of exactly where a surface began. Without the fingertip contact the surface is less distinct.

4. DISCUSSION

The quantitative results of this study show the general trends that were expected. One unanticipated factor was the large subject-to-subject variability present in all tests.

The qualitative assessments reported by the subjects were often more interesting than the numerical results and shed more light on the design of haptic interfaces. These issues are discussed below.

- **Subject to subject variability** - Several factors contribute to the wide range of values that were recorded for different subjects performing the same task. One reason for the variability is that some subjects prefer to undertake the task at higher velocities than others. Future investigations of this sort would benefit from examining each subject’s penetration distance as a function of their average velocity. Another possible explanation for the large variability is subject reaction time. When using ungrounded feedback, a subject's reaction time is the main factor that determines their stopping distance, once they make contact with the wall (assuming a system with reasonable bandwidth and negligible time delays). When grounded feedback is used, the penetration distance is a function of both the subject’s reaction time and the device's impedance. If the impedance is high, then penetration distance is solely a function of impedance. It is therefore reasonable to suspect that subjects with faster reflexes and/or better hand/eye coordination will perform better with ungrounded feedback than subjects with slower reaction times.
- **Benefits of visual feedback** - Not surprisingly, adding vision improved subjects’ performance both in terms of reducing boundary penetration and in comparing the distances travelled to different virtual objects. The benefit appears to result as much from how vision influenced the subjects’ behavior as it does from providing an extra channel of information. With vision, subjects could better anticipate when they were going to make contact with a virtual wall and they generally slowed down as they neared the wall. The lower contact velocities resulted in smaller penetration distances and reduced the effects of any human or machine delays in detecting and responding to the contact.
- **Brake type actuators** - Care must be taken in simulating unidirectional constraints (such as virtual walls) with a device such as a brake that provides bidirectional resistance forces. The pneumatic brake at first seemed like an ideal solution for grounded haptic feedback. It is essentially a one-dimensional analog to the “Cobot” mechanisms discussed by Colgate, et al (1996). These mechanisms have the advantage of being able to provide nearly infinite stiffness in the direction of constraint. However, it is essential to very quickly detect when the human subject is starting to pull back from the wall and to immediately release the brake (or reorient the wheel, in the case of Cobots). Otherwise, subjects will report an unnatural sensation similar to having magnets glued to their fingertips: initially there is a small resistance to retracting the finger and then the finger pops free. In the case of apparatus #1, the delay could have been reduced by sensing forces between the subjects’ fingertips and the harness (rather than relying on motions) and by using a brake mechanism with faster response (e.g., a piezoelectric actuator). However, it is unclear whether such strategies would eliminate the unnatural sensations reported by the users.
- **Subsystem time delays** - When combing several feedback mechanisms (e.g., vision, fingertip contact and grounded resistance to motion) it is important to consider the time delays associated with each and to compensate for them in the control. However, this is not easy to accomplish when the velocity of the human subject is unknown and variable. As mentioned in the description of apparatus #2, we sought to minimize the delay associated with having the force applicator strike the fingertip by predicting when subjects would make contact with the virtual wall and matching their approach velocities with an equal and opposite applicator velocity. However, these predictions were sometimes wrong; subjects sometimes slowed down just before touching the virtual wall. In this case, the applicator contacted the fingertip prematurely. While effects of such occasional miscues can be observed in the results (for example, see Fig. 6), they were not commented on by any of the subjects. The imperfect synchronization between the haptic and visual display was evidently not noticed at the level resolution provided by a standard VGA display. In contrast, subjects did report when the force applicator contact did not correspond closely with the onset of a feedback force from a grounded haptic display. This made it necessary to calibrate the device for each subject as discussed in Section 2.1.

- **Advantages of Grounded + Tactile Feedback** - The addition of touch to a grounded display, with or without vision, did not affect subjects' performance, in terms of boundary penetration, task completion time, or ability to compare the distance travelled to different virtual walls, in a significant way. However, subjects reported that it did qualitatively improve the realism of sensation when contacting a virtual wall.

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