Perceptual Decomposition of Virtual Haptic Surfaces

Louis B. Rosenberg* and Bernard D. Adelstein**

*Center for Design Research, Stanford University, Stanford, CA 94305
**Western Aerospace Laboratories, NASA Ames Research Center, Moffett Field, CA 94035

Abstract

In this paper, the analysis and construction of virtual haptic surfaces are considered from a perceptual point of view rather than from the dynamics and controls approach of prior work. We developed a perceptual decomposition of surface contact sensation by examining three *qualities* associated with the different stages of interaction with a haptic wall simulation. These qualities are the *crispness* of initial contact, the *hardness* of surface rigidity, and the *cleanness* of final release from the virtual wall's surface. These qualities, plus an *overall* rating of wall quality, were employed consistently by seven subjects to evaluate a set of six simple haptic wall simulations. Three of the wall models consisted of single linear springs; the remainder, single viscous dampers. Highest rankings of subjective *hardness* were associated with the spring models; damper models received the highest c*rispness* rankings. Subjects favored the simple spring models as having, *overall*, the more wall-like perceptual character.

1. Introduction

In force-reflecting virtual environments (VEs), computer generated haptic surfaces serve the same function as surfaces in visual computer graphics environments: they define the boundaries of simulated objects. As in a visual VE, simulated objects in a haptic environment can be either dynamic (*i.e.*, they can be free moving and even have inertial properties) or static (*i.e.*, fixed in location with respect to the VE reference frame). In either case, the surface demarcates the spatial location where the human operator's interaction with the VE changes abruptly. Thus, the development of competent force reflecting VEs populated by discrete geometrically-bounded virtual objects is not possible without the ability to produce a satisfactory sensation of surface contact to the human user.

A haptic virtual environment system consists of force-reflecting interface hardware and a computation engine. The interface hardware typically consists of a mechanical linkage in the form of a joystick or exoskeleton which couples the human operator to a source of mechanical power—either electromagnetic, electrohydraulic, or electropneumatic actuators. The computation engine governs the behavior of the actuators and linkage as a function of kinematic and force measurements from interface transducers, according to algorithms and equations that describe the VE models to be simulated. A force reflecting interface thus stimulates the human limb and muscle sense of physical dynamics, and, in most cases, either by default or by design, the tactile sensors in the skin. A distinguishing feature of the haptic channel—unlike VE systems which display visual or aural information and require a physical (typically manual) response—is that the same body part and interface hardware is used to transfer information back and forth between the human and the VE simulation. Consequently, haptic information transfer (*i.e.*, what the human operator "feels") is affected not only by the processing capacity of the computation engine and the comprehensiveness of the VE model, but by the controlled dynamics of the interface linkage and of the human limb itself.

Because of the instantaneous transitions required when moving from one set of mechanical dynamics in free space to another set when in contact with a surface, and because of the inherent physical properties of the coupled interface and human limb system, high fidelity haptic simulation of surface contact presents a demanding technical challenge in the design of force reflecting VEs. Simple virtual haptic surfaces have been demonstrated in a variety of implementations [1], [7], [9], [12], [13], [18]. Acknowledged shortcomings of haptic wall simulations include: high frequency vibration [15]; low frequency instability [6]; excessive compliance [9], [13], [14], [18]; and stickiness [2]. Jex [8], in reporting on informal industry "rules of thumb" for high-performance aircraft simulators, suggested that the ability to produce convincing walls that are not spongy and do not creep is one of four simple simulations that together demonstrate the capacity of a haptic interface to produce *any* general simulation.

The problem of virtual rigid surface contact has been examined from an analytic system dynamics and control perspective with the aim of understanding the bounds for stable human-machine interaction [4], [5], [14]. While

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these investigations have been important in defining hardware and control algorithm limitations in the performance of force reflecting VE systems, they offer few insights into the perceptual aspects of presenting virtual force information.

The goal of our work is the analysis and construction of virtual surfaces from a perceptual, rather than solely a dynamics and controls point of view. In the prior work cited above, virtual haptic surfaces have typically been constructed by simulating a massless boundary object backed by springs and dampers, with their respective stiffness and damping set to within maximum stable limits. Because of hardware limitations, virtual walls are never as rigid as real walls [5]. Given that simply pushing state-of-practice force reflecting hardware and controllers to their maximum capabilities will not produce perfect emulations of rigid walls, we are interested in determining whether more modest requirements on interface performance may achieve sufficient results if the haptic models are based on acceptable perceptual representations of walls.

Thus in this paper we present a method to decompose the various phases of contact with a virtual rigid surface and demonstrate its application on the simple spring- and damper- backed wall elements used in prior implementations.

The remainder of this paper begins with an overview of sensory perception—how we perceive stimuli in the world around us. This leads to the concept of perceptual decomposition to capture the essence of haptically displayed virtual objects. The decomposition is then demonstrated in experiments that employ subjective ratings of the different phases of virtual haptic wall interaction.

2. Perceptual analysis

In performing a perceptual analysis of virtual sensory percepts, it is convenient to define the different stages of sensory perception [11]. A *proximal stimulus* is defined as the sensory information falling upon a receptor. A *distal stimulus* on the other hand is the distant source of such sensory information. Although we, as human beings, interact with an environment of distal stimuli, we only have direct access to proximal stimuli. Thus the act of perception is often described as the transduction of a proximal stimulus coupled with the judgment of what distal stimulus most likely caused that sensation. This act of inference is often called the *perceptual hypothesis* and results in the generation of an internal representation of the outside world known as a *percept.* As long as the perceptual system is presented with enough salient sensory information in a proximal stimulus, a correct perceptual hypothesis can be made and an appropriate internal model of the actual distal stimulus will be created.

For example, a proximal stimulus might be an image of a cube falling upon one's retina. One's perceptual system extracts the salient information such as edges and angles from the proximal stimulus and, as a result, one infers that the distal stimulus is a cube located across the room. This proximal stimulus might be very different from the last time one viewed that cube—lighting conditions may have changed, viewing location may have changed, or it may even be a cube that had never been seen before. Nonetheless one identifies the object as a cube and builds an internal percept. Our ability to draw the appropriate perceptual hypothesis despite changes in viewing conditions is called *perceptualconstancy* and is important in allowing us to generate a robust internal model of the outside world. Clearly, certain sensory information was critical for the identification and generation of the percept, while other information dependent upon viewing conditions may have been ignored. Because sensory perception is a complex process of inference based on certain features and not others, the key to designing a virtual percept is to ascertain which features are vital and which can be ignored.

Whether our visual system is presented with a photograph of a cube or a rough sketch of a cube, the image is likely to be identified as a cube and an appropriate internal perceptual model will be generated. In a sense, the photographic representation is analogous to physical modelling of the distal stimulus while the sketch representation is analogous to perceptual modelling of the proximal stimulus. Although a sketch contains much less sensory information than a photograph, a sketch artist is skilled at providing only the appropriate sensory features that assure the desired perceptual analysis of the image. A good sketch can often be a more effective representation of sensory information than a poor photograph. We can extend the analogy of the sketch and the photograph to more exotic perceptual representations such as the virtual haptic sensations produced by force reflecting systems. Rather than producing a physically accurate "photographic" representation of a haptic sensation, a *perceptual designer* could "sketch" haptic sensations by combining only those appropriate perceptual features which make up the desired percept. Such an approach may be more effective than "photographic" dynamic modelling of a haptic sensation, particularly in cases where force reflecting equipment lacks the fidelity to generate a completely realistic "photograph" of the stimulus.

Thus when developing models of a virtual sensory percept such as contact with a rigid surface, the goal should not be to model most accurately the physical qualities of the real distal stimulus, but rather to provide a perceptually adequate model of the proximal stimulus. When a perceptually adequate model of the proximal stimulus is provided, the user can then make the correct perceptual hypothesis and the appropriate distal stimulus will be inferred. Of course, a strong understanding of the perceptual qualities of the percept being modelled is a basic requirement for the perceptual design of a convincing sensation. This study examines the rigid surface contact problem and attempts to ascertain which perceptual features are important.

3. Perceptual decomposition

The first step in the perceptual design of a virtual rigid surface contact is to develop an effective decomposition of the percept into its salient sensory features. In an initial attempt to develop such a perceptual decomposition, one of the authors spent many hours interacting with the force reflecting joystick described below (METHODS AND MATERIALS), gaining experience into the "feel" of a wide variety of simple virtual models and assessing how the feel of such elements compare with the feel of a *real* rigid surface contact [16]. The goal of this exploration was to isolate distinct perceptual qualities of the real rigid wall and to reveal how these qualities could be reproduced through simple virtual models.

Starting with basic virtual models such as linear springs and linear viscous dampers and expanding to nonlinear and more abstract elements, basic perceptual qualities of the virtual sensations were compared with those of a real rigid surface contact. The real rigid surface contact was implemented by a physical hard stop that could be placed in the path of the joystick in the same location where the virtual models were presented. After extensive comparisons with many such virtual models, a perceptual decomposition of contact with a rigid wall was hypothesized.

The decomposition of the basic percept of rigid surface contact that we propose has three sequential perceptual components: initial dynamic contact with the surface, quasi-static interaction with the hard surface, and the final dynamic release from the surface. These three stages have very distinct perceptual qualities which are described simply as the *crispness* of the initial contact, the *hardness* of the rigid surface, and the *cleanness* of the final release. If the perceptual content of any of these individual stages is not well represented, the overall percept of a rigid surface contact may become distorted and the resulting percept may not be believable.

For example, interaction with a virtual model of a stiff linear spring was found to provide an adequate representation of a *hard* rigid wall when in static contact with the surface. However, when interacting with this model dynamically, the initial contact had a disturbingly "bouncy" feel which distorted the overall illusion of rigidity. A virtual model of a pure linear damper on the other hand produced a very crisp, abrupt force upon initial contact which could be described as being more of a "thud" than a "bounce." Interaction with this model provided a very realistic sensation of a rigid surface for the first instant of contact. Of course, after that first instant, the pure damper could not maintain the illusion because it lacks static rigidity and allows the joystick to sink slowly into the wall model. When pulling away from a virtual wall modelled as a pure linear damper, the percept again fails because it feels "sticky," as if pulling one's hand out of a thick liquid. This sticky feeling could be eliminated by modelling a virtual *directional damper* that only produces an impedance when velocity is toward the wall and has zero impedance when moving away.

From these first few observations, an initial perceptual model of rigid surface contact can be formulated. For example, one perceptual design for a hard wall, based on the exploration of simple springs or dampers, might be a surface boundary layer of high *directional* damping to provide the illusion of crisp initial contact and clean final release, and then use this layer to enclose a stiff linear spring which provides the illusion of static rigidity.

Although perceptual modelling based on personal observation is informative, it is the result of informal exploration rather than formal experimentation. The following empirical study was designed to record systematically the reactions of naïve test subjects while they interacted with various perceptual elements. The aim of these experiments was first to ascertain whether the proposed decomposition of the rigid wall contact is a valid and useful way to analyze the percept of a rigid surface contact. Secondly, the experiments were intended to identify which parts of the perceptual decomposition are most important to the overall percept. Finally, the study was intended to provide insight into which simple virtual models can be used to provide the salient perceptual features of surface contact.

4. Methods and materials

The experiments exposed each subject to a set of simple virtual wall models. Each of the virtual walls used in these tests was modelled as a single basic element such as a pure linear spring or a pure damper. The purpose of using very simple elements was to evaluate the perceptual content of basic building blocks from which more realistic percepts could be composed. The goals of these tests were as follows: 1) to ascertain if subjects could use the proposed decomposition to quantify aspects of the rigid wall sensations; 2) to gain insight into how basic elements might contribute to each aspect of the perceptual decomposition; and 3) to correlate the relative importance of each part of the perceptual decomposition with the overall wall quality rating.

4.1 Experimental Set-up

Virtual wall models were implemented on a two degree of freedom (dof) force reflecting joystick [1], [3]. Each dof of the joystick is powered by a disk armature permanent magnet motors and is instrumented with an optical encoder to sense position, tachometer for velocity, accelerometer, and an interface force transducer. The motors can produce continuous forces up to a maximum of 20 N with zero cogging and negligible force ripple from DC up to 58 Hz at the joystick handle. The minimum friction force threshold of the passive (*i.e.*, uncompensated) joystick is 1 N. The joystick handle's passive inertia corresponds to a mass of 0.35 kg at the hand. The joystick is operated in these experiments under purely digital control through an A/D and D/A card with DMA on an ISA bus Intel 486DX-50 based personal computer. The controller update rates for the haptic models simulated in these experiments exceeded 10 kHz.

Subjects stood facing the joystick as depicted in Figure 1. The joystick handle, which is at a height of 1 m from the floor, was grasped in the right hand. Virtual walls were aligned as shown in Figure 1, allowing approximately 7 cm of right to left motion before contact was made. Since the joystick only produces a 20 N maximum force, the subject could still move the handle another 7 cm to the left after first encountering the wall. To eliminate spurious haptic information to the subject caused by sliding parallel along the wall surface, motion in the corresponding joystick dof (fore and aft) was blocked with a rigid clamp. White-noise presented through an audio headset masked all sound from the joystick mechanism. A partition placed over the handle prevented subjects from viewing their hand during the experiments.

Subjects were instructed to manually explore, using the joystick, a set of six simple virtual wall models and then asked to rate each wall according to the four criteria based on the perceptual decomposition described above. As noted, these criteria were: Initial Contact (Crispness), Surface Rigidity (Hardness), Final Release (Cleanness), and Overall Wall quality ("Wallness"). Between each virtual wall model, subjects were asked to feel a *real* rigid wall that was part of the partition covering the joystick handle. The real wall served as a fixed physical value to help anchor their subjective rating scales. The complete set of six virtual wall models was presented in random order seven times to each subject. The first three sets of six wall models were used as a training session to familiarize the subjects with the range of sensations that they would be asked to rate. During this training session, subjects were instructed to concentrate on defining the limits for each rating scale that they were developing so

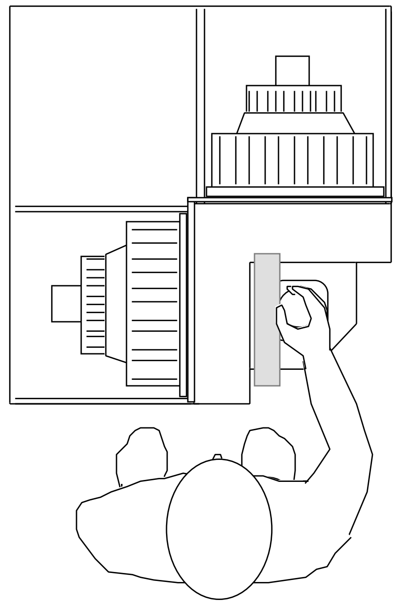

Figure 1. Subject standing at joystick. The subject pushes the handle to the left with the right hand to contact the virtual wall (diagonally shaded rectangle). The subject's hand and the joystick handle are hidden from the subject's view during experiments.

that their personal subjective ratings would span a 1 to 7 range, respectively, for worst to best sensation levels.

4.2 Wall models

The six simple virtual wall models were composed of single elements—*either* springs or dampers—and have the basic structure shown in Figure 2. Spring and damping parameters for the six models are listed in Table 1. A brief description of each wall model follows.

Virtual wall models 1, 2, and 3 consisted of a single pure linear spring element with stiffnesses of 2000 N/m, 4500 N/m, and 7000 N/m respectively. This range of stiffnesses served to examine the effects of increasing stiffness on the quality of the overall percept. Models 4, 5, and 6 were composed of dampers with viscosities of 100 N-s/m. Model 4 was a simple *linear* damper which produces an opposing force proportional to velocity. Model 5 was a *directional* damper that only opposes motion toward the wall and has no effect when moving away from it. Model 6, referred to as a *thresholddamper*, acts like a typical linear damper that becomes a directional damper when velocity away from the wall exceeds a small threshold, v_{thresh} = 5 cm/s. The directional and threshold dampers were devised to reduce the "stickiness" associated with heavily damped wall models.

Wall	Model Description	Spring stiffness (N/m)	Damper viscosity (N-s/m)
1	Linear Spring	K = 2000	—
2	Linear Spring	K = 4500	—
3	Linear Spring	K = 7000	—
4	Linear Damper	—	B = 100
5	Directional Damper	—	B = 100 for $v < 0$ B = 0 for $v \geq 0$
6	Threshold Damper	—	B = 100 for $v < v_{thresh}$ B = 0 for $v \geq v_{thresh}$

Table 1. Wall model summary.

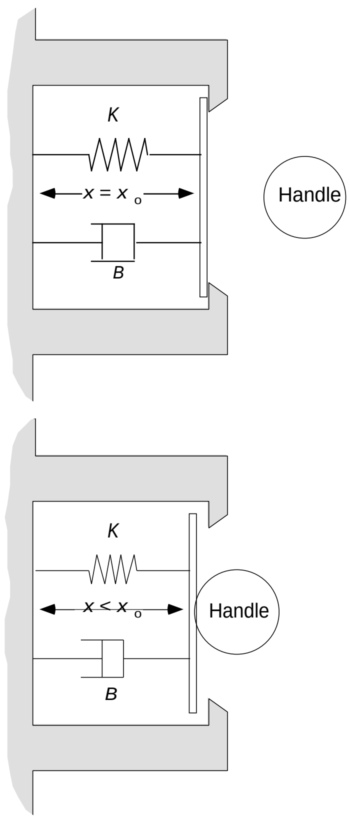

Figure 2. Simple wall model: massless plate at rest position x = xo, backed by spring with stiffness, K, and damper with viscosity, B. Detents prevent the massless plate and springs from extending beyond x = xo. (Top) Away from wall, the handle does not encounter resistance. (Bottom) Once in contact with wall, the handle at position x < xo, encounters the impedance of the spring and damper.

It should be noted that the perceptual decomposition experiment described in this paper comprises a subset of a larger study in which a broader range of virtual wall models were examined [16]. The full set of virtual walls includes not only single spring and damper elements in isolation, but combinations of these single elements as well.

5. Results and discussion

Seven subjects (ages 22-37, all male, all right handed) participated in the experiments. The subjects reported during informal post-test interviews that they did not have difficulty in decomposing the wall percept consistently into the given perceptual elements (initial contact, surface rigidity, and final release) and that they maintained a constant opinion as to how each virtual wall compared with the others.

The average of all coefficients of variation for the raw rating data (*cv* = *stdev/mean*) was 0.16, where each coefficient of variation was computed from the four repeated judgements by each subject of each wall model for each criterion and then averaged over all seven subjects, six walls, and four criteria (N = 7 x 6 x 4 = 168). This value for the average *cv* reflects relatively low variability in the raw rating data and supports the subjects' impressions that they could maintain a uniform rating system through the course of the tests.

Because rating data are subjective (*i.e.*, each subject has his own personal rating system) and intervals on the rating scale are not necessarily uniform (*e.g.*, a rating of 7 was better than one of 5, but does not necessarily correspond to the amount a 6 is better than a 4), the raw rating values were converted into *rankings* for subsequent analysis. Rankings for each criterion (*IC* = Initial Contact, *SR* = Surface Rigidity, *FR* = Final Release, and *OW* = Overall) are based on the average of the four recorded raw ratings by each subject of each wall model. For a particular criterion, the subject's averaged rating of a particular wall was ordered in terms of preference—*i.e.*, the wall with the highest rating was assigned a rank of 6, the next highest a rank of 5, and so on, with the lowest rated wall receiving a 1. When two or more walls tied with the same rating, their rankings were averaged—thus the summed rankings of all six walls by each subject always totals 21. This procedure was repeated for each subject, producing a set of seven rankings between 1 and 6 for each wall model, for each of the four criteria.

Friedman two way analysis of variance by rank statistics (*IC*: $T = 28.51$; *SR*: $T = 29.43$; *FR*: $T = 24.53$; *OW*: $T = 30.43$) allow the null hypothesis—that the subjects show no difference in preference between the wall models—to be rejected ($p < .0002$, chi-squared approximation for $df = 5$). This is taken to indicate that the subjects were able to employ the four criteria (*IC*, *SR*, *FR*, and *OW*) successfully to distinguish between the six wall models. The Kendall coefficients of concordance (*IC*: $W = .839$; *SR*: $W = .888$; *FR*: $W = .784$; *OW*: $W = .899$) demonstrate that the seven subjects concurred very strongly with each other ($p < .0001$; chi-square approximation for $df = 5$) in their individual orders of preference for the walls according to each of the four criteria.

The ranking data for the six wall models, averaged across all seven subjects, are shown for each of the criteria in Figures 3 through 6. Figure 3 depicts two distinct groupings for rankings of initial contact. Damper wall models (4, 5, and 6) all had highest preference in terms of initial contact; simple linear spring wall models 1, 2, and 3, with stiffnesses of 2000, 4500 and 7000 N/m, had the lowest values. Interestingly, although models 4, 5, and 6 were comprised of different types of dampers, little difference is observed in subject preference of the quality of the initial contact.

The subjective surface rigidity rankings in Figure 4 again show the same two groupings. In terms of surface rigidity, however, spring walls (1, 2, and 3) were clearly preferred over the viscous damper models (4, 5, and 6). Furthermore, the increase in linear stiffness from 2000 to 4500 to 7000 N/m in models 1, 2, and 3 respectively is reflected in the increasing surface rigidity rankings assigned by the subjects.

Figure 5 shows that wall models 1, 2, and 3, the linear springs, and 5, the directional damper, were most preferred with respect to the ratings for final release. Wall model 4, the simple linear damper, often described by subjects in post-test interviews as being “sticky,” received the minimum possible (1.0) average ranking.

The overall ranking of the virtual wall models are graphed in Figure 6. These results indicate that the most effective single element wall models were composed of a simple spring. The least preferred, with near minimum possible ranking, was model 4, the “sticky” linear damper. Looking at the overall ranking, there is no immediately discernible relation between linear spring stiffness and overall wall ratings. Thus a spring of 2000 N/m provided about as convincing a wall sensation to the subjects as did a spring of 7000 N/m.

Spearman rank correlations to quantify the significance of the relationship between the four criteria—*IC*, *SR*, *FR*, and *OW*—were computed once the rankings of the six walls by the individual subjects were pooled across all seven subjects (resulting in a total of $N = 6 \times 7 = 42$ rankings) and re-ranked. The correlation coefficients for all criterion pairings, after correcting for tied rankings, are listed in Table 2.

Of note are significant correlations ($df = 40$; $p < .01$) indicating interdependence between the fundamental qualities (*IC*, *SR*, and *FR*) themselves. The negative entries in the correlation matrix between *IC* and all other qualities confirm that damper wall models, which felt better during the initial contact stage generally felt worse both during the other two phases of virtual wall interaction (*SR* and *FR*) and in terms of overall wall (*OW*) quality.

While the negative correlation between *IC* and *OW* in Table 2 could lead to an unreasonable assumption that good *crisp* initial contact has a deleterious effect on overall wall quality, partial rank correlation [10], [17] when both *SR* and *FR* are held constant reveals that the initial contact (*IC*) phase of wall interaction is *not* related significantly ($r_{14.23} = -.266$, $df = 38$; $p > .10$) to the subjects' judgment of *OW*. With partial rank correlation, however, the associations between *SR* and *OW* when *IC* and *FR* are held constant ($r_{24.13} = .563$, $df = 38$; $p < .001$), and between *FR* and *OW* when *IC* and *SR* are held constant ($r_{34.12} = .506$, $df = 38$; $p < .002$), remain highly significant.

	IC (1)	*SR* (2)	*FR* (3)	*OW* (4)
IC	1.000			
SR	–0.714	1.000		
FR	–0.424	0.481	1.000	
OW	–0.696	0.803	0.588	1.000

Table 2. Spearman Rank Correlations between Initial Contact (1), Surface Rigidity (2), Final Release (3), and Overall Wall (4) rankings. Note that the correlation matrix is symmetric.

6. Conclusions

In this paper, we have proposed the perceptual decomposition of virtual haptic surfaces into fundamental qualities based on three phases of contact interaction with a virtual haptic wall model. These qualities and their respective phases of wall interaction are the crispness of initial contact (*IC*), the hardness of surface rigidity (*SR*), and the cleanness of final release (*FR*). Ratings for these three criteria, plus a fourth one to rate the overall quality of a wall (*OW*), were employed by seven subjects in a consistent manner to express preferences among six simple virtual wall models that they had manually explored.

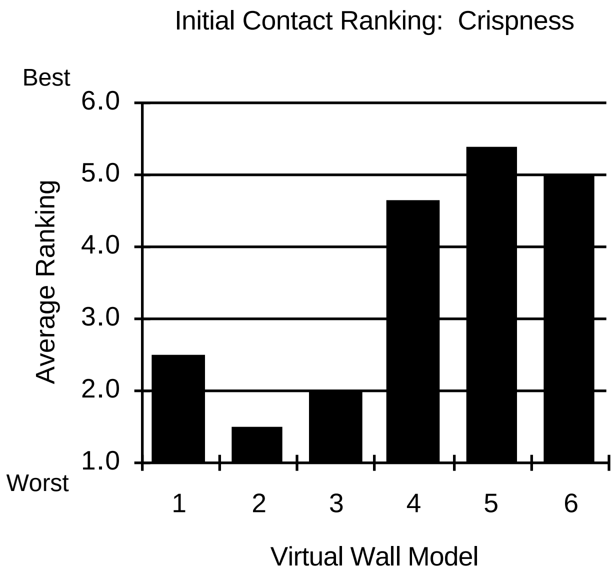

Figure 3. Initial Contact ranking for six simple virtual wall models averaged over all seven subjects. Virtual wall models are identified by number in Table 1.

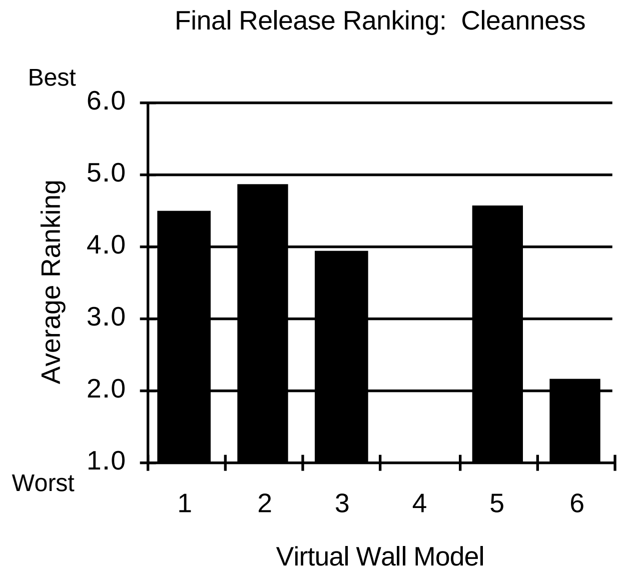

Figure 5. Final Release ranking for six simple virtual wall models averaged over all seven subjects. Virtual wall models are identified by number in Table 1.

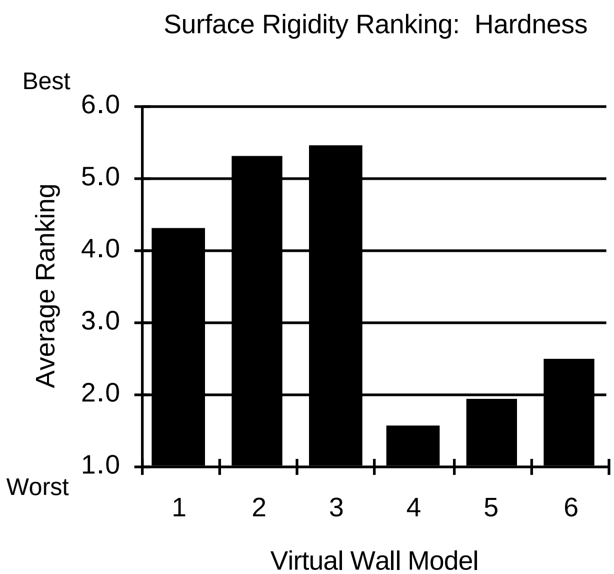

Figure 4. Surface Rigidity ranking for six simple virtual wall models averaged over all seven subjects. Virtual wall models are identified by number in Table 1.

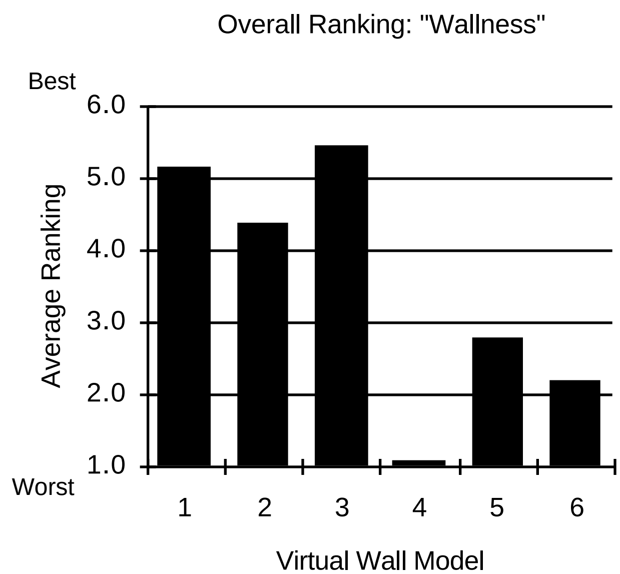

Figure 6. Overall ranking for six simple virtual wall models averaged over all seven subjects. Virtual wall models are identified by number in Table 1.

The six wall models explored by the subjects included three different linear springs with stiffnesses of 2000, 4500, and 7000 N/m, and three dampers—one linear, one directional, and one threshold damper—all with viscosities of 100 N-s/m. The three damper based models received highest rankings for the crispness of *initial contact,* without major distinction as to damper type. On the other hand, for *surface rigidity*, the subjects showed clear preference for the spring wall models over the damper models. The subjects' surface rigidity rankings also showed a slight increase as the modelled spring constant was increased, suggesting that the subjective assessment of stiffness might be a factor in rating wall hardness. For the cleanness of *final release*, the spring models and the *directional* damper were the most preferred, with the "sticky" linear damper receiving the minimum possible ranking. In terms of *overall wall* quality, the spring wall models were favored by the subjects, without systematic distinction according to spring stiffness.

Correlations indicated that, according to subjective rankings from these experiments, fundamental qualities *IC*, *SR*, and *FR* were not independent of each other. Furthermore, partial correlations showed that the overall rankings (*OW*) were strongly related to subject perception of surface rigidity (*SR*) and final release (*FR*), but not with initial contact (*IC*) quality of the haptic wall models.

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References

[1] Adelstein, B.D.: *A Virtual Environment System for the Study of Human Arm Tremor*. Ph.D. thesis, Dept. of Mech. Eng., M.I.T., Cambridge MA, 1989.

[2] Adelstein, B.D., and Rosen, M.J.: A high performance two degree-of-freedom kinesthetic interface. In *Human Machine Interfaces for Teleoperators and Virtual Environments*, NASA Conference Publication 10071, pp. 108-113, 1991.

[3] Adelstein, B.D., and Rosen, M.J.: Design and implementation of a force reflecting manipulandum for manual control research. In *Advances in Robotics*, ed. H. Kazerooni, Amer. Soc. Mech. Eng, New York, pp. 1-12, 1992.

[4] Chin, K.-P.: *Stable teleoperation with Optimal Performance*. Ph.D. thesis, Dept. of Mech. Eng., M.I.T., Cambridge MA, 1991.

[5] Colgate, J.E., Grafing, P.E., and Stanley, M.C.: Implementation of stiff virtual walls in force reflecting interfaces. *Proceedings, IEEE-VRAIS*, Seattle WA, 1993.

[6] Grafing, P.E.: *A Study of a Haptic Interface for a Virtual Environment*. M.S. thesis, Dept. of Mech. Eng., Northwestern University, Evanston IL, 1992.

[7] Fasse, E.D.: *On the Use and Representation of Sensory Information of the Arm by Robots and Humans*. Ph.D. thesis, Dept. of Mech. Eng., M.I.T., Cambridge MA, 1992.

[8] Jex, H.R.: Some criteria for teleoperators and virtual environments from experience with vehicle/operator simulation. In *Human Machine Interfaces for Teleoperators and Virtual Environments*, NASA Conference Publication 10071, pp. 42-47, 1991.

[9] Kilpatrick, P.J.: *The Use of a Kinesthetic Supplement in an Interactive Graphics System*. Ph.D. thesis, Dept. of Comp. Sci., University of North Carolina, Chapel Hill NC, 1976.

[10] Lehmann, R.: General derivation of partial and multiple rank correlation coefficients. *Biometric J.*, 19, 229-236, 1977.

[11] Levine, M. and Shefer, J.: *Fundamentals of Sensation and Perception,* 2nd Edition. Brooks-Cole Publishing Co., Pacific Grove CA, 1981.

[12] Minsky, M., Ouh-Young, M., Steele, O., Brooks, F.P., Jr., and Behensky, M.: Feeling and seeing: issues in force display. *Computer Graphics,* 24, 235-243, 1990.

[13] Noll, A.M.: *Man-Machine Tactile Communication.* Ph.D. thesis, Dept. of Elect. Eng., Polytechnic Institute of Brooklyn, Brooklyn NY, 1971.

[14] Ouh-Young, M., Pique, M. Hughes, J., Srinivasan, N., and Brooks, F.P., Jr.: Using a manipulator for force display in molecular docking. In *Proceedings, IEEE Int. Conf. on Robotics and Automation,* Philadelphia PA, pp. 1824-1829, 1988.

[15] Ouh-Young, M.: *Force Display in Molecular Docking.* Ph.D. thesis, Dept. of Comp. Sci., University of North Carolina, Chapel Hill, NC, 1990.

[16] Rosenberg, L.B. : *Perceptual Design of a Virtual Rigid Surface Contact.* Technical Report AL-TR-1993-XXX, USAF Armstrong Laboratory, Wright-Patterson AFB, OH. In publication.

[17] Sachs, L.: *Applied Statistics: A Handbook of Techniques*, 2nd Edition. Springer-Verlag, New York, 1984.

[18] Winey, C.M., III: *Computer Simulated Visual and Tactile Feedback as an Aid to Manipulator and Vehicle Control*. S.M. thesis, Dept. of Mech. Eng., M.I.T., Cambridge MA, 1981.