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Force Saturation, System Bandwidth, Information Transfer, and Surface Quality in Haptic Interfaces

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Abstract
This paper presents a two-part study of the effects of maximum endpoint force and system bandwidth on haptic perception. First, size identification experiments were performed to determine the effects of system quality, in terms of these two system parameters, on the ability of a human to identify square cross-section ridges by size in a simulated environment. Then, discrimination experiments were performed to determine relationships between haptic interface machine parameters and simulation quality in terms of perceived surface hardness. Results indicate that haptic interface hardware may be able to convey sufficient perceptual information to the user with relatively low levels of force feedback and system bandwidth, yet subjects can perceive improvements in simulated surface quality as levels are further increased.

1 Introduction
Hardware design specifications for haptic interfaces that relate machine parameters to human perceptual performance are notably absent in the literature, although much work has been accomplished in the field in general [see, for example, the surveys 1, 2]. The absence of these specifications is due in large part because establishing a set of haptic interface design specifications must consider issues of human perception. Human perception, in turn, is complex in nature and difficult to assess quantitatively.

Human perception has been quantified via psychophysical experimentation in terms of several haptic perception characteristics, such as pressure perception, position resolution, stiffness, force output range, and force output resolution [for example, 3-5]. However, these experiments were conducted with non-synthetic stimuli, and therefore do not help to define relationships between haptic perception of synthetic stimuli and the hardware that generates them.

Other esearchers have defined performance measures for haptic interfaces, yet these measures are typically disparate from human perceptual measures. When designing high-performance equipment, designers seek to build a device with characteristics such as high force bandwidth, high force dynamic range, and low apparent mass [6, 7, 8, 9]. These are typically qualitative specifications, however, since there is little reference information regarding the quantitative effects of machine parameters on the performance of humans with regards to perception in a haptically simulated environment.

Shimoga outlines design issues for glove-based haptic interfaces, yet they are based on perceptual measures or hardware design criteria [10, 11]. Other work has studied how software parameters affect perceived simulation quality. For example, Lawrence et al. presented rate-hardness as a new performance metric for haptic interfaces [12].

This paper addresses the relationship between haptic interface hardware and human perception, and in particular measures the effects of varying maximum force output and system bandwidth of a device on the information transfer and quality of a haptic environment. Human perception of a simulated environment can be considered in terms of either information transfer or perceived quality. Experiments designed to study information transfer from a simulated environment to a human subject seek to quantify the level of system quality necessary to convey sufficient perceptual information to the user for the purpose of completing a defined task. In the study, machine parameters are varied and subjects are asked to perform size identification of objects and to discern quality of the object surface in terms of perceived hardness.

2 Methods
Two psychophysical concepts, generally used to quantify perception, are utilized in this study to investigate relationships between hardware design and human perception. Discrimination experiments reveal differential thresholds, or more specifically, the smallest perceivable difference in a parameter between a reference and a test object [13]. In this case, discrimination experiments are used to compare simulation quality based on perceived surface hardness of square cross-section ridges placed side by side. Absolute identification paradigms measure a person's ability to categorize parameter values without providing explicit references. For this paper, identification experiments are used to measure haptic performance in a size identification task without regard to perceived quality.

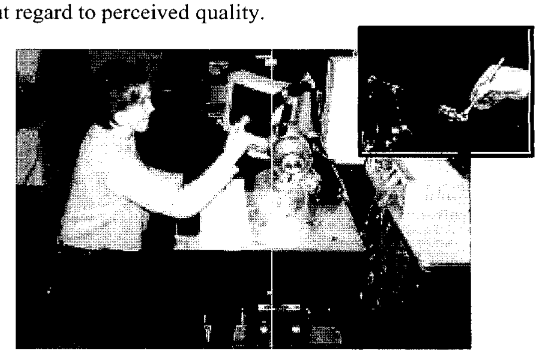


Figure 1. Test subject seated at haptic interface and close-up of stylus

2.1 Apparatus
A three degree-of-freedom manipulator, shown in Figure 1, was designed to exhibit low rotational inertia, minimal friction forces, zero backlash, and high link stiffness [14], which are physical characteristics generally known to facilitate high fidelity haptic simulations [6]. The manipulator is a point-contact force-reflecting device that interfaces with a human through a pencil-type stylus device. Together with computer software designed to simulate virtual environments, the manipulator was used to run several experiments to test the effects of machine design on human perception through a haptic interface. In the experiments

described, the manipulator and haptic simulation were utilized as an impedance operator, as illustrated in Figure 2. The haptic interface therefore measured three-dimensional motion and displayed the appropriate three-dimensional force vector, while the human operator was assumed to perform the inverse (admittance) operation. All simulations ran at a sampling frequency of 3000 Hz. This particular apparatus is capable of displaying constant forces of over 10 N in the spatial region of the haptically displayed ridges, and peak forces of roughly 40 N. Filters on the output command signals limited the range of cut-off frequencies used in simulations to below 100 Hz.

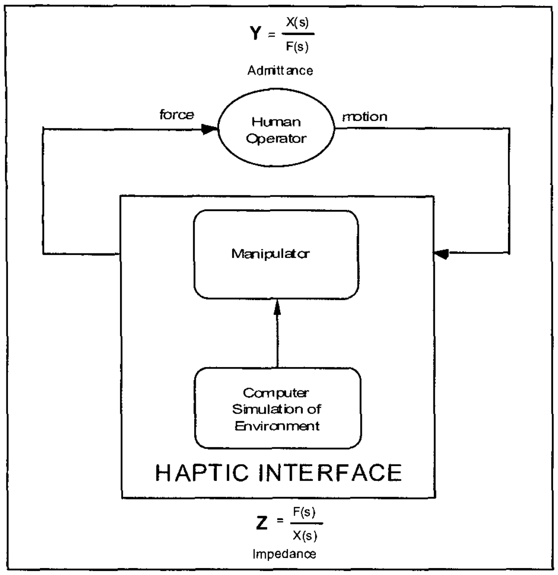


Figure 2. Block diagram of the operator-interface feedback loop

2.2 Experimental Paradigms

Perception experiments were conducted for objects of square cross-section, since the shape can be characterized with a single parameter, namely the edge length for square bumps. Unlike a dynamic task, this experiment is purely perceptual with results that are not time dependent. The complete set of experiments consists of four sets of data. These are size identification (of square cross-section ridges) for varying levels of maximum force output, size identification for varying system bandwidths, and quality discrimination experiments for the two machine parameters.

2.3 Subjects

Six test subjects were used for each size identification experiment block, and eight subjects were used for quality discrimination testing. These subjects were chosen from a pool of individuals with varying amounts of experience using a haptic interface. A cross-section of subject types (gender, dominant handedness, and experience with haptic devices) was chosen for each block of testing. During the training sessions and experiments, each subject sat in front of the haptic interface with the dominant hand holding the stylus and the non-dominant hand typing responses on a keyboard. There were no measures taken to obstruct the subject's views of the haptic interface during testing. Since the objective of this work is to explore only the effects of machine parameters on haptic perception, no synthetically generated visual or audio feedback was included in the simulation. Subjects reported that the tasks relied heavily on their sense of touch and little on their sense of sight, despite the ability to see the motion of their hands.

2.4 Procedures

Identification of Size

Size identification tasks determine the ability of a test subject to classify similarly shaped objects, presented one at a time, by size alone. The objects in this case were synthetic bumps displayed on a virtual floor. The center of each bump was located along the same line, parallel to the z-axis, in the manipulator's workspace. Additionally, the floor of the simulated environment was always along the same xz-plane. Each bump extended across the entire workspace of the manipulator such that if the subject slid the probe along the virtual floor from the front of the workspace to the rear of the workspace in any direction, they would intersect the synthetic ridge. All surfaces were represented as a spring and one-way damper with a spring stiffness of 1100 N/m and a damping ratio of 100 Nsec/m, selected for best overall simulation quality, as determined by the first author.

Each subject was presented with five or six sessions of testing, depending on the machine parameter. A single session consisted of one set of bump sizes and several randomly presented levels of the particular machine parameter. For each session, the smallest bump size remained constant, with an edge length of 20 mm, and the medium and large bumps were generated by adding a length $2d$, where d is referred to as bump discrimination size, to the edge lengths. Force saturation and bandwidth limitations were studied in separate experiments, using the same values for d. Tan found that the same information could be gathered from experiments testing identification of three distinct sizes as could from those testing four or eight sizes [15]. Therefore, to limit the number of trials necessary for experimentation, three distinct sizes of ridges were used in all size identification experiments. Figure 3 illustrates the three bumps sizes for square cross-section bumps.

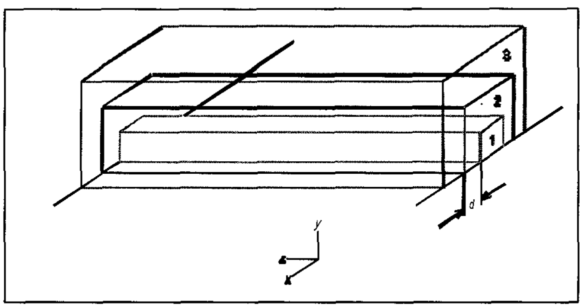


Figure 3. Representation of square cross-section bumps in three rendered sizes showing bump size difference, d

Preliminary experimentation using the first author as a test subject was performed to determine the range of object sizes to use in the final sets of experiments. The synthetic bumps displayed in these preliminary tests were implemented with full force feedback (i.e., no force saturation) and maximum system bandwidth (i.e., no filtering of output). The set of three bump sizes with the smallest d value that was consistently and correctly identified by the author was used as the set with the greatest d value in final experimentation. Smaller d values would be more

Table 1. F_{sat}, f_c, and d values for size identification test sessions

Session Number	Force Saturation Values (N)	Bandwidth (f_c) Values (Hz)	d (mm) Size Difference
1	5, 10	5, 10, 40, 100	1.25
2	0.75, 1.25,3, 5, 10	5, 10, 40, 100	2.50
3	0.5, 0.75, 1.25, 3, 5, 10	5, 10, 40, 100	5.00
4	0.5, 0.75, 1.25, 3, 5, 10	5, 10, 40, 100	7.50
5	0.5, 0.75, 1.25, 3	5, 10, 40, 100	10.00
6	0.5, 0.75	--	12.50

Note: Bandwidth experiments were not performed for d = 12.50 mm

difficult to identify by size and would presumably generate percent correct values less than 100 percent. Table 1 outlines the bump sizes used for each testing session.

Generally, a minimum of $5k^2$ number of trials is sufficient for identification task testing purposes, where k is the number of categories into which items can be categorized [15, 16]. In this case, since three bump sizes were presented in each session, a minimum of 45 bumps (where k = 3) was necessary for each test point, where a test point consisted of one value of d and one value of system parameter. In this experiment, since each session corresponded to one value for d, it was necessary to present 45 times the number of treatment levels used in a particular session to the test subject.

A training session occurred before each testing session, allowing the test subject to learn the three bump sizes displayed without treatment (force saturation or bandwidth limiting) for that particular session. The subjects classified the ridges by entering a 1 (smallest size), 2 (medium size), or 3 (largest size) on the keyboard. Correct-answer feedback was included in the training sessions. Instructions indicated that training should cease when the subject felt comfortable with the bump sizes and confident that s/he could classify bumps by size to the best of their ability. Most test subjects used twenty to fifty trials in the training sessions, depending on the difficulty of the session. The level of force feedback and system bandwidth in the training sessions was not altered so that test subjects were trained with the highest simulation quality possible for this hardware.

During experimentation, the level of maximum force feedback was controlled by a saturation imposed by the computer code. Bandwidth limitations were imposed by adding a bilinear approximation of a 2nd order low-pass filter to the force output command prior to calculating torque commands to the motors. For force saturation testing, a single test session randomly presented objects of three sizes and between two and six levels of maximum force feedback. As a result, bumps in the same session could feel soft or hard, depending on the maximum level of force feedback for that particular trial. For bandwidth testing, each session randomly presented objects of three sizes and four cut-off frequencies. The subjects were instructed to classify the randomly presented bumps into one of the three size categories for that particular trial.

Discrimination of Quality

Size identification tests indicate minimum machine requirements for information transfer purposes. For comparison, additional tests were performed to indicate machine requirements for perceived simulation quality. Surface quality discrimination experiments were designed so that subjects were presented with two square cross-section bumps displayed side by side as shown in Figure 4. In each trial, either maximum force output or system bandwidth was tested, with one of the two bumps displayed with the maximum capable level of that parameter and the other displayed with a lower level of the same parameter. For maximum force output, 10 N was the highest setting, since this was the maximum achievable continuous force output of the haptic interface used in testing. For system bandwidth, a 2nd order digital low-pass filter was added prior to sending torque command signals to the motors. All simulations run at a sampling frequency of 3000 Hz. The only significant limit on system bandwidth when considering the motion to force calculations is a filter on the output command signal to each motor. These signals are low-pass filtered with a cut-off frequency of 100 Hz to remove noise and sample-and-hold in the command signals. Bandwidth levels for testing were then defined in the 10-100 Hz range. Table 2 shows force output and bandwidth setting for the quality discrimination tests. Two sessions of 100 trials each were presented to the subjects, with no training prior to testing. Subjects were instructed to use tapping to determine which bump was harder. Subjects were told that "same" was a valid response, although no trials included two of the same parameters. The ridge with the highest parameter setting was randomly located on either the left or right side of the simulation. A total of 10 presentations of the same parameter combinations were presented in each test session.

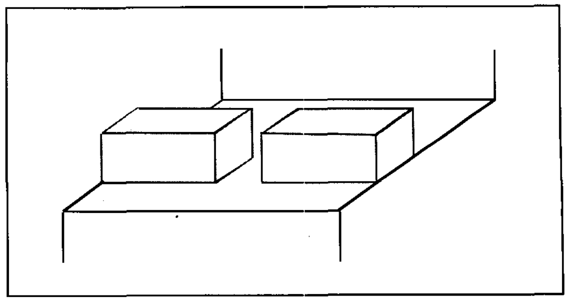


Figure 4. Graphic of quality discrimination test environment

Table 2. F_{sat} and f_c values for quality discrimination test sessions

F_{sat} Combinations (N)	f_c Combinations (Hz)
10 - 3	100 – 50
10 - 5	100 – 60
10 - 7	100 – 70
10 - 8	100 – 80
10 - 9	100 – 90

3 Results

3.1 Identification of Size

The percent correct scores for each test subject were plotted versus bump size difference for each maximum force level. Each data point shown in Figure 5 corresponds to the averaged data for one subject, which represents the percent correct score across 45 trials. The results were then averaged across all test subjects, and a least squares curve fit was performed, utilizing an equation of the form:

$$y = C_1 e^{-\lambda_1 x} + C_2 e^{-\lambda_2 x} \quad (1)$$

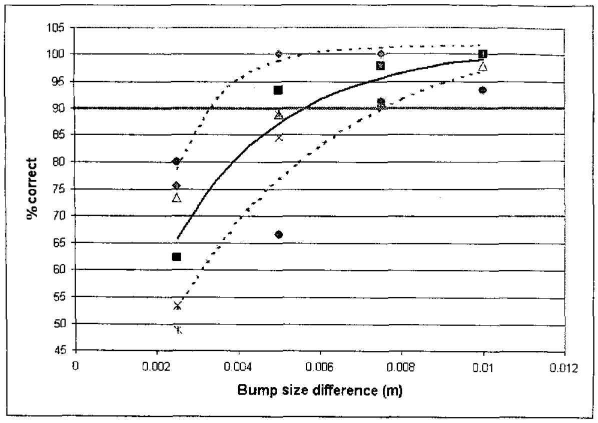


Figure 5. Square size identification data for all subjects (3 N F_{sat}), with average and standard deviation curve fits

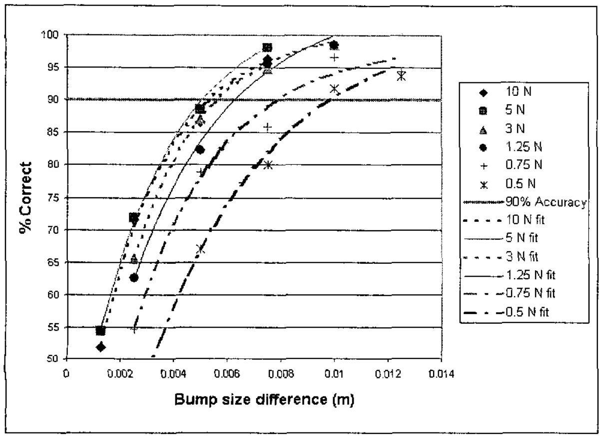
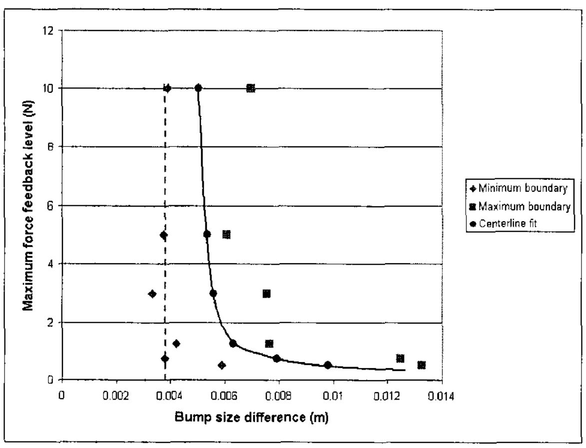


Figure 6. Summary plot of size ID testing for force saturation



Figure'7. Maximum force vs. bump "radius" difference (d) of square cross-section ridges for size identification tests

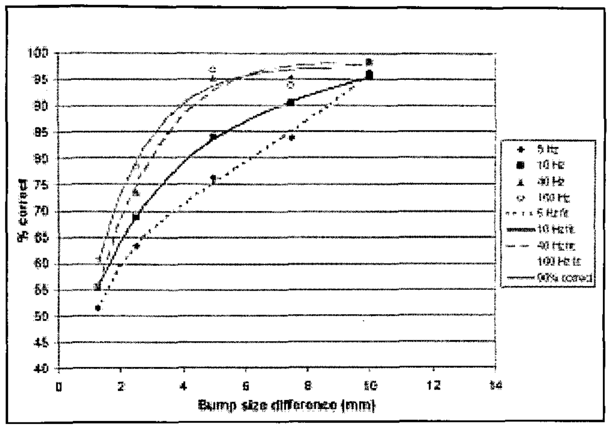


Figure 8. Summary plot of size ID testing for bandwidth limiting

where C_1, λ_1, C_2, and λ_2 were curve-fitting parameters. Note that a two-component exponential curve was utilized because it yielded a noticeably better fit than did a simple exponential. In the figure, the solid line represents this exponential curve fit to the average data across all subjects. The dotted lines show the exponential curve fits to the average plus and minus one standard deviation across all subjects. Note that, as expected, the standard deviation becomes smaller as the bump size difference increases. The data in Figure 5 correspond to one level of maximum endpoint force, and are representative of that for all other maximum force levels.

The exponential curves corresponding to average percent correct scores for all subjects were plotted versus each bump size set for all force saturation levels. The results for square cross-section bumps are pictured in Figure 6. Standard deviation curves are not shown in the figure. A 90% correct line was added to the graph to show what the authors regarded as a good level of correct size identification. The point where each exponential curve fit crossed this 90% correct line was calculated from the curve fit equations, and the resulting data pairs were plotted in Figure 7. The graph shows maximum force feedback levels versus difference in bump radius for the size identification task involving square cross-section bumps. A trend line is overlaid to illustrate this relationship. In addition to the data for the average among test subjects, standard deviations are also plotted. To generate these values, the average values plus and minus one standard deviation, used to create the dotted bands shown in Figure 5, were plotted on the percent correct – bump size difference axes. Exponential curve fits using the two-component equation given previously were performed on the plus/minus standard deviation curves and the 90% correct crossover points were evaluated and plotted on the graph in Figure 7.

The same procedures were followed when recording and compiling data for the size identification tasks involving bandwidth limitations. The summary graph in Figure 8 was constructed from average data across all subjects. Standard deviations are not shown. Figure 9 summarizes the results for square bump size identification testing with bandwidth limiting.

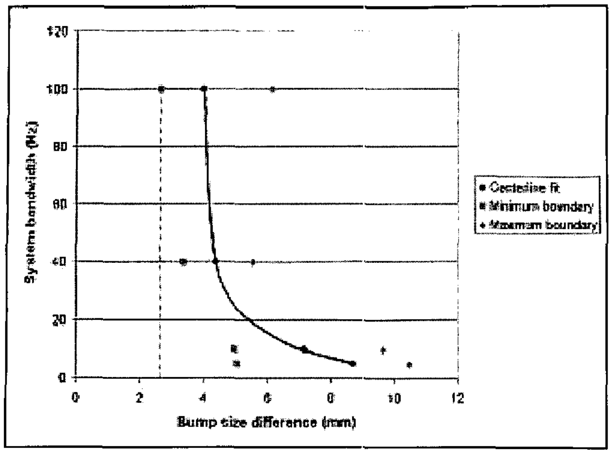


Figure 9. System bandwidth vs. bump size difference (d) of square cross-section ridges for size identification tests

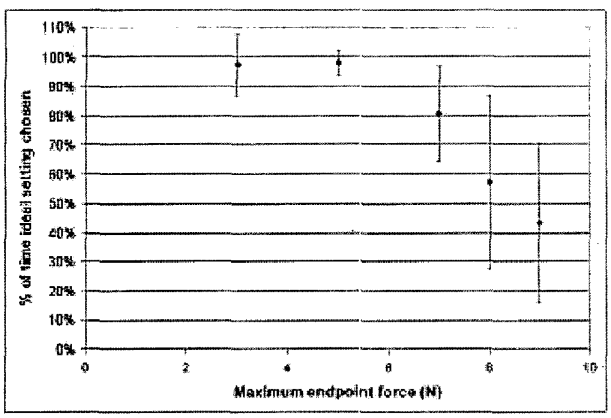


Figure 10. Preference of higher over lower maximum force feedback levels

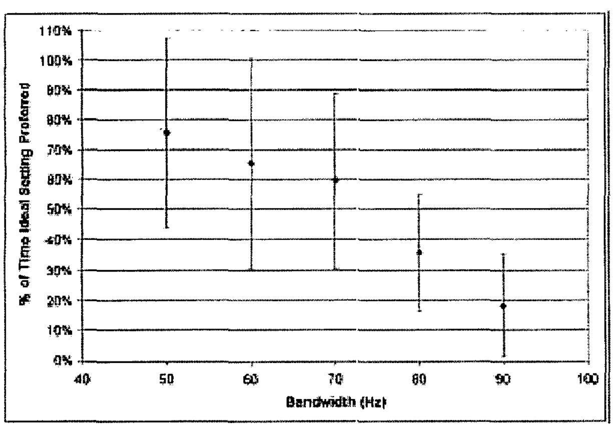


Figure 11. Preference of higher over lower bandwidth levels

3.2 Discrimination of Quality

Discrimination experiments were conducted to assess user preference of machine parameters for hard surface simulation. For interaction with simulated square cross-section ridges via tapping with a probe, subjects responded "right", "left", or "same" when asked which of two bumps felt harder. An average response of 100% indicates that for every presentation of higher/lower quality simulation parameters, the subject chose the higher quality simulation. An average response of 0% indicates that the subject, on average, could not discriminate between the two settings. Results for quality discrimination for varying maximum force feedback levels are shown in Figure 10. Results for varying system bandwidth are shown in Figure 11. Error bars are included to illustrate variance in response across test subjects.

3.3 ANOVA Results

To determine the confidence interval for each size identification experiment, two-way analysis of variance (ANOVA) tests were performed for all perception experiments. Results are shown in Table 3. The treatments are the levels of force saturation or cut-off frequency, and the blocks are the bump size sets with varying values of *d*, depending on the experiment. It should be noted that the variances of the populations in this analysis were not uniform. The ANOVA test method, however, has been shown to be robust to non-uniform variances in treatment-block combinations [17, 18].

Table 3. ANOVA results for size ID experiments

Experiment	Treatment F		Block F		Interaction F	
	95%	99%	95%	99%	95%	99%
Force Saturation	2.6		43.3		1.5	
	Yes	No	Yes	Yes	No	No
Bandwidth Limiting	13.4		110.4		0.5	
	Yes	Yes	Yes	Yes	No	No

4 Discussion

To best represent the trends for the averages among all test subjects, the authors constructed the trend lines visible in each experiment summary graph. As indicated by the trend lines for the size identification tasks shown in Figures 7 and 9, the limit of haptic size identification is approached rather asymptotically, and could be considered as achievable before the maximum force feedback and bandwidth limits of the experimental haptic device were reached. The best average human performance for size identification in this study was reached at maximum force feedback levels of approximately 3 N and bandwidth levels of approximately 40 Hz for square cross-section bumps. By adding higher levels of force feedback or system bandwidth, the designer might be improving the realism of the simulation as compared to touch interactions with non-synthetic objects, but would not, according to the results presented here, convey significantly more usable information to the human with regard to size identification.

A minimum boundary line was drawn vertically across Figures 7 and 9 to indicate one standard deviation below average. The points used when constructing this line for each graph are one standard deviation above the average data points across all subjects. This performance was roughly the same for each experiment, with a minimum identifiable size difference between 4 and 5 mm for force saturation testing and 3 mm for bandwidth testing.

For quality discrimination tests for varying maximum force output, subjects reported that bumps simulated with force levels of 10 N felt harder than those with 3 or 5 N of force feedback over 90% of the time. At force levels greater than 5 N, the percent of responses preferring 10 N of force feedback steadily decreased. Even when comparing 9 N to 10 N, however, subjects preferred the ideal simulation more than 40% of the time. For quality discrimination experiments for varying system bandwidth levels, subjects reported that bandwidths of 100 Hz (the highest bandwidth) felt harder than those with 50 Hz of bandwidth over 70% of the time. The percent of responses preferring the highest bandwidth simulation steadily decreased as system bandwidth of the non-ideally simulated ridge increased. When comparing 90 Hz to 100 Hz however, the subjects felt the higher bandwidth simulated ridge was harder less than 20% of the time.

5 Conclusions

Identification tests were performed to characterize the effect of maximum endpoint force and system bandwidth on haptic size identification. For haptic simulation in a stylus-type interface, the following relationships were observed:

- Endpoint forces above 3 to 4 N do not provide any significant improvements in performance (defined at 90% accuracy) for size identification tasks with ridges of square cross-sections
- System bandwidth above 40 Hz does not provide any significant improvements in performance (defined at 90% accuracy) for size identification tasks with ridges of square cross-sections

To ascertain quality rather than just information transfer, surface hardness discrimination tasks were performed for paired levels of maximum endpoint forces and paired levels of system bandwidth. For the experiments performed, the following conclusion was drawn:

- Perceived simulated surface quality (determined by comparing perceived surface hardness of a simulated bump) increases without bound for the range of system parameters used in these experiments (force output of 0-10 N and system bandwidth of 0-100 Hz)

These observations indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of force feedback and system bandwidth. This being the case, higher levels of force output and bandwidth in a haptic simulation notably improve the quality of simulation in terms of perceived simulated surface hardness.

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