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IMPLICATIONS OF HAPTIC INTERFACE FORCE SATURATION ON THE HAPTIC DISPLAY OF DETAIL

Marcia Kilchenman
Michael Goldfarb

Department of Mechanical Engineering
Vanderbilt University
Nashville, TN 37235

ABSTRACT

The effects of force magnitude on human perception of size in a stylus-type haptic simulation are presented. Identification by size of ridges with both square and round cross-sections was studied while controlling the maximum level of force displayed by the haptic device. Test results indicate that performance, measured as a percent correct score in the identification experiments, improves as the maximum allowable level of force in the simulation increases. However, all test subjects reached a limit in their perception capabilities before reaching the maximum force output capabilities of the haptic interface hardware used in this research. This characteristic indicates that haptic interface hardware may be able to convey sufficient perceptual information to the user with relatively low levels of force feedback. The data is compiled to aid those who wish to design a haptic interface to meet certain requirements for physical detail within a haptic simulation.

1 INTRODUCTION

The proper design of any machine requires a well-defined set of design specifications. Though much work has been accomplished in the field of haptic interfaces (see, for example, Burdea, 1996 and Srinivasan, 1994), much remains when it comes to understanding the effects of machine performance on the human perception of a haptic environment. Indeed, MacLean (1996) concludes from her experimentation that there is a need to investigate the relationship between simulation quality and functionality. With the recent introduction of several commercially oriented haptic devices and applications, the need for a set of design specifications to guide the cost-optimal design of haptic devices is that much more pronounced. The work presented in this paper is an attempt to characterize the effects of one haptic interface design specification, maximum endpoint force, on the ability of a human to haptically perceive and distinguish various object sizes. It is the hope of the authors that the work presented in this paper will help to characterize the relationship between haptic device performance and human perception, and ultimately to form a set of design specifications from which a designer can properly and perhaps optimally design a haptic interface for a given application.

To date, the haptic interface literature generally provides quantitative measures of human factors as a guide for haptic interface design. Psychophysical experiments conducted by several research groups have quantified several haptic perception issues (e.g., pressure perception, position resolution, stiffness, force output range, and force output resolution). Since these experiments have not involved haptic interface equipment, however, they have not been able to create a direct link between machine performance and human perception during haptic task performance. The experiments performed on length resolution by Durlach et al. (1989), for example, quantified the limits of human perception of actual objects, but do not draw parallels between human perceptual ability and haptic hardware design. Related work regarding human factors has investigated the effects of haptic interface software algorithms on human perception. For example, Morgenbesser et al. (1996) looked at the effects of force shading algorithms on the perception of shapes.

At the other end of the spectrum, optimal machine performance has been characterized in the literature, 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 (Ellis et al, 1993; Brooks, 1990). These are typically qualitative specifications, however, since the designers have little reference information, regarding the quantitative effects of these machine parameters on the performance of humans with regards to perception in a haptically simulated environment. While designers are aware of the benefits of "high" bandwidth and "high" force dynamic range, there is a lack of concrete data to illustrate the relationship between these design parameters for a haptic device and human perception. The purpose of the work presented in this paper is to fill the void in establishing a set of quantitative relationships between machine performance and haptic perception. Specifically, this paper presents quantitative data on the effects of force saturation on the haptic display of detail in a stylus-type haptic device.

2 METHODS

Three psychophysical concepts are frequently used to quantify perception, namely *detection*, *discrimination*, and *identification*. Detection experiments used to determine absolute detection thresholds disclose the smallest parameter value that a subject can perceive. Similarly, discrimination experiments can reveal differential thresholds of humans, or more specifically, the smallest perceivable difference in a parameter between a reference and a test object (Gescheider, 1985).

Absolute identification paradigms measure a person's ability to categorize parameter values without providing explicit references. Absolute size identification of synthetic ridges is the focus of this paper. Knowledge of this perceptual measure, in addition to discrimination and detection data, and the effect of haptic simulation quality in terms of machine design parameters on these measures is key to designing hardware that will be considered a high-quality haptic display.

The major goal of current and future research is to reveal trends and develop plots that compare common perception measures including discrimination, detection, and identification, to haptic interface machine parameters, namely maximum force output level, bandwidth, and time delay. All experiments are being conducted with human subjects, studying their perception of basic shapes such as ridges with round and square cross-sections to investigate any differences that may exist between simulations of smooth surfaces and those with sharp corners. During experimentation, varying the machine parameters degrades simulation quality, and perception measures are tallied and compared on the basis of percent correct scores. This paper deals primarily with smallest identifiable size differences for round and square ridges at varying levels of maximum force feedback. Future work will deal with smallest differentiable size differences, smallest sizes for identifiable shape differences, and smallest detectable sizes of different shaped features, all presented as a function of haptic simulation quality in terms of the previously described machine parameters.

The size identification task was chosen because size difference in objects of square and hemi-cylindrical cross-sections can be defined with a single parameter, namely the radius for the rounded bumps and the edge length for square bumps. These two shapes were chosen because of the similarities in their cross-sectional area for bumps of the same base width. Additionally, any differences between sharp-edged and smooth features would presumably appear in test results. These basic geometries can be easily combined to form more complex geometries. Also, unlike a dynamic task, this experiment is purely perceptual with results that are not task dependent.

Previous work (Tan, 1997) investigated the maximum number of different sized spherical bumps that could be identified in a given size range. Using her results as a guide when designing these experiments, it was imperative that the number of trials be kept to a minimum due to the number of maximum force feedback levels that were to be tested, along with testing for two different bump shapes. Her work showed that test subjects could discern at least three different spherical bump sizes within the defined range (10 to 80 mm in radius), while some test subjects could discern as many as four or five. Her work also showed that information transfer rates were independent of the number of identifiable sizes used in experimentation, i.e. the same information could be gleaned from experiments testing identification of three distinct sizes as could from experiments with four or eight sizes. Because of the proportional relationship between number of identifiable test points and necessary number of trials. three bumps per size set were chosen for final experimentation.

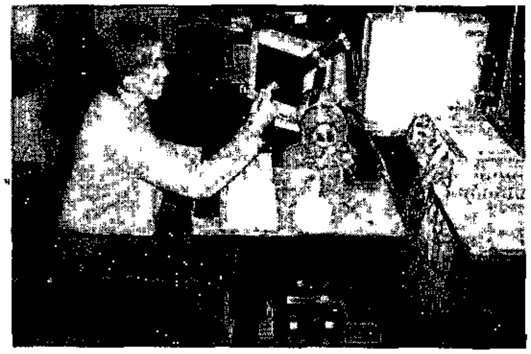

Figure 1. Test subject seated at haptic interface.

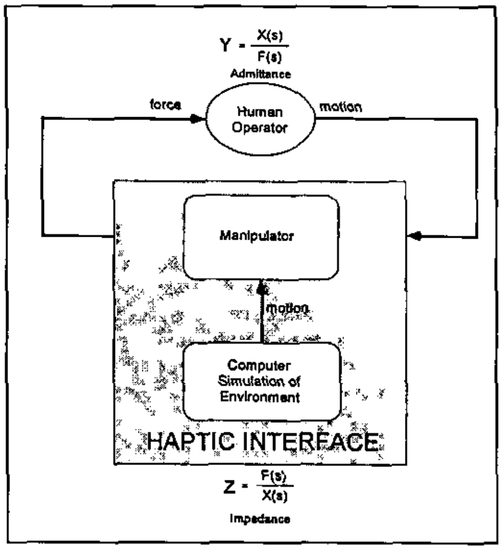

Figure 2. Block diagram of the operator-interface feedback loop.

2.1 Apparatus

A three degree-of-freedom manipulator, shown in Figure 1, was designed to exhibit minimal rotational inertia, minimal friction forces, zero backlash, and maximum link stiffness (Perry, 1997), which are physical characteristics generally known to facilitate high fidelity haptic simulations (Ellis, 1996). The manipulator is a point-contact force-reflecting device that senses the three-dimensional motion of the stylus endpoint and displays a three-dimensional force vector that corresponds to the haptic environment that it is rendering. Together with computer software designed to simulate virtual environments, the manipulator was used to run a battery of experiments to test the effects of machine design on human perception through a haptic interface.

In the experiments described, the manipulator and haptic simulation was utilized as an impedance operator, as illustrated in Figure 2. The haptic interface therefore measured motion and displayed force, 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.

2.2 Stimulus

To test human perception by way of size identification, bumps of varying size were presented to each subject for classification. Objects with both a square and semicircular cross-section were used. Figure 3 shows a three dimensional representation of a hemi-cylindrical bump (i.e., semicircular cross-section).

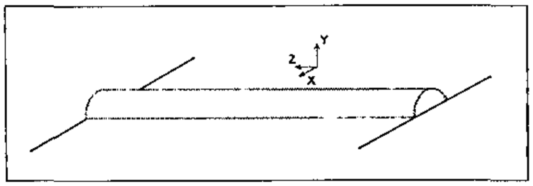

Figure 3. Representation of a haptically rendered bump.

The center of each bump was located along the same line in the x-plane of the manipulator's workspace. Additionally, the floor of the simulated environment was always along the same y-plane. All surfaces were represented as a spring and one-way damper with a spring stiffness of 1100 N/m. The damping ratios utilized were 100 Nsec/m for square bumps and 10 Nsec/m for round bumps, each selected for best overall simulation quality, as determined by the first author.

2.3 Subjects

Six subjects were used for square cross-section bumps and six subjects were used for the semicircular cross-section bumps. For the former set, four males (S1, S2, S3, and S6) and two females (S4 and S5) participated as unpaid volunteers, and three of the six had some previous experience with using a haptic interface (S1, S3, and S6). For the experiments involving hemi-cylindrical bumps, five males (S1, S2, S3, S4, and S6) and one female (S5) participated, also as unpaid volunteers. Three of these six subjects were experienced users of the haptic device (S1, S2 and S5).

2.4 Procedure

Each subject was trained and tested with synthetic bumps displayed on a virtual floor. The location of the centerline of each object was kept constant so that the subject was always comfortable with the location of the bump. 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.

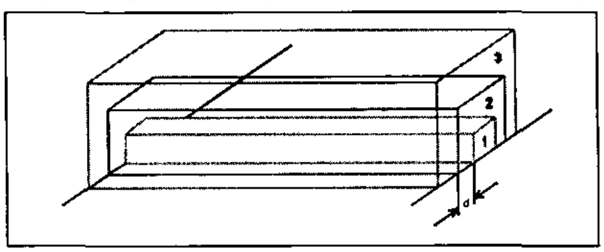

Figure 4. Representation of square cross-section bumps in three rendered sizes showing bump size difference, *d*.

Each subject was presented with six sessions of testing. A single session consisted of one set of bump sizes and a variety of randomly presented levels of maximum force feedback. For each of the six sessions, the smallest bump size remained constant, with a radius of 10 mm for the round bumps, and an edge length of 20 mm for the square bumps. The medium and large bumps for each set of sizes were simulated by adding a constant to the radius of the small round bump and adding twice the constant to the edge length of the small square bump. In both cases, this constant is referred to as the variable *d*, or the bump size difference. Figure 4 illustrates the three bumps sizes for square cross-section bumps.

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). 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 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.

Table 1. Bump sizes (mm) for each test session.

Session Number	Small (1)	Medium (2)	Large (3)	Difference in Bump Size (mm) -- *d*
1	10.00	11.25	12.50	1.25
2	10.00	12.50	15.00	2.50
3	10.00	15.00	20.00	5.00
4	10.00	17.50	25.00	7.50
5	10.00	20.00	30.00	10.00
6	10.00	22.50	35.00	12.50

Note: Bump sizes correspond to half of bump edge length for square cross-section bumps and to bump radius for round cross-section bumps.

A training session occurred before each testing session, allowing the test subject to learn the three bump sizes for that particular session. During the training period, subjects were presented with a virtual bump displayed without force saturation and were then prompted to enter the number corresponding to that bump size on a computer keyboard. The subjects classified the ridges by entering a 1 (smallest size), 2 (medium size), or 3 (largest size) on the keyboard. If correct, the user heard a beep and went directly to a new bump. If incorrect, the size number of the simulated object was displayed on the computer monitor for the subject to see. After hitting <Enter>, the next bump would be displayed. The test subject was allowed to continue training for as long as s/he felt necessary. 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 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. 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. The subjects were instructed to classify the randomly presented bumps into one of the three size categories for that particular trial.

Generally, a minimum of $5k^2$ number of trials is sufficient for identification task testing purposes (Miller, 1954; Tan, 1997), where k is the number of categories into which items can be categorized. 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 maximum force feedback level. In this experiment, since each session corresponded to one value for d, it was necessary to present 45 times the number of force feedback levels used in a particular session to the test subject at a time. The following table outlines the test sessions.

Table 2. Breakdown of F_{sat} and d values for test sessions.

Session Number	Force Saturation Values (N)	*d*, Bump Size Difference (mm)	Number of trials
1	5, 10	1.25	90
2	0.75, 1.25,3, 5, 10	2.50	225
3	0.5, 0.75, 1.25, 3, 5, 10	5.00	270
4	0.5, 0.75, 1.25, 3, 5, 10	7.50	270
5	0.5, 0.75, 1.25, 3	10.00	180
6	0.5, 0.75	12.50	90

During the experiment, 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 human perception, no synthetically generated visual or audio feedback was included in the simulation. Subjects reported that the task relied heavily on their sense of touch and little on their sense of sight, despite the ability to see the motion of their hands.

3 RESULTS

A percent correct score was calculated for each (bump size set) – (maximum force level) pair as given by the following expression:

$$\%_{correct} = \frac{\left(N_{bumps} - N_{incorrect}\right)}{N_{bumps}} \times 100 \qquad (1)$$

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 data for one subject, which represents the percent correct score across 45 trials. The results were then averaged across all test subjects, and an exponential curve fit was performed, utilizing an equation of the form:

$$y = C_1 e^{-\lambda_1 x} + C_2 e^{-\lambda_2 x} \qquad (2)$$

A least squares optimization was performed on the raw data to generate the curve fit. 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 the 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. The data in Figure 5 correspond to one level of maximum endpoint force, and is 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

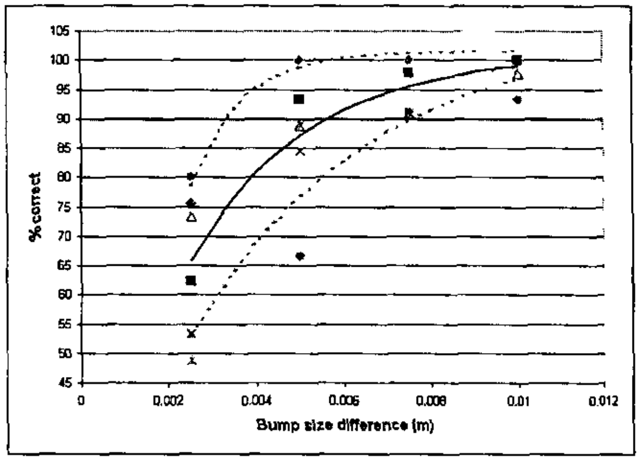

Figure 5. Representative square bump size identification data for all subjects (3 N force saturation), including average and standard deviation curve fits.

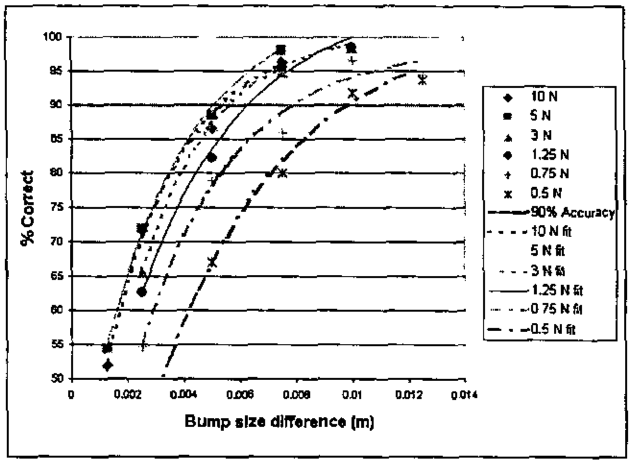

Figure 6. Summary plot of square feature size ID testing.

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% accuracy crossover points were evaluated. These points are plotted on the graph in Figure 7, and are referred to by the authors as the minimum and maximum boundaries.

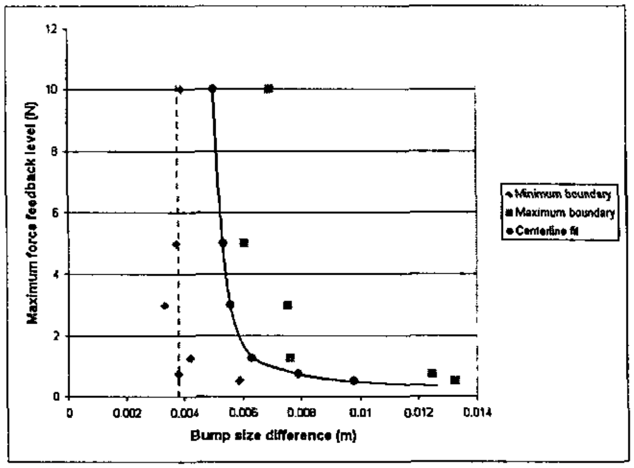

Figure 7. Maximum force vs. bump "radius" difference (d) of square cross-section bumps for size identification tests.

The same procedures were followed when recording and compiling data for the size identification tasks involving objects with semi-circular cross-sections. These results are shown in Figures 8, 9 and 10. Figure 8 contains data for all test subjects at one maximum force feedback level, and is representative of data collected across all maximum force feedback levels. The summary graph in Figure 9 was constructed from average data across all subjects. Standard deviations are not shown. Figure 10 summarizes the results for round bump size identification testing.

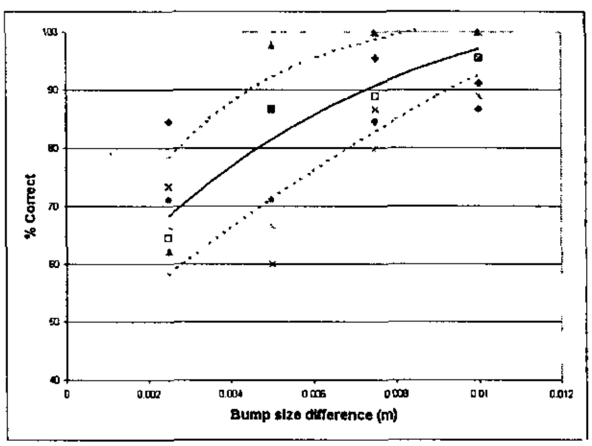

Figure 8. Representative round bump data for all subjects (1.25 N force saturation), including average and standard deviation curve fits.

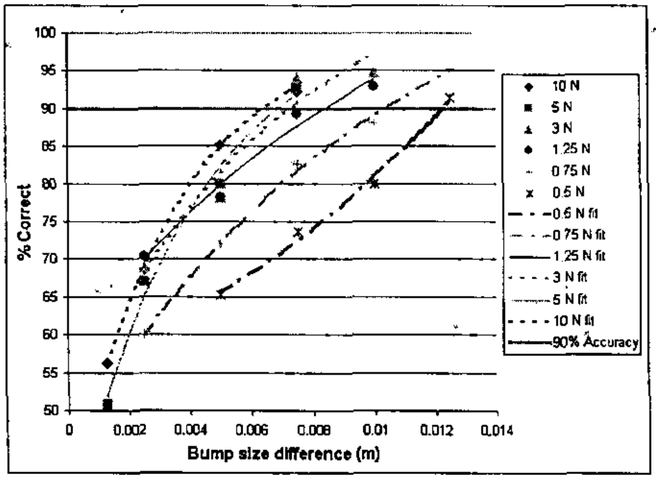

Figure 9. Summary plot of round feature testing.

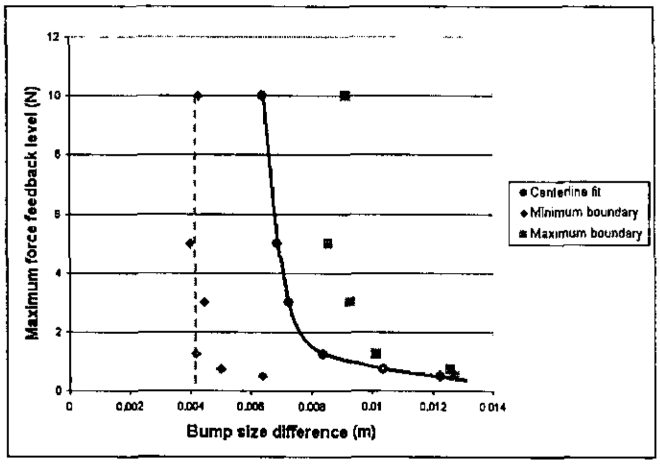

Figure 10. Maximum force vs. bump radius difference (d) of round cross-section bumps for identification tests.

To determine the confidence interval for each experiment, two-way analysis of variance (ANOVA) tests were performed for both the square and round bump size identification experiments. Results are shown in Tables 3 and 4. The treatments are the levels of force saturation, and the blocks are the bump size sets with varying values of d. Results for both experiments indicate that with 95% confidence, the variations in percent correct scores are attributable to the treatment of varying force saturation levels, and with 99% confidence, percent correct scores vary due to the difference in bump size difference. There is no apparent interaction between bump size difference and maximum force saturation level. 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 (Gaito, 1973; Box and Anderson, 1956)

Table 3. ANOVA summary chart for square bumps

Source	DF	Sum Squares	Mean Square	F	F > 95 %	F > 99 %
Treatment	5	1774	354.9	2.6	yes	no
Block	5	29519	5903.8	43.3	yes	yes
Interaction	25	5171	206.8	1.5	no	no
Residual	124	16901	136.3			
Total	148	53364				

Table 4. ANOVA summary chart for round bumps

Source	DF	Sum Squares	Mean Square	F	F > 95 %	F > 99 %
Treatment	5	2281	456.1	2.8	yes	no
Block	5	20164	4032.8	24.7	yes	yes
Interaction	25	4193	167.7	1.0	no	no
Residual	124	20265	163.4			
Total	148	46902				

In order to show actual force output levels that are generated in the simulation, unsaturated and saturated force data were recorded during simulations with both square and round cross-section ridges. Figure 11 illustrates force versus time data for a typical square bump simulation. For this case, forces were saturated at 10 N. The majority of time spent sliding the stylus over the simulated ridge sees forces in the range of 5 to 10 N. When the user taps the stylus on a rigid surface, forces of up to nearly 25 N are generated. For this simulation, the user felt the saturated forces, and both saturated and unsaturated force levels were recorded in a data file. Figure 12 illustrates force versus time data for a typical interaction with a round ridge. For this case, force levels were saturated at 2 N. Again, the user felt the saturated forces, but both saturated and unsaturated force levels were recorded in a data file. The motion of sliding over the bump generates forces in the range of 2 to 8 N, while tapping on the rigid surfaces generates forces of over 10 N.

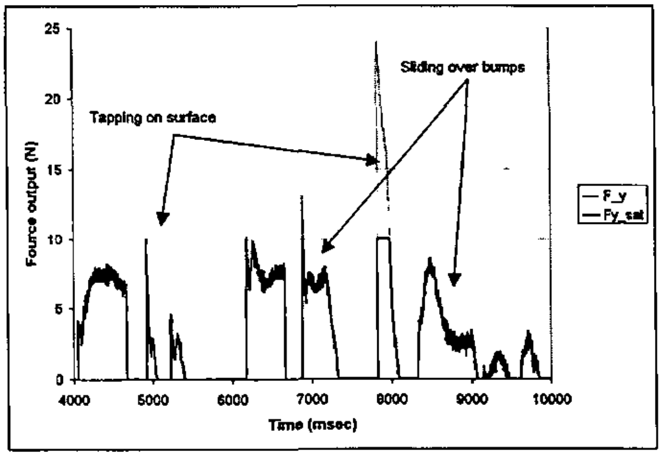

Figure 11. Y-axis force output for user interaction with square bump, saturating at ± 10 N

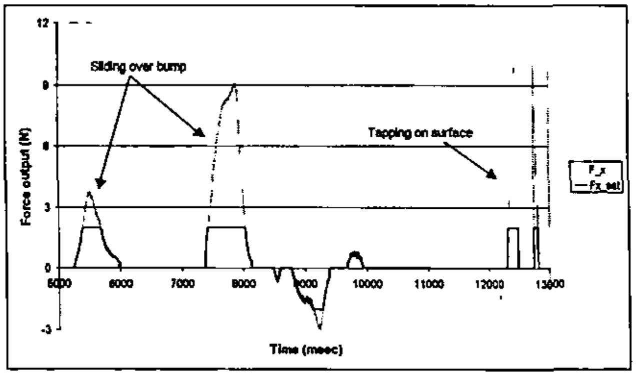

Figure 12. X-axis force output for user interaction with round bump, saturating at ± 2 N

For both simulations, generated forces are consistently above roughly 3 N. This level of force was the same as that force found necessary for maximum performance for the size identification tasks performed in these experiments. Results of the testing indicate that despite an imposed saturation on the output forces at a level lower than normal interaction with the simulated features would generate, subjects can correctly identify square and round ridges by size.

4 DISCUSSION

The authors, to best represent the trends for the averages among all test subjects, constructed the trend lines visible in Figures 7 and 10. As indicated by both trend lines, the limit of human perception in terms of the size difference identification task is approached rather asymptotically, and could be considered as achievable before the maximum force feedback limits of the experimental haptic device were reached. The best average human performance for this study was reached at maximum force feedback levels of near 3 N for square cross-section bumps and 2 N for round cross-section bumps, while the haptic device used in this experiment was capable of displaying constant force output beyond 10 N. The trend lines in Figures 7 and 10 highlight a design trade-off for haptic interfaces. By adding higher levels of force feedback, better size resolution for the identification task described here is achieved, but only to a point. Beyond this point, the designer might be improving the reality of the simulation as compared to touch interactions with non-synthetic objects, but would not, according to the results presented here, convey any more usable information to the human with regard to performing the size identification task.

A minimum boundary line was drawn vertically across Figures 7 and 10 to illustrate a visible limit in human performance for the size identification task. The points used when constructing this line for each graph are one standard deviation below the average data points across all subjects. These lines are believed to represent the "best" performance achievable by the average test subject when performing the size identification test with square and round cross-section features. This performance was about the same for square and round cross-section bumps, with a minimum identifiable size difference between 4 and 5 mm.

Overall, the results for round and square bumps are quite comparable. The minimum boundary lines on each summary plot fall at approximately the same location, indicating the smallest resolvable size difference that human subjects can identify in a purely haptic environment. The shapes of the superimposed trend lines for square and round bump size identification data are quite similar, implying that the trade-offs between maximum force feedback levels and minimum identifiable size differences transcend bump shapes, at least for those investigated in the experimentation described here.

5 CONCLUSIONS

Testing of human perception with a haptic interface in terms of size identification of objects with round and square cross-sections was carried out. Subjects were asked to classify synthetically displayed ridges by size, with one of three possible sizes displayed each trial. During testing, maximum force feedback levels in the simulations were varied to characterize the effect of force feedback level on a person's ability to classify haptically presented objects by size. The minimum identifiable size difference for both round and square bump shapes was about 4 to 5 mm. Maximum performance was achieved at a force level of about 3 N for square cross-section bumps and about 2 N for semicircular cross-section bumps. These force levels were well below the maximum force output capabilities of the hardware used in testing, and also were below the maximum force feedback levels chosen for experimentation. Additionally, these force levels were lower than those generated during unsaturated interaction with the haptically simulated square and round bumps.

The test results indicate that, with 95% confidence, percent correct scores for the size identification experiments improve as the maximum allowable level of force in the simulation increases. This phenomenon holds only for a small range, however, since maximum performance measures are reached before the limits of the hardware are exceeded. Implied by this observation is the idea that haptic interface hardware may be capable of conveying sufficient perceptual information to the user, at least in terms of stylus-based size identification tasks, at fairly low levels of force feedback. While higher levels of force output in a haptic simulation may improve the simulation in terms of how realistic it feels, the results of these experiments imply that high levels of force feedback are not required to reach maximum performance for size identification.

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