ORIGINAL ARTICLE

The Influence of Texture on Perceiving Haptic Stiffness

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Abstract: The sense of touch is essential to perform discriminating tasks in virtual reality applications or virtual training systems. To discriminate between different virtual objects, a human operator needs to clearly perceive the stiffness of each object. Stiffness is not only a material property, but also a characteristic of the particular object and express how it is being touched. Stiffness affects the perception of surface topography and depends on the area of applied force. While haptic-enabled virtual reality training systems have been received considerable attention in recent years, our main criticism on these systems is that their virtual environments provide homogeneous haptic stiffness and less perceptually accurate virtual space. This paper investigated how texture affects the perception of haptic stiffness of the virtual object. By performing a psychophysical experiment, we determined that human operator's average accuracy in discriminating perceived haptic stiffness of the virtual object is depending on its texture information and spatial variations. Our findings underscore the importance of implementing spatially varying haptic parameters.

Keywords: haptic stiffness, perceived stiffness, texture effects, psychophysics

1. INTRODUCTION

Touch is a versatile sense for humans; hence, haptic interaction with vision offers users to experience and create touch sensations in virtual environment and hyper media [1]. Haptic technology and simulating tactile feedback for virtual reality applications have been widely studied in numerous fields, including computer-aided design, entertainment, education, medical simulation, rehabilitation, etc. [2, 3]. Our previous works on development of haptic-enabled systems have been focused on implementing realistic and efficient force feedback for real-time applications including 3D design support systems, virtual training and games [4-6] (see Figure 1). The main criticism on existing systems including our previous developments is that their virtual environments are not perceptually accurate and data-driven. Because the geometric objects in the virtual environments may be based on real-world data, but haptic properties like stiffness, texture, and friction are almost procedurally generated, and very homogeneous.

Our long-term research objective is to develop the data-driven haptic systems with perceptually validated intuitive operations. The present research and developments extend our previous work by investigating perceptual spaces for haptic properties and operations. Stiffness is a very important haptic property to discriminate between

different virtual objects, and a human operator needs to clearly perceive the stiffness of each object. While a number of research works on haptic perception and perceived instability has been focused [10, 12, 14], less effort has been spent to investigate the influence of texture on perceiving haptic stiffness. The main contribution of this paper is thus in the design and execution of the psychophysical experiments to explore how texture affects the perception of haptic stiffness.

The rest of this paper is organized as follows. Section 2 reviews background literature on haptic rendering and perception of stiffness. In Section 2, we introduce procedures and methods of psychophysical experiment. Results and discussion are presented in Section 4. Finally, section 5 summarizes the conclusions, and discusses possible future work.

Haptic-enabled virtual training systems

Figure 1: Haptic-enabled virtual training systems

2. BACKGROUND

In the recent years, extensive research and development have been done on haptics rendering and psychophysical properties in haptics. The purpose of this brief overview is to review some related works on haptic perception and haptic stiffness.

2.1 Haptic Perception and Stiffness

Haptic perception relies on sensory signals emerging from haptic interaction with a virtual environment [3]. Haptic interaction involves several haptic variables like force/torque, stiffness, friction, masses, etc. The most significant issue for haptic perception involves understanding how human operators perceive these haptic variables and properties. Recently, researches on haptic texture and roughness perception have been extensively studied [7, 8, 12, 14]. Srinivasan et al. investigated the influence of visual information over tactile information in a comparison of two springs with different stiffness [17]. Walker and Tan presented how stiffness affects the perception of surface topography and found that the relative stiffness of two surfaces may affect users' ability to feel a step deformity [9].

Forrest et al. measured the haptic perceptual abilities of veterinarians and veterinary students when identifying the stiffness of a virtual surface [8]. Choi et al. demonstrated that given two adjacent surfaces, their perceived height difference depended on both the surface stiffness values as well as the relative heights of the surfaces [11]. Otaduy et al. presented a new approach to haptically render complex interaction due to fine surface details using simplified representations of the original models and the corresponding haptic textures [16]. However, their approach ignores important texture cues arising from spatial variation in the textures. As mentioned above, there is a small number of literature works on perceiving haptic stiffness. The present study is the first to compare carefully controlled haptic stiffness stimuli with different textures.

3. EXPERIMENTS

The main objective of this experiment was to examine the effect of texture on perceiving haptic stiffness of the virtual object. To understand how texture affects the perception of haptic stiffness, we must study virtual objects with a range of haptic stiffness and force under varied texture conditions. To do this, we created two groups of stimuli that would allow us to systematically explore combinations of identical and different stiffness values and their impact on the identical and varied texture information of objects in the haptic enabled virtual environment (see Table 1).

Table 1: Groups of experiments: combination of texture and stiffness

	Stiffness	Texture
Group 1	different	identical
Group 2	identical	different

3.1 Participants

A total of twenty healthy volunteer Japanese subjects (10 female and 10 male) between 20 to 28 years of age participated in our psychophysical experiments. The subjects were undergraduate and graduate students of Department of Media and Image Technology, Faculty of Engineering, Tokyo Polytechnic University. All subjects were naive to the design and purpose of the experiment, and all were right handed and reported normal or corrected-to-normal vision. No subject was known to have any neurological disorders.

3.2 Stimulus Generation

The haptic stimuli were generated by the force-feedback device. As shown in Table 2, we created twenty set of haptic stimuli from each group that focused range of stiffness, texture, and geometry. Each stimulus consisted of two identical virtual objects in a neutral gray background, one on the left and the other on the right. The illumination is exactly the same for each object in the scene, and there is no interreflection and shadowing between objects. Resolution (interface size) of each stimulus is 1280×1024. Figure 2 shows an example haptic stimulus from Group 1, objects consisting different stiffness (k_1 and k_2) and graphically rendered with same texture. The purpose of considering stimuli of Group 1 was to estimate the threshold for haptic stiffness. Figure 3 presents an example haptic stimulus from Group 2, objects consisting identical stiffness (k_i) and graphically rendered with different textures. In order to examine the effect of texture on perceiving identical stiffness, stimuli of Group 2 were experimented.

3.2.1 3D Models

Three-dimensional objects in stimuli were created using AutoDesk Maya 2008 3D modeling software package, and were exported polygon data to the Wavefront OBJ file format. As shown in Figure 4, 3D models of *Banana* and

Table 2: The number of stimuli in each stimulus group

	Stiffness	Texture	No. of haptic stimuli
Group 1	different	identical	For Apple = 10 For Banana = 10
Group 2	identical	different	For Apple = 10 For Banana = 10

Figure 2: Example of stimulus from Group 1, different stiffness (k_1 and k_2) and identical texture.

Figure 3: Example of stimulus from Group 2, identical stiffness (k_i) and different texture.

Figure 4: 3D models in the stimuli

Apple were selected. The banana model consists of 3483 vertices and 6960 faces. The apple model in Figure 4 has 1373 vertices and 2396 faces.

3.2.2 Texture

In order to create realistic textures for selected virtual objects, UV-coordinates of the 3D models were used and painted using Adobe Photoshop CS5 software package. This preprocessed texture data and parameterized mesh data were used to create texture atlas for program of experimental interface which render haptic-enabled textured virtual objects. The perception of color appearance of familiar objects depends on the degree of naturalness of the stimuli [15]. Therefore, the five different versions of realistic textures were considered for each object as depicted in Figure 5 and Figure 6.

Apples have a natural coloring that is red, green, yellow or a mixture of all three. A set of apple textures was

Figure 5: Textured 3D Apple models used in the stimuli

Figure 6: Textured 3D Banana models used in the stimuli

selected based on popular varieties available in the market such as *Granny Smith*, *Golden Reinette*, *Golden Delicious*, *Cox Orange Pippin* and *Fuji*. As shown in Figure 5, we labeled them with their colors, Green(G), Greenish Yellow(GY), Yellow(Y), Orangish(O) and Red(R). A set of textures for banana was selected based on the ripening process as illustrated in Figure 6, and labeled such as Green(G), Greenish Yellow(GY), Yellow(Y), Ripe(R) and Dark Ripe(DR).

3.2.3 Stiffness

Five different stiffness ($K[N/mm] = \{0.1, 0.3, 0.5, 0.7, 0.9\}$) values were used in the stimuli of Group 1, which generated ten different pairs of stiffness values for k_1 and k_2 . The identical stiffness (k_l) of stimuli in the Group 2 was $0.5 N/mm$.

3.3 Apparatus

As a force-feedback device, a PHANToM Omni (Sensable Inc. [21], user can interact with 6-DOF inputs and 3-DOF haptic feedback) was used to render virtual objects, which can assign a variety of stiffness values. The subject was comfortably seated (with an armrest) in front of calibrated LCD display (Planar PX1910, 48cm diagonal, 1280×1024 pixels of resolution, sRGB color space, max luminance $250 cd/m^2$) holding the PHANToM stylus with the right hand.

As shown in Figure 7, the experiments were performed in a white colored experimental booth under controlled office light conditions. This was done to eliminate possible visual and illumination cues. The program of the experimental interface was executed on a standard PC equipped with a 3.33 GHz Intel Xeon CPU and a NVIDIA Quadro FX 4600 graphics board with a 768MB video memory. The program refreshes the screen 60 Hz to give the user feeling of continuous movement of virtual scene while

Figure 7: Experimental setup, the subject was comfortably seated in front of the LCD monitor holding the PHANToM stylus with the right hand in an experimental booth.

haptic device is permitting a much higher rate of 1 kHz for force feedback.

3.4 Procedure

After instructing about their task, the subjects were allowed to complete a training session of the stiffness discrimination. In the proper sessions, haptic stimuli from each group were randomly presented to the subjects. The subjects were asked to feel both virtual objects using the haptic probe and judge whether the two objects were of same stiffness. They were allowed to answer with “Yes”, “No”, or “Don’t Know”. To avoid possible lapses in concentration, subjects were explicitly instructed and allowed to take a short break if they grew tired or fatigued arm.

4. RESULTS

In the experiment, subjects were asked to judge the all stimuli from both groups, all of which were randomly presented. In order to study the effect of texture and the effect of gender, the analysis was performed separately for identical and different textures.

The results of the experiment indicate that the perception of haptic stiffness of virtual objects greatly affected by the texture data. As shown Table 3, subjects’ average accuracy is rather high when discriminating stiffness of the objects on identical textures, but it significantly reduces on different textures. For the apple textures, subjects’ average accuracy drops from 78% to 46%. Subjects’ average accuracy drops from 77% to 37.5% when perceiving on banana textures.

4.1 Identical Textures

Differences between subject groups and stiffness discrimination thresholds were tested with a one-way analysis of variance (ANOVA). Figure 8 compares the average response values of accurate stiffness discrimination made by male (10 subjects) and female (10 subjects) subject groups on different pairs of stiffness values for identical apple textures. The means and standard deviations for average accuracy of response were: male (mean = 0.76, sd = 0.2366) and female (mean = 0.8, sd = 0.2). However, one-way ANOVA demonstrated that there is no significant (at the 1% level) difference ($F(1, 18) = 0.17, p = 0.685$) between the male and female subjects. Because classic

Table 3: Average accuracy for each stimulus group

	Stiffness	Texture	Average accuracy
Group 1	different	identical	Apple texture 78%
			Banana texture 77%
Group 2	identical	different	Apple texture 46%
			Banana texture 37.5%

The Influence of Texture on Perceiving Haptic Stiffness

Figure 8: Comparison of accurate response and stiffness combinations for apple texture

ANOVA often assume that the populations are approximately the same form (normally distributed), in the sense that if they differ it is by a shift or translation.

The comparison of male and female subject groups on perceiving haptic stiffness is presented in Figure 9 as plots of the average value of accurate response versus the stiffness combination for identical banana textures. The means and standard deviations for each gender were: male (mean = 0.8, sd = 0.1826) and female (mean = 0.74, sd = 0.1897). These variation values were not large enough to produce any significant effect in ANOVA. Therefore, one-way ANOVA demonstrated that the effect of gender is not significant (at the 1% level) for stiffness discrimination on identical banana textures ($F(1, 18) = 0.52, p = 0.48$). However, male subjects more accurately judged (with 100% accuracy) the different stiffness (0.3, 0.9) on identical banana texture when female judged with 80% accuracy.

To examine the threshold values for perceived stiffness difference, the absolute difference of stiffness values ($\Delta k = |k_1 - k_2|$) were considered. Figure 10 and Figure 11 illustrate the average values of correct response plotted against the absolute difference of stiffness values for apple and banana textures respectively. From the results of the comparison between correct response and perceived stiffness difference (Δk), we can conclude that subjects are able to more accurately judge perceived stiffness on identical textures when Δk is higher.

Figure 9: Comparison of accurate response and stiffness combinations for banana texture

Figure 10: Comparison of accurate response and intensity of stiffness difference for Apple texture

Figure 11: Comparison of accurate response and intensity of stiffness difference for Banana texture

4.2 Different Textures

In order to examine the difference between male and female subjects on perceiving identical stiffness for different textures, the average values of accurate responses were plotted against the different texture combinations as shown in Figure 12 (for apple textures) and Figure 13 (for banana textures). A one-way ANOVA confirmed that the difference between male and female subjects on perceiving identical stiffness for different apple textures is not significant at the 1% level ($F(1, 18) = 7.09, p = 0.0159$), but significant at the 5% level. For the different apple texture combinations as depicted in Figure 12, female subjects (mean = 0.56, sd = 0.143) more accurately perceived the identical stiffness than male subjects (mean = 0.36, sd = 0.189).

For the different banana texture combinations as depicted in Figure 13, the means and standard deviations for each gender were: male (mean = 0.33, sd = 0.157) and female (mean = 0.42, sd = 0.155). A one-way ANOVA confirmed that these variations were not large enough to produce significant (at the 1% level) effect of gender on perceiving identical stiffness ($F(1, 18) = 1.67, p = 0.213$).

From the comparison of Figure 12 and Figure 13, we can conclude that the subjects are unable to reliably perceive the identical stiffness of virtual object on different textures. However, the subjects could judge (more

Figure 12: Comparison of accurate response and texture variations for Apple

Figure 13: Comparison of accurate response and texture variations for Banana

than 60% accuracy) the identical stiffness on different apple texture combinations for (G : GY) and (O : R), which has the same range of hue. For different banana textures, subjects' accurate response is higher for (G : Y) and (GY : R) combinations. Therefore, it will be required to conduct more psychophysical experiments in order to

study and clearly analyze the effect of spatial variations and color cues on perceiving haptic stiffness. This analysis and the data in Figure 8 to 13 verify whether different subsets of the data have the same probability distribution. The future analysis will be based on non-parametric statistics. Specially, hypotheses will be tested with the Kruskal-Wallis analysis of variance [22]. Unlike classic ANOVA, it does not make the assumption of normally distributed data.

The findings from the present study have guided to implement spatial varying haptic parameters such as stiffness, by means of image-based techniques (see Figure 14). Our present implementations are focusing to improve partial varying stiffness calculations based on data-driven techniques [19, 20].

5. CONCLUSION

In this paper, we investigated the effect of texture on perceiving haptic stiffness of virtual objects. To assess the effect of texture, a set of psychophysical experiments were performed. Despite the limitation of this analysis, it was clearly shown that the perception of haptic stiffness of virtual objects greatly affected by the texture data. We also found that there was no significant effect of gender on perceiving haptic stiffness. As future work, experiments could include the influence of spatial-variations or user Kansei, as well as more detailed psychometric analysis. It would also be interesting to undertake further work to investigate possible methods for interactive synthesis of haptic stiffness data.

Figure 14: Our approach for rendering spatially-varying haptic force

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REFERENCES

1. S. J. Biggs and M. A. Srinivasan, Handbook of Virtual Environments: Design, Implementation, and Applications, (Human Factors and Ergonomics), Lawrence Erlbaum Associates, ISBN:0-8058-3838-4, pp.93-115, (2002).
2. V. Haymard, O. R. Astley, M. Cruz-Hernandez, D. Grant and G. R. De-La-Torre, Haptic interfaces and devices, Sensor Review, Vol 24 (1), pp.16-29, (2004).
3. M. C. Lin and M. Otaduy, Haptic Rendering: Foundations, Algorithms and Applications, A. K. Peters, Ltd., ISBN:97815688133254, (2008).
4. Y. Tokuyama, R. P. C. J. Rajapakse, Y. Nakazawa and K. Konno, Torque display method for free-form deformation with haptic device, Proc. of the ICROS-SICE International Joint Conference 2009, pp.3803-3808, (2009).
5. R. P. C. J. Rajapakse, Y. Tokuyama, and K. Konno, A Framework for Constructing 3D Shape Modification System Based on Haptic Display, Proc. of the International Workshop on Advanced Image Technology 2010, pp.1-6, (2010).
6. R. P. C. J. Rajapakse, Y. Tokuyama, and K. Konno, PhysX-based Framework for Developing Games with Haptic Feedback, Proc. of NICOGRAPH International 2011, pp.1-7, (2011).
7. B. Unger, R. Hollis, and R. Klatzky, Roughness Perception in Virtual Textures, IEEE Transactions on Haptics, Vol 4 (2), pp.122-133, (2011).
8. N. Forrest, S. Baillie, P. Kalita, and Hong Z. Tan, A Comparative Study of Haptic Stiffness Identification by Veterinarians and Students, IEEE Transactions on Haptics, Vol 4 (2), pp.78-87, (2011).
9. L. Walker and H. Z. Tan, A perceptual study on haptic rendering of surface topography when both surface height and stiffness vary, Proc. of the 12th international conference on Haptic interfaces for virtual environment and teleoperator systems, pp.138-145, (2004).
10. N. Gurari, K. J. Kuchenbecker, and A. M. Okamura, Stiffness discrimination with visual and proprioceptive cues, Proc. of the World Haptics 2009, pp.121-126, (2009).
11. S. Choi, L. Walker, H. Z. Tan, and S. Crittenden, and R. Reifengerger, Force constancy and its effect on haptic perception of virtual surfaces, ACM Trans. Appl. Percept., pp.89-105, (2005).
12. S. Choi, and H. Z. Tan, Perceived Instability of Virtual Haptic Texture. I. Experimental Studies, Presence: Teleoper. Virtual Environ., Vol 13 (4) pp.395-415, (2004).
13. S. Choi, and H. Z. Tan, Perceived Instability of Virtual Haptic Texture: III. Effect of Update Rate, Presence: Teleoper. Virtual Environ., Vol 16 (3) pp.263-278, (2007).
14. S. Choi, and H. Z. Tan, An Analysis of Perceptual Instability During Haptic Texture Rendering, Proc. of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp.129-136, (2002).
15. M. Olkkonen, T. Hansen, and K. R. Gegenfurtner, Color appearance of familiar objects: Effects of object shape, texture, and illumination changes, Journal of Vision, Vol 8 (5) pp.1-16, (2008).
16. M. A. Otaduy and M. C. Lin, A perceptually-inspired force model for haptic texture rendering, Proc. of the 1st Symposium on Applied perception in graphics and visualization, pp.123-126, (2004).
17. M. A. Srinivasan, G. L. Beauregard, and D. L. Brock, The impact of visual information on the haptic perception of stiffness in virtual environments, Proc. of the ASME Dynamic Systems and Control Division, pp.555-559, (1996).
18. C. H. Ho, C. Basdogan, and M. A. Srinivasan, Efficient Point-Based Rendering Techniques for Haptic Display of Virtual Objects, Presence: Teleoper. Virtual Environ., Vol 8 (5) pp.477-491, (1999).
19. B. Bickel, M. Bächer, M. A. Otaduy, H. R. Lee, H. Pfister, M. Gross, and W. Matusik, Design and Fabrication of Materials with Desired Deformation Behavior, ACM Trans. on Graphics, Vol 29 (3) pp.1-16, (2010).
20. B. Bickel, M. Bächer, M. A. Otaduy, W. Matusik, H. Pfister, and G. Markus, Capture and modeling of non-linear heterogeneous soft tissue, ACM Trans. on Graphics, Vol 28 (3) pp.1-9, (2009).
21. PHANTOM haptic device, by Sensable Technologies, <http://www.sensable.com>, (2011).
22. W.H. Kruskal and W.A. Wallis, Use of ranks in one-criterion variance analysis, Journal of the American Statistical Association, Vol 47 (260) pp.583-621, (1952).

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