Factors Affecting Discrimination of Surface Property Using an Integrated Tactile Display : Roughness and Vibration

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Abstract: In this paper, we describe a study on the influence of the frequency variation of normal vibration using an integrated tactile display. It is necessary to consider this study because we want to find a method of displaying finer texture and know that the perception of fine textures is heavily influenced by temporal variation. Our tactile display system used in this experiment can simulate the micro shapes and roughness of surface textures by individual drives of a 6x8 pin array. Two experiments are performed. The first is a psychophysical experiment on the definition and range decision of roughness, and through the experiment, we clear up the meaning of roughness. The second is the main experiment about the frequency variation of normal vibration. We find the correlation between the vibration frequency and the texture and the condition for better display and perception of fine surfaces. The experimental results yielded two pieces of information. One is that lateral movement affects texture discrimination, and another is that normal vibration can make the perceived texture feel finer than real texture. That is, the vibrating stimulus is more effective for displaying a fine surface than static pressure, and it makes possible to display finer texture, exceeding the physical limit of the device.

Keywords: pin array, tactile display, vibration, frequency variation, roughness

1. INTRODUCTION

We humans feel kinesthetic force through our arm joints or fingers, and we feel tactile force through stimulation of the surface of our skin. We can sense the stiffness and shape of an object from the kinesthetic force, and we can discriminate the roughness, the micro shape and the texture of an object from tactile force. A number of studies on haptic rendering methods have been undertaken together with the development of the haptic devices; in the haptic rendering method, the reaction force is stimulated by the stiffness or shape of a material. However, researches on the tactile display device are at an early stage. Moreover, the tactile rendering method, which effectively generates tactile feedback, has not been sufficiently researched [1].

In recent researches, for realistic tactile rendering, researchers have studied on human tactile sensing and they have applied the studies to developments of their own tactile display devices. Essick has performed cognitive-physiologic research on the method of rubbing a fingerpad and on the effects of the material properties when the rubbing method is used to sense textures [2]. Shimoho *et al.* have been researching the effect of gaps between pins and shape in tactile sensation; they used a device that can generate the exact shape of an object when the object is inserted under the device [3]. Asamura used mechanoreceptor characteristics to separately generate vibrotactile stimulation and a pressure distribution [4]. Lederman researched the difference between active touch and passive touch [11]. Their devices, above-mentioned, were not enough to display tactile feedback, however, because the studies on tactile display were emerging fields of research and had limitations of device developments.

We have already proposed a pin-arrayed type tactile display device that combines the elements of tactile sensation as discussed in the literature, especially with respect to literature on the mechanism of nerve signal translation of the tactile sensation of skin [5, 12]. Moreover, it was confirmed that vibration is effective for discriminating fine textures, through the experiments on the effects of stimulating methods on tactile discrimination [13]. In this paper, we describe a study concerning the influence of the frequency variation of normal vibration using the tactile display. Subjects compare artificial tactile feeling by tactile display with real tactile feeling of sample in order to investigate a tactile sensitivity with different roughness samples. We make subjects exclude their prior experience and learning of the experimental setup so that they use only their sense of touch to sense the artificial and real tactile feeling of objects.

In Section 2, we introduce the characteristics of the human sense of touch and the principles of designing a tactile display unit. In Section 3, we present an outline of the tactile display unit. In Section 4, we describe the psychophysical experiment by asking about roughness and our own definition of it. In Section 5, we investigate the effects of variation of vibration frequency on human tactile perception.

2. CHARACTERISTICS OF SKIN RECEPTORS

To develop a tactile display device and to choose the manner of stimulation when the tactile display is used, it is necessary to understand human tactile perception through the psychophysics of tactile perception and cognitive physiology. In this section, we describe the characteristics of the skin's tactile receptors and the requirements of a tactile display device.

Vallbo and Johanson have researched mechanoreceptors in connection with tactile perception and the anatomical structure of glabrous skin such as the palm or finger pad. Fig. 1 shows the structure of the skin's tactile perception receptors.

As shown in Fig. 1, four mechanoreceptors exist in the glabrous skin of the palm and fingertip regions [7, 8]. Meissner's corpuscles and Merkel's discs are located in the upper layers, and the Ruffini endings and the Pacinian corpuscles are located deeper. These receptors are divided into the following two classes according to their adaptation rate: the slowly adapting afferent receptors and the rapidly adapting afferent receptors. The slowly adapting afferent receptors comprise Merkel's discs (SA I) and the Ruffini endings (SA II), while the rapidly adapting afferent receptors comprise Meissner's corpuscles (RA I) and the Pacinian corpuscles (RA II).

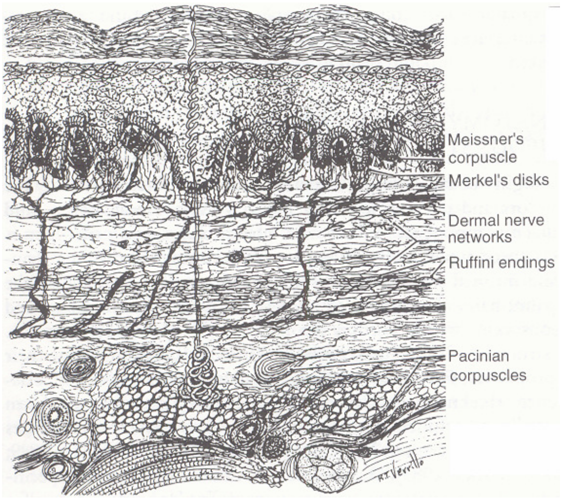


Fig. 1 The structure and location of mechanoreceptors in the glabrous skin [7]

The four mechanoreceptors each have different functions [7-9]. The SA I afferent receptors respond to static shape deformations of the skin, such as pressure in the frequency range of 1 Hz to 10 Hz. These receptors play an important role in detecting spatial structures in static contact, such as an edge or a bar. The SA II afferent receptors provide a neural image related to the direction of the skin being stretched. The frequency response of the receptors ranges from 100 Hz to 500 Hz, and the RA I afferent receptors, which have a frequency range of 2 Hz to 40 Hz, detect dynamic deformations of the skin such as fluttering. The RA I afferent receptors are four times more sensitive than the SA I afferent receptors; in addition, the RA II afferent receptors, which have a frequency response between 40 Hz and 500 Hz, are the most sensitive to vibration and are especially known to serve as detectors of acceleration or vibration.

Hollins *et al.* found that texture perception is mediated primarily by spatial encoding for coarse textures and by vibrotactile encoding for fine textures [10]. This finding means that vibrotactile stimulation is essential for our proposed tactile display system in order to display fine textures.

Bolanoski *et al*. suggested a four channel model of vibrotaction which showed the variation of the displacement threshold to frequency, and Verrillo *et al*. found that sensation magnitude can be changed by stimulating frequency [7]. The displacement threshold of the tactile stimulus on human skin is about 10~25dB ㎛ (3.16~17.8㎛) in low frequency band and about -20~10dB ㎛ (0.1~3.16㎛) in high frequency band. Weinstein showed the tactile acuity and perception threshold at various body sites [7].

We determined the principal requirements of a tactile display device for simulating a realistic sense of touch based on the previous researches. The requirements are as follows:

• Normal stimulus to skin in the frequency range of 0Hz to 500Hz

• At least 10 times the displacement of threshold value of a nerve system

- 60dB ㎛(about 1 mm) in low frequency band
- At least 35dB ㎛ (about 56.2 ㎛) in high frequency band

• Distributed pressure for displaying the static small-scale shape

• Sufficient ability to deform the skin's normal direction up to 1mm

• Small size to enable embedded into a PC mouse

• Mechanical structure to provide force and tactile feedback simultaneously

• Selectively providing an active touch mode and a passive touch mode

We applied the guidelines and achieved several psychophysical and cognitive-physiological experiments to the design of a new tactile display unit [5, 12]. Subsequently, we determined the following: the tactile perception for each method of stimulation, the limitation of using only kinesthetic feedback, and the effects of recognizing the surface of an object when the kinesthetic and tactile feedback were displayed together[13].

3. DESCRIPTION OF TACTILE DISPLAY SYSTEM

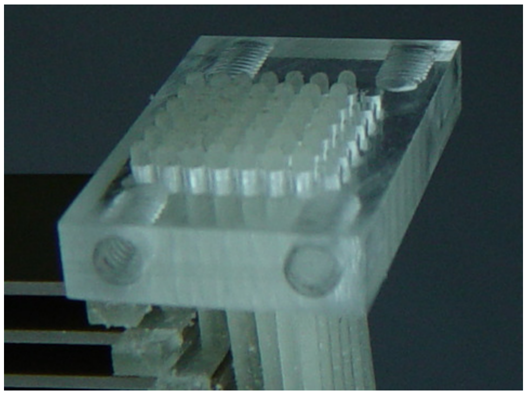


Fig. 2 The implement for normal stimulation

Fig. 2 shows how we implemented the normal stimulation described above. The device is comprised of a pin array and eight piezoelectric bimorphs for normal vibrotactile stimulation. Piezoelectric bimorphs are clamped with 1 mm spacing and the 6 pins are attached to the tip of each bimorph in line. The pin spacing is 1 ~ 1.5 mm and the diameter of each pin is 0.5 or 0.7 mm enabling the display of a texture 8 mm wide. Each piezoelectric bimorph has a displacement larger than 1 mm and a low operating input voltage (60V). In addition, its response time is on the order of milliseconds, and it can provide force up to 0.5N. The tactile stimulator is adequate for normal vibrotaction satisfying the required frequency range and stimulation intensity. We also experimentally confirmed that the actuator does not deflect by the normal rubbing on the surface to sense the texture.

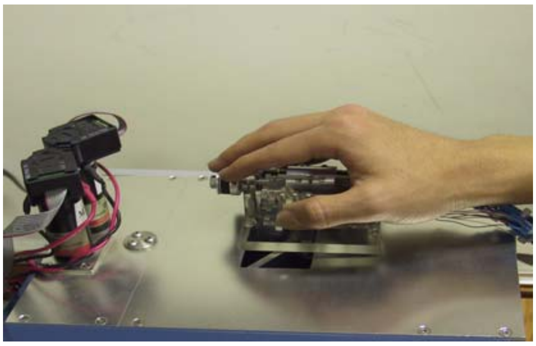


Fig. 3 Implemented System

As shown in Fig. 3, the mouse body was attached to a five-bar linkage to simultaneously feel the kinesthetic and tactile force by grabbing the mouse. The kinesthetic force is transmitted to the wrist, and the tactile display stimulates the thumb. We confirmed that the proposed device can provide translation force of up to 5N in each axis, normal displacement of up to 1mm or more of the stimulus pin, and the pressure distribution along an axis and lateral movement of up to 120mm/sec. The results of our experiment revealed that a bending actuator could travel up to 1mm in a 200Hz frequency range, and it generated enough vibration to stimulate the skin at over 800Hz. Fig 4 shows an example of the pressure distribution of the pin array to display small-scale shapes. We anticipate that the proposed system can serve as a test bed for studies on tactile display algorithm.

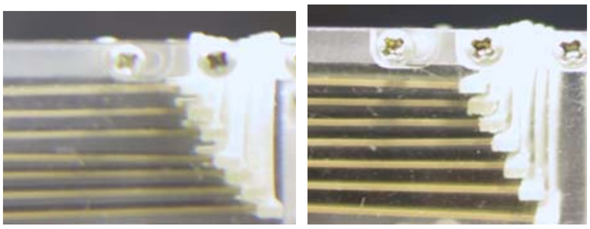


Fig. 4 The small-scale shape display

4. RESEARCH FOR DEFINITION AND RANGE DECISION OF ROUGHNESS

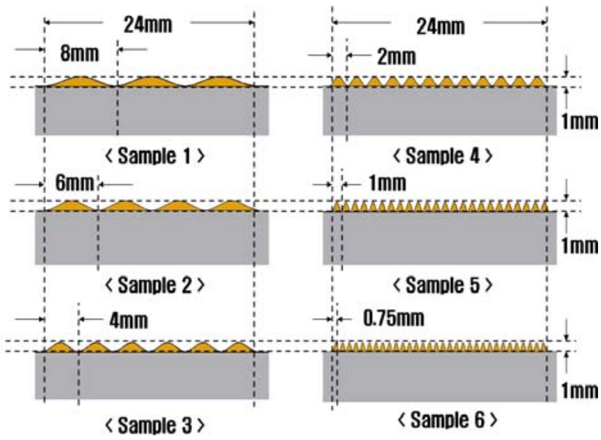
4.1 The Objective of Experiment

Humans feel tactile sensing through the stimulation of the surface of the skin, and can discriminate the roughness, the micro shape and the texture of an object from the tactile force. It is known that the vibrating stimulus can modify the perceived texture of a haptically-examined surface [10]. Our tactile display system can deliver the several stimulations including vibrating stimulus to the skin. So we can use our system to know the effect of vibration on the tactile sensing process. Prior to this experiment, we need to define roughness to obtain the objective results about connection between vibration and roughness The definition and the measurement techniques of roughness can be found in manufacturing, tribology, and so on, but the definition is different from the psychophysical meaning. Because the tactile display system is touched direct by human's fingers, the definition of roughness in psychophysics is needed, but cannot be found. Therefore, we define the roughness and find the boundary between the roughness and the shape, before starting the main experiment.

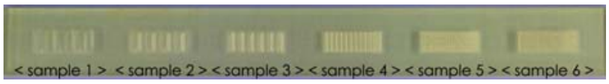
4.2 The Experimental Method

In this experiment, we used specimen, roughness-sample, made for the experiment of vibration stimulus. To define the roughness, subjects were requested to answer, after feeling specimen long enough, which sample felt roughest and whether samples' surfaces had boundaries between bent surfaces and planes with stripes.

Fig. 5 shows the design drawings and prototypes of the experimental specimens. The material used in the specimens was identical to that used in the pins of the tactile display. They were made through rapid prototyping.



(a) Crosssectional view of designed Specimen



(b) Prototype Specimen

Fig. 5 Experimental Samples of Specimen

The surface textures are sine waves with 0.5mm-amplitudes and several wavelengths: 8, 6, 4, 2, 1, and 0.75mm. Each sample has an 8mm-width, equal to the stimulus part of device, and 24mm-length, which subjects can touch with lateral finger movement. From the longest wavelength-sample, samples were assigned numbers: 1, 2, 3, 4, 5, and 6.

4.3 The Experimental Results

Fig. 6 shows the percentage of each answer. In this result, we found that people felt a threshold between sample 3 and 4. The answers to two questions are summarized as followings: samples 1, 2, and 3 are bent surfaces and their spatial frequencies become higher from 1 to 3; and samples 4, 5, and 6 are planes, and their grains become finer from 4 to 6. That is, the grooves of samples 1, 2, and 3 are a kind of shape and the grooves of samples 4, 5, and 6 are included in a range of roughness.

On the basis of the result, we can define roughness as a groove on surface which feels like plane, and as the groove widths are smaller, the surface seems to be finer. In the case of the specimen used in this experiment, the surface which groove widths are 2mm or less was considered as plane. This result can be related to the fact that two-point spatial discrimination for the fingertip is 2.5mm [7]. Sample 1, 2 and 3 are not in a range of roughness, hence, we can express that each sample has a different micro-shape.

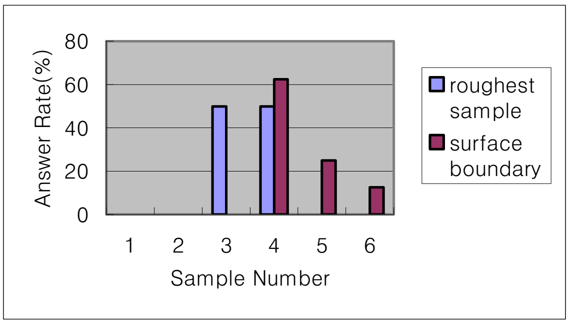


Fig. 6 Answer rates about roughness

5. EFFECT OF VARIATION OF VIBRATION FREQUENCY ON DESCRIMINATING TEXTURE

5.1 The Objective of Experiment

There are several stimulating methods in discriminating texture using our tactile display, and specifically, we have made an intensive study on the vibrating stimulus. It is well-known that vibration is the mainstay of discriminating fine texture [10]. Our questions are as follows:

- Does vibration make spatial acuity feel different? That is, as the frequency of the vibration increases, does spatial discriminability become worse and do the groove widths feel smaller?
- How different are discriminations of texture by three stimulating methods: static stimulation, vibration, and vibration and active touch?
- We focused on "Can finer textures be displayed exceeding the physical limit of the device by the inclusion of vibration?" rather than "Can textures be displayed similarly?"

5.2 The Experimental Method

The tactile display system used in this experiment can give various vibration stimuli to the skin as mentioned in Section 3. In this section, the characteristics of human tactile perception through variations in vibration frequency will be described in a psychophysical experiment.

Six real specimen prototypes, the same as those used in the previous experiment, were given to participants and a simulated stimulus of one of them was presented through the tactile display. Each stimulus except sample 6 was randomly presented six times to the user, and participants were instructed to check the most similar or the same tactile feeling in the real specimen. The participants were not allowed to change their answers because they may not discriminate samples with relative difference; actually, during the experiment, they often wanted to change their answers in the case of continuous presentations of close samples. The stimulating method was only the vibration of a pin array.

Sample 6 could not be simulated because the gap between pins is 1mm and wavelength of sample 6 is 0.75mm; however the sample 6 was included in real specimen prototypes, and we intended to verify that finer textures can be displayed by vibration. Subjects were informed that all samples, from 1 to 6, were display in random distribution. During vibration stimulus only, subjects were not allowed to move their fingers on the stimulating part. Identical experiments were repeated with frequencies which changed from 0, 4, 8, 15, and 30, 60Hz. Subsequently, while users were allowed to move their fingers, whole process was performed again. Five men and three women participated in the experiment.

5.3 The Experimental Results and Analyses

From the experimental results, we made confusion matrices, Table 1, and found out the following:

Table 1 Confusion Matrices of Correction Rate

sample \ answer	1	2	3	4	5	6
1	36.1	41.7	13.9	0	8.3	0
2	27.8	52.8	19.4	0	0	0
3	13.9	8.3	44.4	30.6	2.8	0
4	13.9	2.8	2.8	72.2	5.6	2.8
5	11.1	11.1	11.1	19.4	47.2	0

(a) Vibration, 0Hz

sample \ answer	1	2	3	4	5	6
1	22.2	61.1	16.7	0	0	0
2	13.9	61.1	16.7	8.3	0	0
3	0	8.3	58.3	27.8	5.6	0
4	16.7	5.6	5.6	52.8	11.1	8.3
5	36.1	5.6	13.9	5.6	25	13.9

(b) Vibration, 4Hz

sample \ answer	1	2	3	4	5	6
1	38.9	33.3	25	2.8	0	0
2	8.3	55.6	27.8	2.8	5.6	0
3	2.8	11.1	41.7	27.8	11.1	5.6
4	8.3	5.6	8.3	52.8	25	0
5	13.9	13.9	2.8	13.9	36.1	19.4

(c) Vibration, 8Hz

sample \ answer	1	2	3	4	5	6
1	47.2	30.6	2.8	13.9	5.6	0
2	16.7	50	8.3	13.9	11.1	0
3	0	11.1	50	25	11.1	2.8
4	5.6	11.1	11.1	50	13.9	8.3
5	5.6	0	13.9	13.9	36.1	30.6

(d) Vibration, 15Hz

answer / sample	1	2	3	4	5	6
1	38.9	22.2	8.3	22.2	5.6	2.8
2	11.1	30.6	2.8	27.8	25	2.8
3	0	16.7	22.2	33.3	8.3	19.4
4	0	0	5.6	61.1	33.3	0
5	8.3	2.8	8.3	11.1	52.8	16.7

(e) Vibration, 30Hz

answer / sample	1	2	3	4	5	6
1	13.9	38.9	2.8	19.4	25	0
2	11.1	16.7	8.3	13.9	44.4	5.6
3	0	0	19.4	41.7	27.8	11.1
4	2.8	2.8	2.8	36.1	44.4	11.1
5	0	8.3	5.6	5.6	41.7	38.9

(f) Vibration, 60Hz

answer / sample	1	2	3	4	5	6
1	86.1	13.9	0	0	0	0
2	13.9	75	11.1	0	0	0
3	8.3	19.4	52.8	19.4	0	0
4	0	0	2.8	83.3	13.9	0
5	5.6	0	0	2.8	72.2	19.4

(g) Vibration + Active touch, 0Hz

answer / sample	1	2	3	4	5	6
1	50	30.6	5.6	2.8	11.1	0
2	27.8	38.9	16.7	13.9	2.8	0
3	2.8	2.8	50	44.4	0	0
4	0	8.3	11.1	63.9	16.7	0
5	5.6	19.4	5.6	2.8	52.8	13.9

(h) Vibration + Active touch, 4Hz

answer / sample	1	2	3	4	5	6
1	50	36.1	2.8	5.6	5.6	0
2	16.7	47.2	13.9	13.9	5.6	2.8
3	2.8	11.1	52.8	25	8.3	0
4	0	5.6	13.9	58.3	19.4	2.8
5	2.8	11.1	0	11.1	55.6	19.4

(i) Vibration + Active touch, 8Hz

answer / sample	1	2	3	4	5	6
1	55.6	19.4	13.9	2.8	8.3	0
2	13.9	50	13.9	11.1	8.3	2.8
3	0	8.3	50	33.3	8.3	0
4	0	5.6	2.8	61.1	27.8	2.8
5	0	0	8.3	13.9	58.3	19.4

(j) Vibration + Active touch, 15Hz

answer / sample	1	2	3	4	5	6
1	30.6	27.8	5.6	19.4	5.6	11.1
2	8.3	38.9	13.9	22.2	11.1	5.6
3	0	11.1	22.2	47.2	13.9	5.6
4	0	2.8	13.9	63.9	19.4	0
5	2.8	2.8	11.1	2.8	58.3	22.2

(k) Vibration + Active touch, 30Hz

answer / sample	1	2	3	4	5	6
1	19.4	33.3	2.8	13.9	25	5.5
2	13.9	33.3	8.3	11.1	27.8	5.5
3	2.8	5.6	13.9	66.7	8.3	2.8
4	0	0	0	36.1	47.2	16.7
5	0	0	0	13.9	44.4	41.7

(l) Vibration + Active touch, 60Hz

5.3.1 The Effects of Active Touch

The effects of active touch are found well at a frequency of 0Hz: Table 1(a) and (g). Table 1(a) is static pressure stimulus, and Table 1(g) is static pressure stimulus and active touch.

• In the case of static pressure stimulus, subjects did not discriminate micro-shapes well; they confused not only similar samples like 'samples 1 and 2' or 'samples 4 and 5' but also 'samples 1 and 5'. Sample 1 is displayed only one wavelength and its groove is though only as a shape; and sample 5's wavelength is same as the pins' interval, and it was simulated by moving all pins with same amplitudes and phase. In these two cases, subjects judged that the two samples had different shape but same roughness, and when they compared the two samples only with static pressure, they could not perceive the difference of shape.

• In the case of active touch, matrix (g), subjects can sense the concave of sample 1 by lateral movement of fingers, so they perceived shape-differences and discriminated sample 1 and 5 easily; and they also could perceive the difference between grooves of similar samples well. This result is identical with Hollins' theory that vibration affects the discrimination of fine textures, and vibration includes lateral movement. In conclusion, lateral movement affects discriminating texture [10].

• The cases of nonzero frequency are similar to 0Hz. In the confusion matrices of active touch, answers have a tendency to gather around the diagonal line. In low frequency, 8Hz or under, active touch makes the discrimination of samples 1 and 5 far better. But in high frequency, the use of active touch seems to have no relevance to the correct answer rate.

5.3.2 The Effect of Frequency Variation of Vibration

• when subjects were stimulated with vibration, they tended to give answers to the finer sample side, regardless of use of active. They judged the samples to be finer than they are. As the frequency increases, subjects' answers have a tendency to be shifted to the right side more. That is, as the frequency increases, texture is perceived to be finer. In the case of high frequency, in spite of displaying sample 1, 2, and 3, answering 4 or 5 is more common than in the case of low frequency.

• The case of displaying sample 5 is noteworthy because the rate of answering 6 is similar to the rate of answering 5. This result shows the possibility that finer textures can be displayed exceeding the physical limit of the device by controlling vibration frequency, and it will be an important point in deciding tactile modeling methods.

- These experimental results are expressed from two points of view. One point is that lateral movement affects on discriminating texture, and another point is that normal vibration makes it possible to display finer texture.

5.3.3 The Effect of Stimulus Energy

In this experiment, subjects generally compared groove width in the process to choose the closest one. If the tactile display had a similar gap as a real specimen though it did not have the same feeling, then subjects judged it as a similar one. The reason of difference in feeling can be explained the standpoint of energy. As the frequency increases, stimulus energy also increases, and the shapes with same parameters feel different because of difference of stimulus energy. The reason why the case of 0Hz and active touch has the highest correct answer rate is that the process of perceiving texture in that case is most similar to the real act, and also the process has no forced stimulus energy.

6. CONCLUSION

In this paper, we defined roughness as a groove on surface which feels like plane, as a result of research for a definition of roughness, and the smaller groove widths are, the finer the surface seems to be.

This paper also describes a study on the characteristics of human tactile perception through variations of vibration frequency using an integrated tactile display system. As results of the experiments, we made two discoveries. One is that lateral movement affects the discrimination of texture, and another is that normal vibration makes possible to display finer texture. That is, as the frequency increases, spatial discriminability become less accurate and the groove width is felt smaller. Using this result, finer textures be displayed exceeding the physical limit of the device by control of vibration frequency.

In this experiment, we use a frequency of 60Hz or less, because the range has the same gain in frequency response of the actuator. Experiments in a larger range of frequency will yield more extended results.

Also, it is known that human tactile perception has a close relation to intensity of energy, and we found some connection through the experiments. As the frequency of vibration increases, energy of stimulus increases, so it will affect on perception of surface texture. Accordingly we plan to research about whether vibration makes pin's normal displacement feel different.

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REFERENCES

[1] G.C. Burdea. "Haptic Issues in Virtual Environment", Proceeding of Computer Graphics International, pp. 295 – 302, 2000

[2] G.K. Essick, "Factors Affecting Direction Discrimination of Moving Tactile Stimuli", Neural Aspect of Tactile Sensation (Editor : J.W. Morley), pp.1~54, Elsevier Science B.V., 1998

[3] Makoto Shimojo, Masami Shinohara, Yukio Fukui. "Human Shape Recognition Peformance for 3-D Tactile Display", IEEE Transaction on Systems, Man, and Cybernetics – PART A: Systems and Humans, Vol. 29, No. 6, pp.637~644, 1999

[4] N. Asamura, N. Yokomu, H. Shinoda. "Selectively Stimulating Skin Receptors for Tactile Display", IEEE Computer Graphics and Applications, pp.32-37, 1998

[5] K.U. Kyung, S.W. Son., D.S. Kwon, M.S. Kim. "Design of an Integrated Tactile Display System", IEEE International Conference on Robotics and Automation, pp. 776-781, 2004

[6] R.S. Johansson, A.B. Vallbo, "Tactile Sensibility in the Human Hand: Relative and Absolute densities of Four Types of Mechanoreceptive Units in Glabrous Skin", Journal of Physiology, Vol. 286, pp.283-300, 1979

[7] L. Kruger, Pain and Touch, San Diego, Academic Press, 1996

[8] J. W. Morley, Neural Aspects in Tactile Sensation, Amsterdam, Elsevier Science B.V., 1998

[9] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors", Current Opinion in Neurobiology, vol. 11, pp. 455-461, 2001

[10] M. Hollins, S. J. Bensmaia, and E. A. Roy, "Vibrotaction and texture perception", Behavioral Brain Research, Vol. 135, pp. 51-56, 2002

[11] S. J. Lederman, "The Perception of Surface Roughness by Active and Passive Touch", Bulletin of the Psychonomic Society, Vol. 18, pp.253~255, 1981

[12] S.W. Son, K.U. Kyung, G.H. Yang, D.S. Kwon, M.S. Kim, "A Conceptual Design of an Integrated Tactile Display Device", International Conference on Control, Automation, and System, 2003

[13] S.W. Son, "Development of a Novel Tactile Display System", Master Thesis, KAIST, 2004