主　論　文

The Journal of the
Acoustical Society of America

Vol. 105, No.4, April 1999

ヒトの触覚における微細テクスチャー弁別のメカニズム

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Published by the Acoustical Society of America
through the American Institute of Physics

Mechanisms of fine-surface-texture discrimination in human tactile sensation

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(Received 10 March 1998; revised 20 August 1998; accepted 11 December 1998)

The purpose of this study was to evaluate the ability of touch to discriminate fine-surface textures and to suggest possible mechanisms of the discriminations. Two experiments were performed. In experiment 1, aluminum-oxide abrasive papers were adopted as stimuli, and psychometric functions and difference thresholds were determined in fine-surface-texture discrimination tasks. The grit values of abrasive papers were 400, 600, 1200, 2000, 3000, 4000, and 8000; corresponding average particle sizes were 40, 30, 12, 9, 5, 3, and 1 μm, respectively. Ten subjects participated in experiment 1. The difference thresholds obtained in experiment 1 were between 2.4 and 3.3 μm. In experiment 2, the tasks were discriminations of ridge height. The cross sections of the etched ridges were rectangular and the ridge heights were 6.3, 7.0, 8.6, 10.8, 12.3, 18.5, and 25.0 μm. Six subjects participated in experiment 2. The difference thresholds in experiment 2 were between 0.95 and 2.0 μm. It was reasoned, based on the Weber fraction values calculated from the difference thresholds and on the limit of neural information-processing ability of humans, that the subjects discriminate fine roughness only from the amplitude information presented in surface unevenness. © *1999 Acoustical Society of America.* [S0001-4966(99)05903-2]

PACS numbers: 43.66.Wv [RVS]

INTRODUCTION

There are many studies which have investigated the perception of surface textures through the sense of touch. Most of them treated the perception of rather rough surfaces: sizes of surface elements were larger than several hundred micrometers. Only a small number of studies have focused on the tactile perception of fine-surface textures: sizes of elements were smaller than 50 μm. However, humans are very good at discriminations of fine-surface textures. Sometimes they discriminate fine-surface textures better by touch than by vision. For example, they can discriminate roughness of abrasive papers with 5-μm particles from 9-μm particles by touch, but cannot discriminate them by vision. This study was designed to investigate possible mechanisms of fine-surface-texture discrimination.

Some previous studies used abrasive papers as stimuli for research of rough-texture perception, but many recent studies have adopted gratings (Goodwin and John, 1991; Johnson and Phillips, 1981; Lederman, 1974; Lederman *et al.*, 1982; Morley *et al.*, 1983; Sathian *et al.*, 1989; Sathian and Zangaladze, 1996; Taylor and Lederman, 1975; Van Boven and Johnson, 1994) or raised dots (Blake *et al.*, 1997; Connor *et al.*, 1990; Connor and Johnson, 1992; Johnson and Hsiao, 1994; Johnson and Lamb, 1981; Lamb, 1983; Lederman *et al.*, 1986) as stimuli. In grating experiments, the researchers found that roughness magnitude increased as grooves became wider (Goodwin and John, 1991; Lederman, 1974; Sathian *et al.*, 1989; Taylor and Lederman, 1975). Goodwin and John (1991) investigated the skin mechanoreceptors which took part in the roughness perception of gratings, and showed that the responses of all three mechanoreceptors (RA, PC, and SA) contributed to the perception of roughness. In raised-dot experiments, Connor *et al.* (1990) found that subjective roughness magnitude was an inverted U-shaped function of dot spacing that peaked near 3-mm spacing. Connor *et al.* (1990) and Blake *et al.* (1997) showed that perceived roughness decreased as dot diameter increased. Johnson *et al.* (Blake *et al.*, 1997; Connor *et al.*, 1990; Connor and Johnson, 1992; Johnson and Hsiao, 1992; Johnson and Hsiao, 1994) had investigated relations between firing of mechanoreceptors of monkeys and perceived roughness of human subjects using embossed-dot patterns as stimuli. They showed that spatial variation in SA (SAI) firing rates had very high correlations with the perceived roughness. Phillips *et al.* (1990) investigated the human mechanoreceptors which were responsible for Braille recognition, and found that SAI discharges showed the most precise resemblance to the Braille pattern.

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In the small number of studies related to the fine-surface-texture perception of touch, Heller (1989) compared vision and touch in the accuracy of extreme fine-surface-texture discrimination tasks using Japanese abrasive sharpening stones as stimuli. He found that touch was superior to vision for discrimination tasks. Miyaoka and Mano (1991) measured the absolute-detection threshold of fine-surface texture with very fine abrasive papers, and found that the detection threshold was between 1 and 3 μm in particle sizes. Several researchers studied tactile-detection thresholds of edges and dots, not fine textures, with minimal heights. Johansson and LaMotte (1983) measured height-detection thresholds using edges and raised dots as stimuli, and found that the thresholds were 0.85 μm for edges and from 1.09 to 5.97 μm for dots. The detection thresholds of raised dots decreased as the dot diameters increased: the threshold was 5.97, 2.94, and 1.09 μm for dots with diameters of 40, 231, and 602 μm, respectively. LaMotte and Whitehouse (1986) showed that the detection threshold of a raised dot of 550-μm diameter was 2.1 μm, and that the responses of RA alone accounted for the sensory capacity to detect the dot. LaMotte and Srinivasan (1991) measured the detection thresholds of parallel bars and of a matrix of dots. They found the heights of bars and dots at the thresholds were lower than the threshold height of a single dot.

Perception of fine-surface textures by touch is one of the most important functions of tactile information processing. However, there has been only a small number of studies about the perception of fine-surface textures. Also, perceptual mechanisms of fine textures have not been systematically studied. This study was designed to investigate possible mechanisms of fine surface-texture discrimination. There were two purposes for this study. One was to measure the discrimination ability of fine-surface textures. The difference thresholds of fine surface textures were measured in experiment 1. The other was to propose a hypothesis of tactile mechanisms which make the discriminations of fine-surface textures possible. We proposed the hypothesis that subjects discriminate fine-surface textures using amplitude information of the surface unevenness of stimuli. Experiment 2 was performed to measure difference thresholds of ridge-height discrimination, and to check whether subjects had the ability for amplitude discriminations. The results of experiment 2 strengthened the possibility of the hypothesis.

I. EXPERIMENT 1

Experiment 1 adopted fine abrasive papers as stimuli and measured the subjects' discrimination ability of fine-surface textures with the two-alternative, forced-choice technique. There were two reasons for the adoption of abrasive papers or natural stimuli. One reason was that, in the first stage of the study, adopting natural stimuli was a convenient choice to find the characteristics making fine surface-texture discrimination possible. The natural stimuli have many characteristics which might be related to fine-surface discrimination. This study should reveal which characteristic is the most essential for discrimination. The other reason was that producing many different types of stimuli was difficult because of the limits in production techniques. At the beginning of the study, we had no information as to what characteristics might be responsible for the fine-surface discrimination, and could not produce suitable artificial stimuli for the investigation.

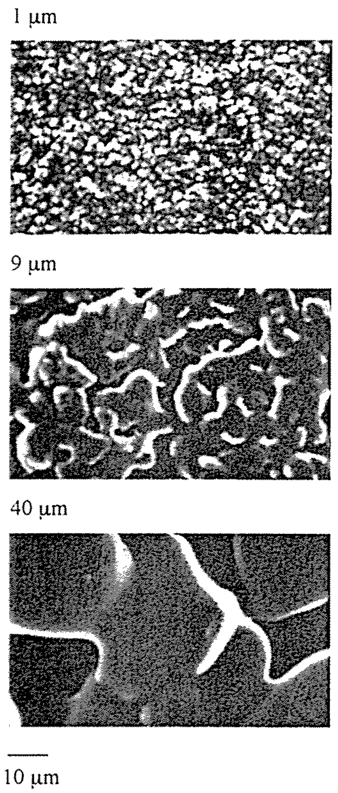

FIG. 1. Pictures of the abrasive-paper surfaces taken with a scanning electron microscope (JEOL, JSM5400). The particle sizes of the abrasive papers are 1, 9, and 40 μm from top to bottom, respectively. The horizontal bar shows a 10-μm length.

A. Method

1. Subjects

Ten subjects, nine men and one woman, aged from 19 to 41 years, took part in experiment 1. Eight of the male subjects were undergraduate students with no previous experience in psychophysical experiments. The other two subjects had previously participated in several other psychophysical experiments.

2. Stimuli

The stimuli were seven aluminum-oxide abrasive papers (Sumitomo 3-M). The grit values assigned by the manufacturer were 400, 600, 1200, 2000, 3000, 4000, and 8000, representing corresponding average particle sizes of 40, 30, 12, 9, 5, 3, and 1 μm, respectively. Observation with a scanning electron microscope (JEOL, JSM5400) confirmed that the sizes of the large particles in each paper corresponded to the particle-size values reported by the manufacturer (Fig. 1). A contact-profile meter (Kosaka, SE-30D) showed that the peak-to-peak amplitudes of the surface unevenness of abrasive papers did not always coincide with the particle-size values of the papers. However, the amplitudes displayed a monotonic relation to the particle size values (Fig. 2).

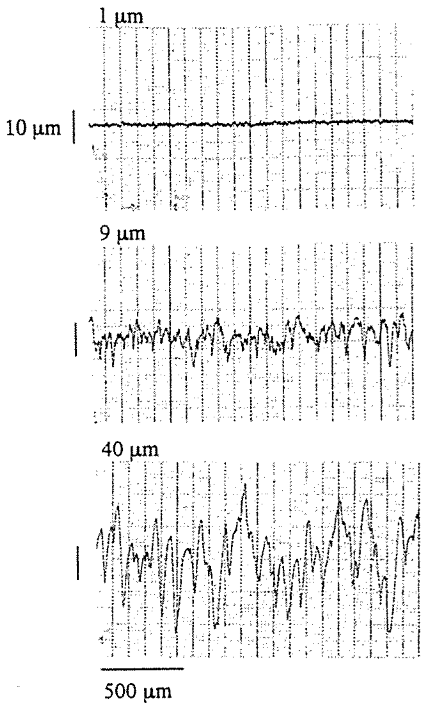

FIG. 2. Cross-section profiles of abrasive papers observed with a contact profile meter (Kosaka, SE-30D). The particle sizes of the papers are 1, 9, and 40 μm from top to bottom, respectively. The three vertical bars show a 10-μm length and the horizontal bar shows a 500-μm length.

The abrasive papers were cut into 5×5-cm squares, and two squares each were glued on boards sized 12×18 cm. Fifty-six stimulus boards were used in experiment 1. Pairwise combinations of seven distinct stimuli plus self-combinations equaled 28 boards. As it was necessary to counterbalance the right and left positions of the squares on each board, the total number of boards was 56.

3. Procedure

The subject was seated in a chair and wore a mask to prevent visual inspection of the test materials. He/she touched the stimuli with the index finger or the middle finger preferred, and determined which abrasive paper on the board felt rougher with the two-alternative, forced-choice technique. Maximum allowed time for the determination was 15 s for each stimulus board. The interstimulus interval was 20 s. Each subject executed ten discrimination trials for each board. The total number of the experimental trials was 560 for each subject. During the experiment, the temperature of the laboratory was maintained between 25 and 27 deg centigrade, and the temperature of the stimulated skin of subjects was greater than 30 deg. Several researchers revealed no or only slight improvements to vibrotactile thresholds when the skin temperature was higher than 30 deg (Bolanowski and Verrillo, 1982; Gescheider *et al.*, 1997; Verrillo and Bolanowski, 1986).

B. Results

Because the experimental results of ten subjects were similar to each other, data was accumulated for each combination, psychometric functions were then calculated. The psychometric functions based on the total data are shown in Fig. 3. Each psychometric function illustrates the probability that the subject judged a comparison stimulus to be rougher than a standard stimulus. For example, in the uppermost function, the subjects judged the 3-μm comparison stimulus to be rougher than the 1-μm standard stimulus with a probability of greater than 95%.

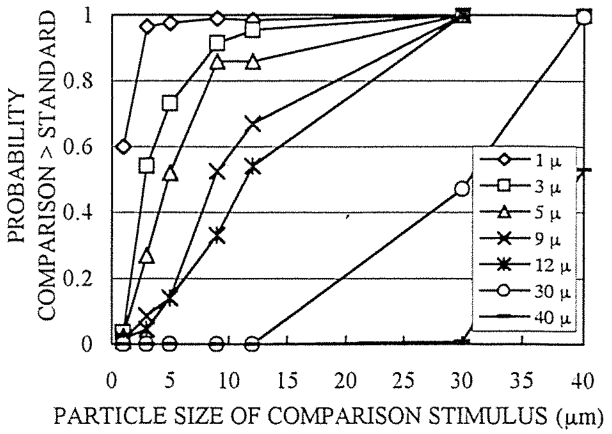

FIG. 3. Psychometric functions based on the data of the fine-surface-texture discrimination experiment. The vertical axis shows the probability that the comparison stimuli were judged rougher than the standard stimuli. The horizontal axis shows the particle sizes of the comparison stimuli. Each symbol in the figure represents the results of each standard stimulus, respectively. The unit of the values in the legend is micrometers.

Difference thresholds were determined for four psychometric functions with 3-, 5-, 9-, and 12-μm standard stimuli. It was impossible to determine difference thresholds when the particle sizes of standard stimuli were 1, 30, and 40 μm because these stimuli were almost completely discriminated from other stimuli. The data of the four psychometric functions were normalized and normal-distribution curves were fitted to them with the method of least squares. The difference thresholds were calculated from the fitted curves. They were 2.4, 2.5, 2.7, and 3.3 μm for the particle sizes of 3, 5, 9, and 12 μm, respectively. Weber fractions were calculated as the ratios of the difference thresholds and the particle sizes of corresponding standard stimuli. The values of Weber fractions were 0.81, 0.50, 0.30, and 0.28 for the particle sizes of 3, 5, 9, and 12 μm, respectively (Fig. 4). The fraction values

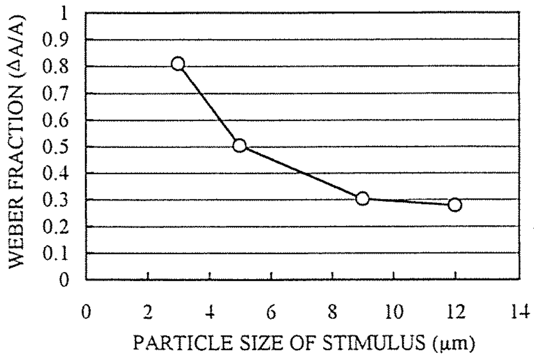

FIG. 4. Weber fractions calculated from the fine-surface-texture discrimination data. The vertical axis shows the Weber fractions and the horizontal axis shows the particle sizes of the stimuli.

changed as a function of particle size, decreasing as the particle size became larger.

C. Discussion

The results of experiment 1 show that human subjects can discriminate fine-surface textures very well with the sense of touch. What tactile information-processing mechanisms make possible the discrimination of fine-surface texture? We propose the hypothesis that subjects discriminate fine-surface textures by the amplitude of the surface unevenness of stimuli. Before the explanation of the "amplitude information hypothesis," we will examine three alternative hypotheses and show that they do not hold.

The first hypothesis is that the subjects use temporal information of surface unevenness for fine-surface discrimination. When they discriminate fine-surface textures, they move their fingers tangentially across the surface to get texture information. Viewing from one point on the stimulated skin, the stimulus unevenness is presented as a kind of vibration, and the information of the vibrotactile stimulus is encoded into neural discharges. Assume that the size of large particles in the stimulus, reported by the manufacturer, represents the vibration wavelength and that the wave form is sinusoidal. For example, the 3-μm stimulus is approximated as a sinusoidal wave with a 3-μm wave length. During experiment 1, it was observed that the subjects moved their fingers at velocities from about 20 to 100 mm/s and gave judgments. If they move their fingers at a velocity of 30 mm/s on the 3- and 30-μm stimuli, they will feel vibrations on the skin equivalent to 10 kHz and 1000 Hz, respectively. On the other hand, mechanoreceptors in the glabrous skin cannot discharge higher than 1000 Hz. If the subjects attempt the discrimination tasks depending on the temporal information of discharge, it is impossible for them to discriminate the 3-μm stimulus from the 30-μm stimulus.

The second hypothesis is that the subjects use spatial information of surface unevenness for the fine-surface-texture discrimination. The density of mechanoreceptive units in the finger tips is lower than 250/cm^2 (Johansson and Vallbo, 1979), and the centers of each receptive field are separated by at least 600 μm. It is obvious that the densities are too low to discriminate the 3-μm from the 30-μm stimulus. Even if each mechanoreceptive unit has several mechanoreceptors (Johansson, 1978; Zelená, 1994), the situation remains the same.

The third hypothesis is that the subjects discriminate surface textures using the friction information between skin and stimuli. A preliminary experiment revealed that no difference existed in the difference-threshold values of fine-surface-discrimination tasks between a low-friction and a high-friction condition. The low-friction condition used stimuli applied with silicone oil (Shin-Etsu Silicone, KF-96-10CS), and the high-friction condition used stimuli without the oil. Although the friction values of the two conditions were different from each other, no difference was found in the results.

Since none of the three alternative hypotheses adequately explains our results, we now consider the hypothesis that the subjects use the amplitude information of surface unevenness for the fine-surface-texture discrimination tasks. We will show that it is possible to discriminate fine-surface textures if the subjects use the amplitude information of the stimulus unevenness. We do this by comparing the results of experiment 1 with the results of a vibrotactile experiment. The Weber fraction was 0.81 for the 3-μm stimulus, and 0.28 for the 12-μm stimulus in experiment 1. The Weber fraction function decreased monotonically as the size of particles increased (Fig. 4). In many sensory modalities, it is observed that the Weber fraction tends to greatly increase at extremely low intensities of stimulus (Gescheider, 1985). As mentioned in the introduction, Miyaoka and Mano (1991) found that the absolute threshold of fine-surface-texture recognition was between 1 and 3 μm. The results of experiment 1 and of Miyaoka and Mano (1991) show that the intensity of the 3-μm stimulus was less than 10 dB SL. Gescheider *et al.* (1990) measured difference thresholds for vibrotactile amplitudes with three methods between 5 and 40 dB. They found that the Weber fractions were from 0.25 to 0.5 at 5 dB and were from 0.15 to 0.3 at 20 dB, depending on the experimental methods. The values of the Weber fractions were independent of stimulus frequency (25 and 200 Hz). Comparison of the Weber fractions of experiment 1 with those of Gescheider *et al.* (1990) showed that the Weber fractions of experiment 1 were larger than the fractions of Gescheider *et al.* at about the same intensity level. These results suggest that it is possible to accept the hypothesis that the subjects performed the fine-surface-texture discrimination tasks in experiment 1 using amplitude differences of surface unevenness of stimulus.

The tactile information-processing system has low-pass filter characteristics and does not pass frequencies higher than 1000 Hz. The tactile system uses the amplitude information passed through the filter to perform the discrimination tasks. Measurements with the contact profile meter (Kosaka, SE-30D) showed that the amplitude information of surface unevenness remained after the wave passed through the low-pass filter. The monotonic relation was maintained between the peak-to-peak amplitudes of surface unevenness and the particle sizes after passing the waves through the filter, which dropped the waves shorter than a 250-μm wavelength (Fig. 5). If the subjects move their fingers on the stimuli at the speed of 30 mm/s, a wave with a 250-μm wavelength has a frequency of 120 Hz. The subjects obtain amplitude information of surface unevenness from waves passed through the filter, and discriminate the fine textures. The results presented here strongly suggest that peak-to-peak amplitude information of surface unevenness, passed through the filter, is the primary source of fine-surface discrimination with touch.

II. EXPERIMENT 2

In experiment 1, the difference thresholds for fine-surface-texture discrimination using abrasive papers as stimuli were measured. The hypothesis was proffered that subjects performed the fine-surface-texture discrimination tasks using the amplitude information of the stimulus surface unevenness. If the subjects really used the amplitude information in the discrimination of fine roughness, they would

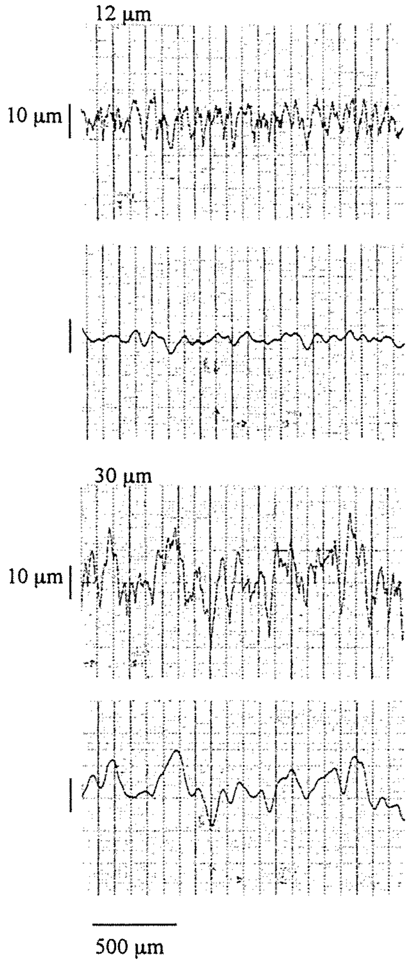

FIG. 5. Cross-section profiles of abrasive papers observed with the contact profile meter with and without a filter. The top two profiles are the cross sections of 12-μm particle abrasive paper. These two profiles show the same part of the same abrasive paper. The upper of the two shows the profile without a filter. The lower shows the profile passed through a filter. The filter passed waves with wavelengths which were greater than 250 μm. The bottom two profiles are the cross sections of 30-μm abrasive paper. The upper shows the profile without a filter. The lower shows the profile passed through the same filter used in the 12-μm abrasive paper.

show at least the same discrimination ability for ridge-height discrimination tasks. In experiment 2, ridge-height discrimination was measured using etched ridges. The purpose of experiment 2 was to measure difference thresholds of ridge heights and to show that the experiment of ridge-height discrimination would have the same or smaller difference thresholds than the abrasive-paper experiment. If the smaller thresholds were found in experiment 2, it would strengthen the possibility of the hypothesis that the subjects use amplitude information for the discrimination of fine-surface texture.

A. Method

1. Subjects

Four males and two females ranging between 20 and 40 years of age participated in the experiment. All subjects except one male were undergraduate students. All of the subjects had experience in psychophysical experiments.

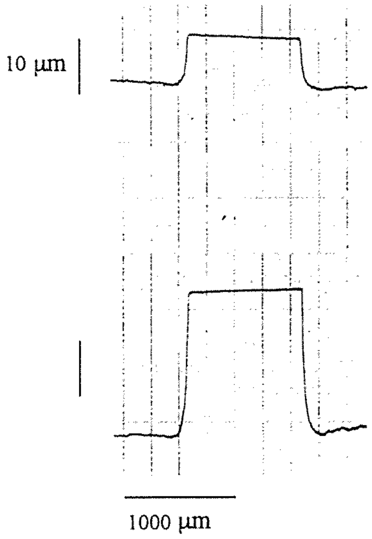

FIG. 6. Cross-section profiles of the ridge stimuli observed with the contact profile meter. The vertical bars show a 10-μm length. The horizontal bar shows 1000 μm. The height of the top ridge is a 8.6 μm and the height of the bottom one is 25 μm.

2. Stimuli and apparatus

The stimuli, ridges 20 mm in length and 1 mm in width, were produced by etching 20×20 mm square stainless-steel plates (SUS 304). The amplitude of surface unevenness on the plate was 0.1 μm before the etching, and was about 0.5 μm after etching, except for the ridge portion, which remained in its original condition. Seven ridges were produced, having heights of 6.3, 7.0, 8.6, 10.8, 12.3, 18.5, and 25.0 μm. Observation with the contact profile meter (Kosaka, SE-30D) showed that the cross sections of the ridges were rectangular (Fig. 6).

During the experiment, the temperature of the glabrous skin of the hand and of the ridge stimuli was controlled. The control device consisted of two parts; one part controlled the temperature of the hand, the other controlled the temperature of the stimuli. The temperature control device was connected to a water circulator (Yamato, CTE82W), which could control the temperature of the device at any temperature between 5 and 45 deg centigrade.

3. Procedure

The subject was seated in a chair and wore an eye mask to prevent visual inspection of the stimuli. He/she touched the stimuli with the index finger or the middle finger of choice and determined which ridge felt higher by means of the two-alternative, forced-choice technique. The maximum time allowed for determination was 20 s for each combination. The interstimulus interval was 20 s. The number of stimulus combinations was 56, determined by the same procedure as in experiment 1. Each subject performed ten trials for each combination of the ridge stimuli; therefore, the number of total experimental trials for each subject was 560. The temperature of the stimuli and the stimulated area of the skin was maintained at 30±1 deg centigrade during the experiment.

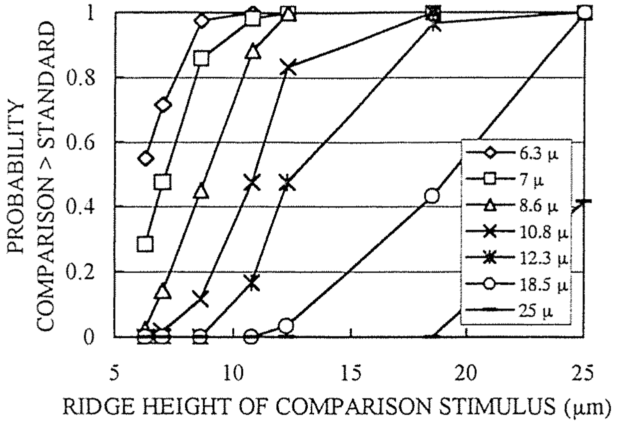

FIG. 7. Psychometric functions based on the data of the ridge-height discrimination experiment. The vertical axis shows the probability that comparison stimuli were judged higher than standard stimuli. The horizontal axis shows the ridge heights of the comparison stimuli. Each symbol in the figure shows the results of each standard stimulus, respectively. The unit of the values in the legend is micrometers.

B. Results

Data were accumulated for all subjects for each combination, psychometric functions were then calculated. The psychometric functions of ridge-height discrimination are shown in Fig. 7. Each psychometric function shows the probability of the comparison stimulus being judged higher than the standard stimulus. For example, when the height of the standard stimulus was 7.0 μm (open squares), the 8.6-μm comparison stimulus was judged higher than the standard stimulus with a probability of 0.86.

The difference thresholds of the ridge-height discrimination tasks were calculated from the curves fitted to the data of the psychometric function by the method of least squares. The four difference thresholds were 0.95, 1.1, 1.2, and 2.0 μm for the standard stimuli of 7.0, 8.6, 10.8, and 12.3 μm, respectively. The difference thresholds were not determined for the 6.3-, 18.5-, and 25.0-μm standard stimuli because they were almost perfectly discriminated from all other stimuli. Weber fractions were calculated as the ratios of corresponding difference thresholds and the ridge heights. The Weber fractions were 0.14, 0.13, 0.11, and 0.16 for 7.0-, 8.6-, 10.8-, and 12.3-μm ridges, respectively (Fig. 8).

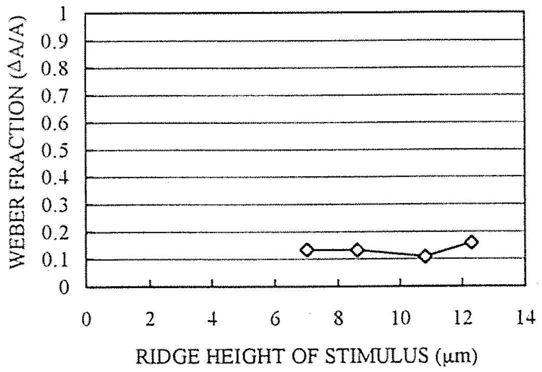

FIG. 8. Weber fractions calculated from the ridge-height discrimination data. The vertical axis shows the Weber fractions and the horizontal axis shows the ridge heights of the stimuli.

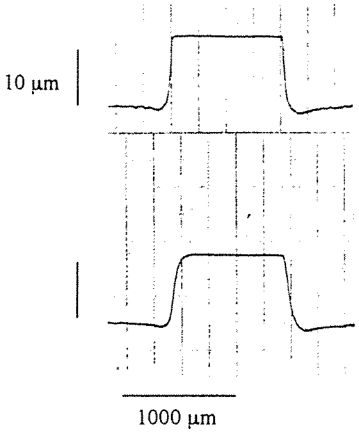

FIG. 9. Cross-section profiles of a ridge observed with the contact profile meter with and without a filter. The top is the profile of the 12.3-μm ridge without a filter. The bottom is the profile, passed through a filter, of the same part of the same ridge shown on the top. The filter passed waves with wavelengths greater than 250 μm.

C. Discussion

Experiment 2 was performed to measure the difference thresholds and to strengthen the possibility of the hypothesis that humans discriminate fine-surface textures using amplitude information of stimulus surface unevenness. The difference thresholds of ridge-height discrimination were from 0.95 to 2.0 μm. These results showed that humans can discriminate very small differences in ridge heights using tactile sensation. The Weber fractions, calculated from the difference thresholds, were 0.14, 0.13, 0.11, and 0.16 for 7.0-, 8.6-, 10.8-, and 12.3-μm ridges, respectively. The Weber fractions showed no increasing nor decreasing tendency in their values depending on the changing of ridge heights (Fig. 8). This phenomenon means that the absolute-detection threshold of ridge height is considerably lower than 6 μm. Johansson and LaMotte (1983) determined that the detection threshold of edge height was 0.85 μm, and LaMotte and Whitehouse (1986) found that the detection threshold of a raised dot, with a diameter of 550 μm, was 2.1 μm. Assuming that the detection threshold of a ridge is 1 μm, then the 7.0-, 8.6-, 10.8-, and 12.3-μm ridges are 17, 19, 21, and 22 dB SL, respectively. Comparing the Weber fractions of ridge heights with the fractions of a vibrotactile stimuli (Gescheider *et al.*, 1990) at the same intensity level, the Weber fractions of the ridge heights were the same or only slightly smaller than those of vibrotactile stimuli. The results of the ridge-height experiment support the hypothesis that the subjects used amplitude information of surface unevenness in the discrimination of ridge height. Tactile nervous systems have low-pass filter characteristics. The ridge height, however, remained the same after passing through the filter, which excluded wavelengths shorter than 250 μm, as shown in Fig. 9. It is logical to assume that the subjects perceived the ridge heights as waves because they moved their fingers tangentially across the ridge stimuli in the experiment.

Comparing the Weber fractions of experiment 2 with the fractions of the fine-surface-texture discrimination experiment (experiment 1), the former fractions were smaller than the latter ones. The Weber fractions of experiment 2 were from 0.11 to 0.16. On the other hand, the fractions of experiment 1 were from 0.28 to 0.81. When comparing the Weber fractions of the texture experiment and the ridge experiment with similar-sized standard stimuli, the Weber fraction of the texture experiment was about two times larger than that of the ridge experiment; the Weber fractions were 0.28 for texture and 0.16 for ridges when the standard stimulus sizes were 12 μm for the texture and 12.3 μm for the ridge, respectively. A possible reason for this result is as follows: during the ridge experiment, the discrimination tasks were easy because the stimulated mechanoreceptors discharged simultaneously at the ridge; however, during the texture experiment the tasks were more difficult because the mechanoreceptors do not show these simultaneous discharges.

The stimuli in experiment 2 were simple, and the results strongly suggested that the subjects used amplitude information for the discrimination of ridge heights. If the subjects discriminate the ridge heights using the amplitude information of ridges which passed through a low-pass filter, they can use the same ability for the discrimination of fine-surface textures. The results of experiment 2 strengthened the possibility of the hypothesis that the subjects discriminate fine-surface textures depending on the amplitude information of surface unevenness.

III. CONCLUSION

The purpose of this study was to investigate possible tactile mechanisms for making fine-surface-texture discriminations. In experiment 1, the discrimination of fine-surface textures at the finger tips, using abrasive papers as stimuli, was measured. The Weber fractions of texture discriminations were between 0.28 and 0.81. Based on the results of experiment 1 and other psychophysical and neurophysiological data, the following hypothesis was proposed: the subjects perform the discrimination tasks based on the amplitude information of surface unevenness.

If the amplitude information hypothesis is valid, the subjects would have shown at least the same ability in ridge-height discriminations as in texture discriminations. In experiment 2, the difference thresholds for the discrimination of ridge height was measured. The Weber fractions calculated from the difference thresholds were between 0.11 and 0.16. The results of experiment 2 strengthen the possibility of the hypothesis. Further experimentation is needed to determine if these explanations can account for the results reported here.

ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Science and Culture, No. 07610093, and by the Mikiya Science and Technology Foundation.

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