Measurement of Human Tactile Sensation Capability to Discriminate Fine Surface Textures Using a Variable Step-height Presentation System

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Abstract

The purpose of this study was to analyze human sensory information processing of fine-surface textures in three psychophysical experiments. We measured difference thresholds of fine step-height discrimination. These values are important in examining the sensitivity of human mechanoreceptive units. To begin with, we developed a computer-controlled measurement system to present fine step-heights of 0 to 30 μm to five human subjects. To obtain the thresholds efficiently, the subjects distinguished between two step-heights presented in a PEST (Parameter Estimation by Sequential Testing) trial sequence. In Experiment A, the subjects actively touched the step-heights (active-touch). In Experiment B, they passively touched the step-heights that were driven linearly by an X-table with cyclic movement (passive-touch). In Experiment C, they actively touched the step-heights cooled to 15 °C. The result was that the thresholds in the active-touch experiment agreed almost with those in the passive-touch experiment. Also, the distinctive sensitivity did not decline even if the step-heights were cooled at 15 °C. Therefore, we concluded that human tactile discrimination ability was independent of touching manner, and that FA I of human tactile mechanoreceptors plays an important role in determing the degree of a fine-surface texture.

1 Introduction

Human beings can recognize subtle differences in fine-surface textures. Researchers have investigated the mechanism of fine-surface texture recognition[1]-[5]. An inspection machine implemented on the basis of this recognition mechanism shall be applied widely to inspection works, since the human sensation is more robust than a surface roughness tester. Therefore, the analysis of the recognition mechanism is important for engineering as well as neuroscience.

So far several researchers have examined the tactile recognition mechanism of the human hand in detail with microneurography and psychophysical experimentation. Microneurography is a method to examine a reaction to a given stimulus via signals sensed by a tungsten microelectrode inserted into a nerve fiber. Psychophysical experiments are methods to examine a human subject's replies to questions regarding the strength of stimulus. The studies have used these experimental methods to reach several conclusions. The mechanoreceptive units of human tactile organs are the Fast adapting type I unit (FA I), Fast adapting type II unit (FA II), Slowly adapting type I unit (SA I) and Slowly adapting type II unit (SA II)[1][2]. FA II can perceive a mechanical vibration of 0.2 μm in amplitude[3]. FA I or FA II can perceive a surface-unevenness of 3 μm in amplitude[4]. SA I can perceive a pattern formed by Braille dots[5].

The mechanical vibration and the Braille pattern are perceived easily by common instruments. Acceleration sensors can measure small mechanical vibrations and robot vision can recognize Braille patterns. However, perceiving the surface texture of various items incapable of being brought into a measuring room is difficult to realize with the surface roughness tester because the tester needs an environment controlled by an air conditioner and a vibration-proof foundation. The analysis of the recognition mechanism for surface-unevenness shall create a new method for surface-inspection machines and material-handling robots used outside of the measuring room. Therefore, this paper attempts to analyze experimentally the surface-unevenness recognition mechanism of human tactile organs.

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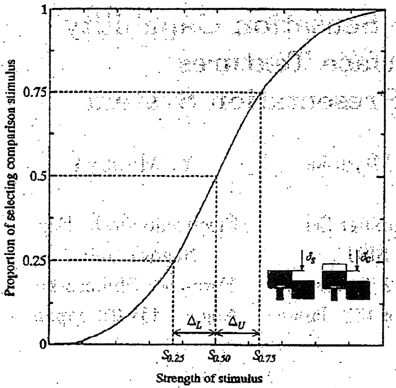

Fig. 1 An example of discrimination characteristic curve

The authors reported in another paper that the human tactile sensation capability to discriminate fine surface textures (as evaluated with a difference threshold) was determined to be between 2.4 and 3.0 μm in a psychophysical experiment that used aluminum oxide abrasive papers as the stimuli. It was suggested that the human subjects determined degrees of roughness from amplitudes present in the surface unevenness. However, more reasonable stimuli should be chosen to confirm the above mentioned conclusion, since the abrasive paper stimuli included both amplitude and frequency information. In addition, the experimental procedures were troublesome because the stimuli had to be changed several hundred times by hand to obtain a single difference threshold.

Therefore, we decided to use the fine-steps as the stimuli and developed a computer controlled measurement system that presented fine step-heights of 0 to 30 μm to the human subjects. Furthermore, to determine efficiently the difference threshold, we optimized an experimental procedure based on the PEST (Parameter Estimation by Sequential Testing) method to adjust the stimuli strength according to responses from the human subjects.

In the experiments, five human subjects were presented with two step-heights in a PEST sequence of random order and determined which step-height was larger. One of the two step-heights was the comparison stimulus with a step-height calculated by the PEST algorithm. The other was the standard stimulus with a step-height that was not varied for one experiment. In Experiment A, the human subjects actively touched aluminum plates at 37 °C (active-touch). Standard step-heights of 5, 7.5, 10, 12.5 and 15 μm were used to examine the relationship between difference thresholds and step-heights in the active-touch method. In Experiment B, the subjects passively touched aluminum plates driven linearly by an X-table with cyclic movements (passive-touch). Passive-touch velocities of 10, 20, 30, 40 and 60 mm/s were used to examine the relationship between difference thresholds and velocities in the passive-touch method. The temperature and standard step-height of the plates were 37 °C and 10 μm, respectively. In Experiment C, the subjects actively touched plates that were cooled to 15 °C and the standard step-height was 10 μm. The dependence of surface unevenness sensitivity on temperature will be discussed based on the results of Experiment C.

2 PEST (Parameter Estimation by Sequential Testing) method

It is assumed that human subjects distinguish between two stimuli with their fingers. In this paper we used the step-height as the stimuli. One of the stimuli is a standard stimulus and the other is a comparison stimulus. The strength of the standard stimulus and the comparison stimulus are denoted by δ_s and δ_c, respectively. The standard stimulus, δ_s, is designated to be fixed strength and the comparison stimulus, δ_c, is varied. Several pairs of δ_s and δ_c were presented to examine the discriminating ability of the stimuli and have the human subjects judge which stimulus is stronger, δ_s or δ_c. When δ_c was smaller than δ_s, only a small percentage of responses selected δ_c as being higher. Conversely, when δ_c was larger than δ_s, the majority of responses selected δ_c as being higher than δ_s. Figure 1 shows a characteristic curve of the percentage that selected δ_c. The comparison stimuli for the proportions equal to 0.25, 0.5 and 0.75 are denoted by $S_{0.25}$, $S_{0.5}$ and $S_{0.75}$, respectively. The values of $\Delta_U = S_{0.75} - S_{0.5}$ and $\Delta_L = S_{0.5} - S_{0.25}$ are the upper and the lower thresholds, respectively. Moreover, the average of the upper and lower thresholds $\Delta = (\Delta_U + \Delta_L)/2$ is called the (average) difference threshold. The generic name for the upper threshold, the lower threshold and the (average) difference threshold is the difference threshold, since they usually coincide with each other.

The PEST method developed by Taylor and Creelman is a method to determine the above-mentioned thresholds in a psychophysical experiment where the stimulus strength is controlled by a computer[6]. The standard and comparison stimuli are presented in random order in each trial. The stimulus strength in each trial is determined based on the human subject's successive responses according to the following PEST algorithm constituted by three groups of rules.

Rule #1. Condition for changing stimulus strength

A PEST sequence consists of several trial blocks composed of several trials. Let us consider the n-th trial block. The comparison stimulus is constant throughout the same block. Let L_n, T_n and C_n be the stimulus strength, the trial number and the number of the human subject's correct answers at the current block, respectively. For a specified P, the proportion of C_n against T_n, the fault-answer number E_n is given as the following:

$$E_n = P \cdot T_n - C_n. \tag{1}$$

Let E_p be the permitted error number. If the condition:

$$| E_n | \;<\; E_p \tag{2}$$

is satisfied, then the experiment continues with the same comparison stimulus. If the condition is not satisfied, then the comparison stimulus is varied and the trial block is incremented to the $(n+1)$-th trial block. The comparison stimulus is decreased whenever Eq. (3) is satisfied and increased whenever Eq. (4) is satisfied.

$$E_n \;\leqq\; -E_p \tag{3}$$

$$E_n \;\geqq\; E_p \tag{4}$$

Rule #2. Incremental stimulus strength

The incremental width of the stimulus strength in the n-th trial block, W_n, should decrease as the number of trials increase to converge the comparison stimulus. If the current comparison stimulus differs considerably from the convergent value of the comparison stimulus, the incremental width should increase to reach rapidly the convergent value. Taylor and Creelman empirically determined the rules for the adjustment of the incremental width. In their rules, the convergence condition is judged by the variation in fluctuation direction of the stimulus strength. The fluctuation direction (increase or decrease) in the n-th trial block is denoted by D_n. The incremental width in the $(n+1)$-th block is specified as the following:

(a) If the direction D_n becomes contrary to the direction D_{n-1} of the $(n-1)$-th trial block, then the incremental width W_n is a half of W_{n-1}, the incremental width in the $(n-1)$-th trial block.

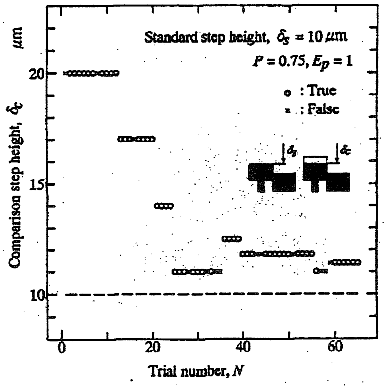

Fig. 2 Variation in comparison step-height calculated by the PEST algorithm

(b) If D_n and D_{n+1} are the same direction, then W_{n+1} is the same as W_n.

(c) If D_{n-1}, D_n, and D_{n+1} are the same direction and W_{n-2} is twice W_{n-3}, then W_{n+1} is the same as W_n. However, if D_{n-1}, D_n, and D_{n+1} are the same direction and W_{n-2} is equal to W_{n-3}, then W_{n+1} is twice W_n.

(d) If D_{n-2}, D_{n-1}, D_n, D_{n+1}, … continue in the same direction, then W_{n+1}, W_{n+2}, W_{n+3}, … are each twice the previous incremental width.

Rule #3. Condition of termination

The incremental width W_n becomes small as the comparison stimulus approaches the standard stimulus. The minimum incremental width, W_{min}, is specified by the PEST algorithm. If the condition of termination:

$$W_n \;\leqq\; W_{min}, \tag{5}$$

is satisfied, then the processing is terminated. The difference between the next stimulus, L_{n+1}, and the standard stimulus, δ_s, is the difference threshold.

Experimental results using PEST are exemplified in Figure 2 to explain the above mentioned PEST procedure. In the example, P, E_p, and W_{min} were assumed to be 0.75, 1.0, and 0.3 μm, respectively. Also, δ_s and the initial increment W_1 were presumed to be 10 μm and 3 μm, respectively. While the calculated result of Eq. (1) satisfies the condition given by Eq. (2), the human subject repeats the comparison of the standard

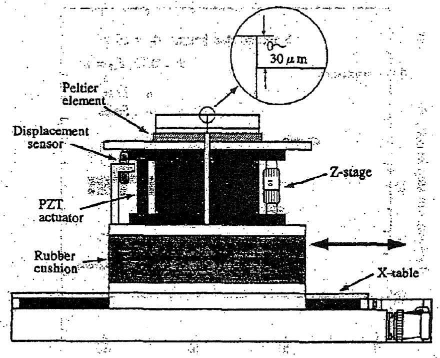

Fig. 3 Step-height presentation device

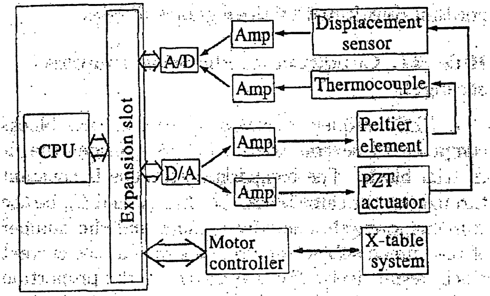

Fig. 4 Schematic diagram of step-height presentation device

step-height of 10 μm with the initial comparison step-height of 20 μm. Since after twelve trials the right side of Eq. (1) yields $0.75 \times 12 - 10 = -1$ and the result satisfies the condition given by Eq. (3), the comparison step-height is reduced to 17 μm according to Rule #2 (incremental of stimulus strength). As is evident from Figure 2, the comparison step-height decreases as the trial number increases. Thereafter, the comparison step-height increases when the condition given by Eq. (4) is satisfied for a the trial block with an 11 μm step-height. Therefore the comparison step-height is bounded because the calculated results alternatingly satisfy the conditions given by Eq. (3) and (4). However, the wave amplitude decreases gradually due to Rule #2. Finally the calculated W_n satisfies the condition of Eq. (5). The terminated comparison step-height is 11.2 μm and its upper threshold is obtained from the experiment as $\Delta_u = 1.2$ μm.

3 Measurement system

Based on our previous studies, we utilized the fine-steps as the stimuli and developed a measurement system to present these 0 to 30 μm high fine-steps to human subjects. The fine-steps are formed between two aluminum plates of 20 × 30 × 5 mm mounted on the step-height presentation device shown in Figure 3. The schematic diagram of this system is shown in Figure 4. One of the plates is driven by a piezoelectric ceramic actuator equipped on the Z-stage and the other is driven by a micrometer used to adjust the initial height difference between the two plates. Displacement measured by the displacement sensor is transmitted to a computer that uses feedback control techniques to control the step-height with an accuracy of 0.2 μm. Also, Peltier elements (thermoelectric cooling elements that use Peltier effect) maintain the aluminum plates at constant temperature within a range of 8 to 50 °C. The velocity of the aluminum plates mounted on the step-height presentation device is controlled linearly by cyclic movement of the motor-driven X-table. In addition, a switch box containing two switches is used to input the human subject's judgment.

4 Experimental method

The difference threshold for fine-steps was determined through three psychophysical experiments using the measurement system we developed. Five human subjects approximately 20 years old touched two fine-steps formed between the two aluminum plates with the index fingers or the middle fingers. Each step-height was presented twice and the subjects judged which step-height was larger in a trial of the PEST procedure. The subjects pressed the right switch if they felt the step-height presented first was larger, and they pressed the left switch if they felt the step-height presented second was larger. Even if they were not able to judge the difference between the step-heights, the subjects had to press one of the switches. The comparison step-height presented at the next trial was calculated by the PEST algorithm based on their answer. The above procedure was repeated, and as a result, one difference threshold was determined. In the following three experiments, W_1, W_{min}, P and E_p, the initial values used in the PEST rules, were 3 μm, 4 μm, 0.75 and 0.8 respectively.

Experiment A

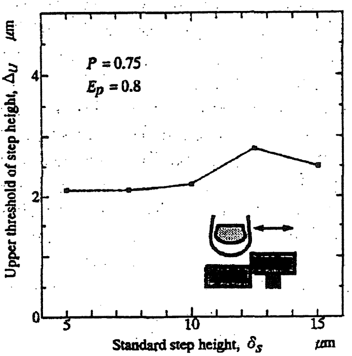

Fig. 5 Relationship between upper threshold and standard step-height in active-touch discrimination tasks

In this experiment, the human subjects actively touched step-heights formed between two aluminum plates of 37 °C . The subjects determined both movement velocity and the number of times they touched the step-height with their fingers. Step-heights of 5, 7.5, 10, 12.5 and 15 μm used as the standard stimuli were compared with initial comparison step-heights of 15, 17.5, 20, 22.5 and 25 μm, respectively.

Experiment B

The human subjects passively touched the aluminum plates of 37 °C that were driven linearly by the X-table until they could distinguish the difference between the first and second step-heights. The average movement velocities were 10, 20, 30, 40 and 60 mm/s. The standard step-height and the initial comparison step-height were 10 and 20 μm, respectively.

Experiment C

FA I and FA II are believed to be mechanoreceptive units used to sense the surface unevenness. Bolanowski and Verrillo reported that at temperatures below 20 °C, the sensitivity of FA II decreased considerably from that of room temperature[7]. Using this phenomenon, we masked the sensitivity of FA II by cooling the aluminum plates to 15 °C. In Experiment C the human subjects actively touched the cool step-heights. As in Experiment A, the subjects determined both movement velocity and the number of times to touch the step-height with their fingers. Moreover, the human subjects placed their fingers on an ice pack while waiting between PEST trials to prevent their fingers from returning to body temperature. The standard step-height and the initial comparison step-height were 10 and 20 μm, respectively.

5 Experimental results and Discussion

5.1 Relationship between difference thresholds and step-heights for active-touching

The difference thresholds for discriminating between step-heights were determined in the active-touch experiments. Each human subject was tested twice to determine 10 upper thresholds for each standard step-height. However, if the deviation of an upper threshold was greater than 2σ (two times the standard deviation of 10 data points) from an average of the 10 data values, the upper threshold was not used and an additional test was performed to obtain 10 data values that had deviations within 2σ.

Figure 5 demonstrates the relationship between the upper thresholds and the step-heights in the active-touch experiment. The upper threshold of step-height is almost constant in the range from 2 to 3 μm for variations in the standard step-height of 5 to 15 μm. We have previously reported that for aluminum oxide abrasive paper with maximum particle diameters of 3, 5, 9 and 12 μm, the average thresholds were 2.4, 2.5, 2.7 and 3.3 μm, respectively. The average thresholds of abrasive paper were approximately equal to the upper thresholds obtained from tests using fine-step stimuli. Therefore, we confirmed that our measurement system has the capability to measure precise difference thresholds for fine-step discrimination.

5.2 Relationship between difference thresholds and velocities for passive-touching

The difference thresholds for discriminating a 10 μm step-height were determined for five velocities in the passive-touch experiment. Each human subject was tested twice for each velocity to determine 10 upper thresholds.

Figure 6 shows the relationship between upper thresholds and velocities in the passive-touch experiment. The upper threshold of step-height remains almost constant in the range of 2 to 3 μm when the velocity is varied from 10 to 60 mm/s. Moreover, the difference thresholds for a 10 μm step-height agreed approximately with the value of 2.2 μm obtained in the previous active-touch experiment. As a result, it was found that the human capability for discriminating fine-steps with the passive-touching was equal to that of active-touching.

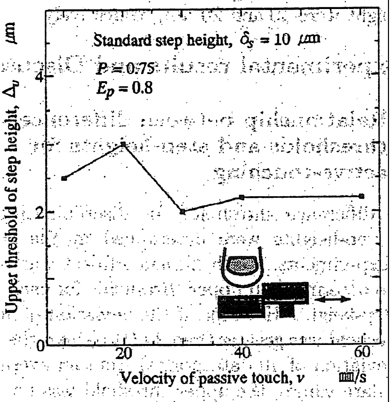

Fig. 6 Relationship between upper threshold and standard step-height in passive-touch discrimination tasks

From the results of Experiments A and B, we concluded that the upper threshold for step-height was constant against variations in the velocity of finger movement and that the human capability for discriminating fine-steps did not depend on the manner they were touched, either actively or passively.

5.3 Difference thresholds for active touching at a temperature of 15 °C

In Experiment C the difference thresholds for discriminating 10 μm step-heights were determined for active-touching at 15 °C. Each human subject was tested twice to determine 10 upper thresholds. The average upper threshold is 2.8 μm, as shown in Table 1. If FA II participates in the recognition of surface unevenness, the sensitivity at 15 °C will decline considerably as shown in the experimental results conducted by Bolanowski and Verillo [7]. However the sensitivity declines only 20 % of the aforementioned threshold for active-touching at 37 °C. Therefore it can be concluded that FA I plays an important role in discriminating degrees of the step-height.

6 Conclusion

In order to analyze the mechanism in human beings that detects surface unevenness, we developed a fine step-height presentation system to determine the difference thresholds of discriminating fine step-heights using a PEST algorithm. The five human subjects distinguished step-heights in the three psychophysical experiments using this system. In Experiment A the difference thresholds for passive-touching were determined to be in the range between 2 and 3 μm. In Experiment B the difference thresholds for passive-touching agreed approximately with the thresholds for active-touching regardless of the touching manner. Therefore the human subjects discriminated the fine step-heights without having information of active movement. To examine which mechanoreceptor, FA I or FA II, participates in fine-step recognition, we performed Experiment C and obtained the difference thresholds at 15 °C where the sensitivity of FA II declined considerably. The resulting difference threshold was 2.8 μm and the sensitivity declined slightly. Therefore we conclude that FA I plays an important role in discriminating between degrees of step-heights.

Tab. 1 Upper threshold for active-touching at a temperature of 15 °C

Step height 10 μm

Human subjects	Upper threshold (μm)	
A	2.9	2.1
B	5.9	3.6
C	1.4	3.6
D	5.1	0.6
E	2.1	0.3
Average (μm)	2.8	

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