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Measurement System of Fine Step-Height Discrimination Capability of Human Finger's Tactile Sense

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1. Introduction

In this study, to measure the human finger's tactile sensation capability of recognizing a fine surface texture using psychophysical experiments, a computer-controlled measurement system that presents fine step-heights of 0 to 1000 μm to human subjects' fingers at various presentation angles were developed. The measurement system can control four parameters of fine step presentation, i.e., the step-height, presentation velocity, presentation angle, and presentation temperature. In psychophysical experiments of this study, the measurement system calculates the amounts of step-heights based on the Parameter Estimation by Sequential Testing (PEST) method (Taylor & Creelman, 1982) and presents the step-heights to subjects' fingers in order to measure difference thresholds and subjective equalities for fine step-heights. Those values are considered to be the fine step-height discrimination capability of finger's tactile sense.

Human finger's tactile sense is a measurement system that can detect subtle surface roughness and smoothness by touching the surface. This finger's tactile sense is much more robust than the tactile sensors developed so far for robot tactile recognition. These sensors for robot still cannot reach the performance of recognizing such fine roughness or smoothness as humans can. Therefore, it is important for engineering, as well as for psychology, to investigate the finger's tactile recognition mechanism.

So far several researchers have examined the finger's tactile sense mechanism in detail using microneurography and psychophysical experimentation. In the microneurography, a tungsten microelectrode was inserted into tactile-related nerve fibers in an arm of humans or monkeys and the reactions of the tactile sense to the stimuli presented to the hand were examined via the signals sensed by the microelectrode. In the psychophysical experiments, on the other hand, several magnitudes of stimuli were presented to human hands and the responses of the tactile sense to the stimuli are analyzed through the replies to questions regarding the stimulus magnitudes.

The microneurography found out that the human tactile organs consist of four types of mechanoreceptive units: 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) (Vallbo & Johansson, 1984; Salentijn, 1992), and it is considered that FA II responds to a subtle mechanical vibration, FA I or FA II to surface unevenness and SA I to a pattern like Braille dots, respectively (Heller, 1989). On the other hand, the psychophysical experiments (Miyaoka et al., 1993, 1996, 1997) determined that the human tactile mechanism is able to detect a mechanical vibration of 0.2 μm in amplitude and a surface unevenness of 3 μm in amplitude. Also, the psychophysical experiment (Kawamura et al., 1996) revealed that FA I plays an important role in discriminating the magnitudes of step-height of around 10 μm. From these experimental results, it is considered that, like the human visual sense, the human tactile sense has several kinds of module mechanisms, and it is supposed that the human tactile modules are classified based on the stimulus magnitudes they can detect and discriminate and their information processing characteristics: the subtle stimulation detection module, fine texture recognition module, two-dimensional pattern recognition module, and three-dimensional shape recognition module. So far the authors have been investigated the tactile sensation capability of recognizing fine step-heights with respect to the fine texture recognition module.

Using a measurement system that presents fine step-heights of about 10 μm to subjects' fingers (Miyaoka et al., 1996; Kawamura et al., 1996), the difference thresholds for a 10 μm step-height were determined when the subjects actively touched the step-height with their fingers moving over the step-height and when they were passively touched the step-height presented to their fingers by the movement of the step presentation device. As a result, the difference thresholds for a 10 μm step-height in the active- and passive-touch experiments agreed approximately. Therefore, it was concluded that the finger's discrimination capability of fine step-heights of about 10 μm does not depend on the touching manners. Also, the paper (Kawamura et al., 1998) suggested that when the subjects discriminated a pair of the 10 μm step-heights presented at the different presentation velocities of 20 and 40 mm/s to their fingers, they perceived the height of the fast moving step-height to be a larger stimulus than that of the slowly moving step-height due to the influence of the stimulus velocity. Furthermore, the authors developed a measurement system that can create fine step-heights of 0 to 1000 μm and present the step-heights to subjects' fingers at various presentation angles (Kawamura et al., 2009).

In this paper, to measure the finger's tactile sensation capability of discriminating fine step-heights, the developed measurement system is used. In the psychophysical tests, the presentation angle of a step is defined as the angle to finger's length and several pairs of fine step-heights of 0 to 100 μm are presented to subjects' fingertips at various presentation angles. This paper first describes the measurement system that controls the amounts of step-heights according to the experiment procedure based on the PEST method in order to determine subjective equalities and difference thresholds for fine step-heights, then examines the effects of the touching manner of human finger, finger's motion direction, and fingertip region on the tactile recognition of fine step-heights. In the psychophysical tests, first, the subjects discriminate step-heights of 10 to 100 μm in active- and passive-touch manners using the center of their fingertips. Next, the subjects discriminate step-heights of around 10 μm using the top and center of their fingertips in various motion directions of their fingers.

2. Psychophysical experiment

2.1 Subjective equality and difference threshold

In the psychophysical experiments of this study, the relationships between the stimulus magnitudes of fine step-heights and the sensitivity of the finger's tactile sensing mechanism are examined. Subjective equalities and difference thresholds for fine step-heights determined using the experiments are important values for investigating the human tactile sensation. The meanings of those values are explained in the following (Gescheider, 1985).

In an experiment, human subjects touch several pairs of stimuli with their fingers and try to distinguish them. One of the stimulus pair is the standard stimulus and the other is the comparison stimulus. The magnitudes of the standard and comparison stimuli are denoted by δ_s and δ_c, respectively. The standard stimulus is designed to be constant and the comparison stimulus is variable. Several pairs of δ_s and δ_c are presented to the subjects and for each pair they are asked to tell which stimulus of δ_s and δ_c they feel stronger. When δ_c is smaller than δ_s, the proportion of the responses that δ_c is chosen as stronger than δ_s is supposed to be low. Conversely, when δ_c is greater than δ_s, the proportion of the responses that δ_c is chosen as stronger than δ_s is supposed to be high. Figure 1 shows a characteristic curve of the proportion that δ_c is chosen as stronger than δ_s. The horizontal axis shows the comparison stimulus while the vertical axis shows the proportion of the subjects selecting the comparison stimulus. The comparison stimulus magnitudes 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 value of $S_{0.5}$ is called the subjective equality for δ_s. If the standard and comparison stimuli are presented under the same condition, $S_{0.5}$ should be equal to δ_s.

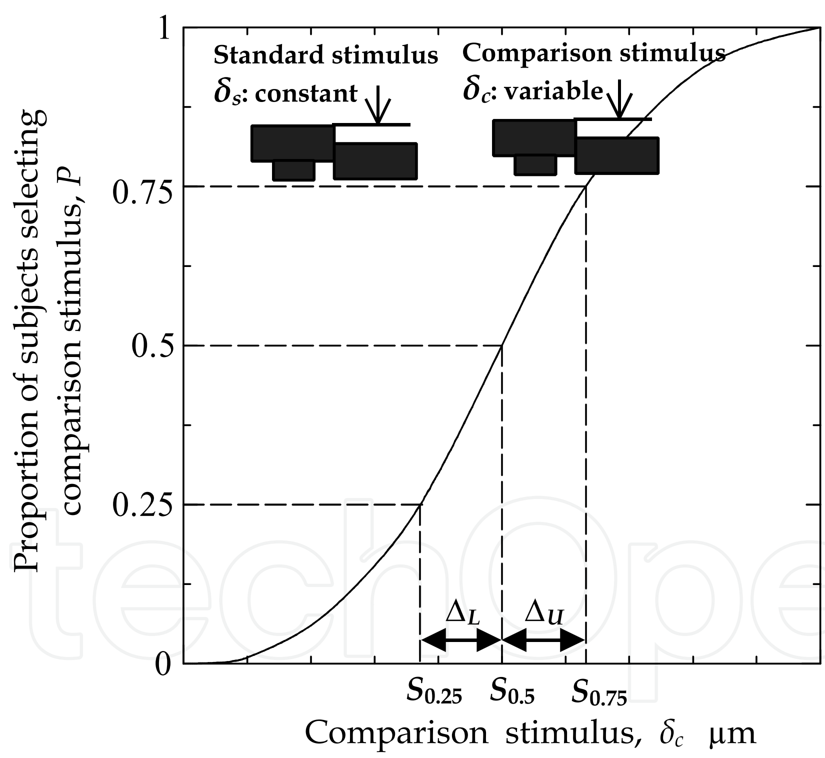

Fig. 1. An example of a discrimination characteristics curve.

The values of $\Delta_U = S_{0.75} - S_{0.5}$ and $\Delta_L = S_{0.5} - S_{0.25}$ are the upper and lower thresholds for δ_s, respectively. Moreover, the average of the thresholds, $\Delta = (\Delta_U + \Delta_L)/2$, is called the difference threshold. In addition, these thresholds usually have very close values because the upper and lower thresholds become almost equal. Also the value of the ratio of Δ to δ_s is called the Weber fraction. The value is known to be constant over the range of stimulus magnitude in tactile sensing mechanisms, as well as in visual and auditory.

2.2 Parameter Estimation by Sequential Testing (PEST) method

Taylor and Creelman developed the PEST method to determine the above-mentioned difference thresholds and subjective equalities through the process of a psychophysical experiment without calculating the characteristics curve (Taylor & Creelman, 1982). The PEST algorithm consists of three groups of rules in the following, and, as shown in Fig. 2, calculates the magnitudes of comparison stimuli to present to a subject based on the subject's responses in the experiment. In this study, the authors have developed the measurement system that calculates the magnitudes by computer based on the PEST algorithm and determines the difference thresholds and subjective equalities.

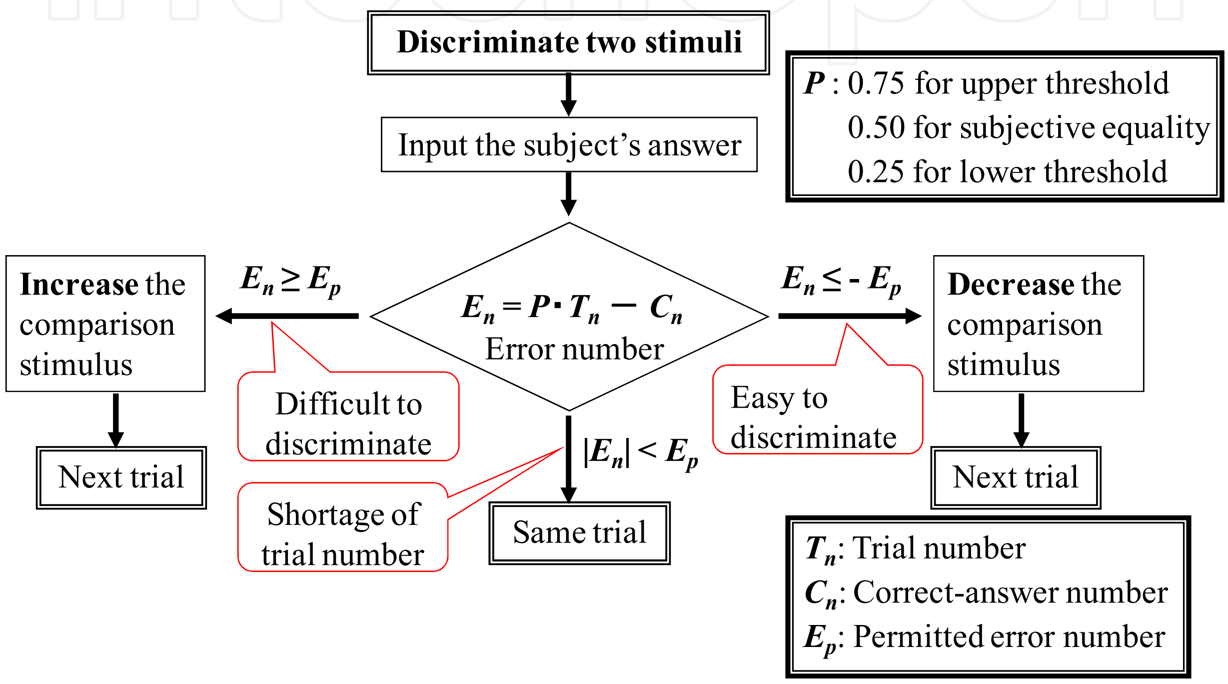

Fig. 2. Flowchart of changing the magnitude of comparison stimulus using the PEST algorithm.

Rule #1: Condition for changing the magnitude of comparison stimulus

A PEST sequence consists of several trial blocks composed of several trials as shown in Fig. 3. Let us consider the n-th trial block. The magnitude of comparison stimulus is constant throughout the same block. Let δ_{cn}, T_n and C_n be the comparison stimulus magnitude, the trial number and the number of the human subject's correct answers in the current n-th trial block, respectively. For a specified P, the proportion of C_n against T_n, the error number E_n is given as follows:

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

where the value of P is 0.25, 0.5, or 0.75 to obtain the lower threshold, the subjective equality, or the upper threshold, respectively. 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 δ_{cn} is varied and the trial block is incremented to the $(n + 1)$-th trial block. δ_{cn+1} is decreased whenever (3) is satisfied and increased whenever (4) is satisfied. Equations (3) and (4) are given as follows:

$$E_n \leq -E_p \, , \tag{3}$$

$$E_n \geq E_p \, . \tag{4}$$

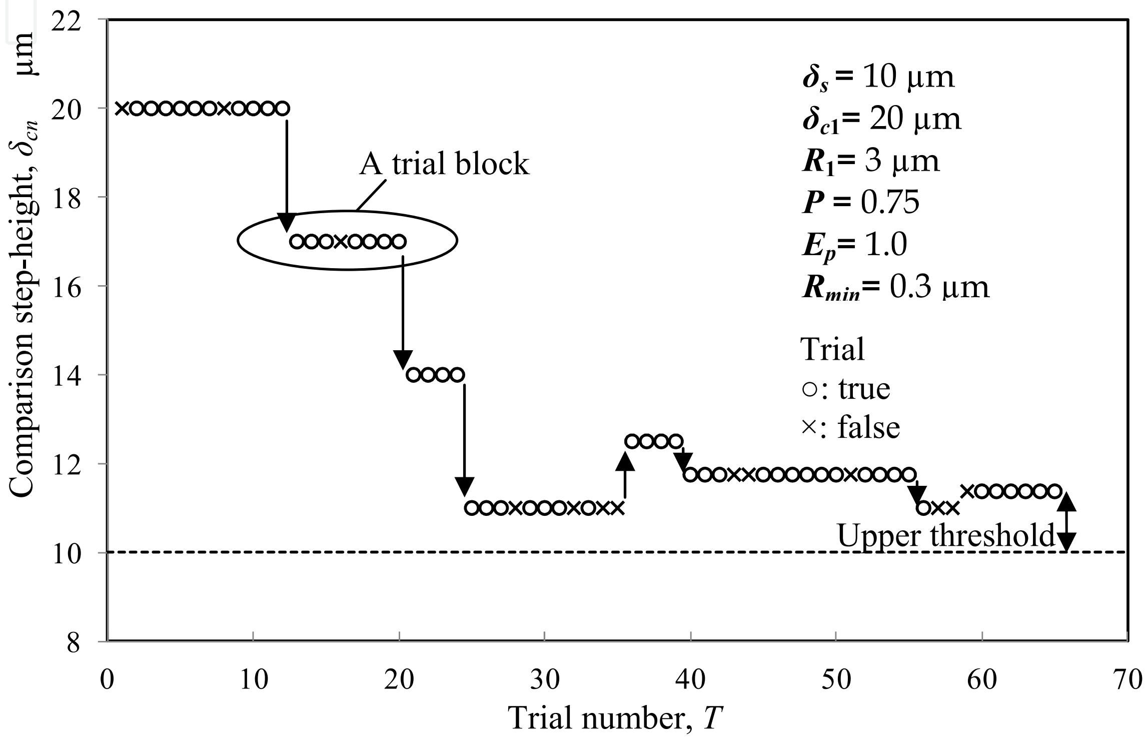

Fig. 3. An example of variation in comparison step-height calculated by the PEST algorithm.

Rule #2: Incremental stimulus magnitude

The incremental range of the comparison stimulus magnitude in the n-th trial block, R_n, should decrease in order for δ_{cn+1} to converge as the number of trials increases. Here δ_{cn+1} is given as follows:

$$\delta_{cn+1} = \delta_{cn} \pm R_n \, . \tag{5}$$

If δ_{cn} differs considerably from the convergent value, R_n should increase to reach rapidly the convergent value. Taylor and Creelman empirically determined the rules for the adjustment of the incremental range. In their rules, the convergence condition is judged by the variation in fluctuation direction of the stimulus magnitude. The fluctuation direction (increase or decrease) in the n-th trial block is denoted by D_n. R_n is specified as follows:

a. If the direction D_n becomes contrary to the direction D_{n-1} of the $(n - 1)$-th trial block, then R_n is set half R_{n-1}.
b. If D_{n-1} and D_n are the same direction, then R_n is set the same as R_{n-1}.

c. If D_{n-2}, D_{n-1} and D_n are the same direction and R_{n-2} is half R_{n-3}, then R_n is set the same as R_{n-1}. However, if D_{n-2}, D_{n-1}, and D_n are the same direction and R_{n-2} is equal to R_{n-3}, then R_n is set twice R_{n-1}.
d. If D_{n-3}, D_{n-2}, D_{n-1}, D_n, … continue in the same direction, then R_n, R_{n+1}, R_{n+3}, … are each twice the previous incremental range.

Rule #3: Condition of termination

R_n becomes small as δ_{cn} approaches the standard stimulus magnitude, δ_s. The minimum incremental range, R_{min}, is specified by the PEST algorithm. If the condition of termination:

$$R_n \leq R_{min} \tag{6}$$

is satisfied, then the processing is terminated. The difference between δ_{cn} and δ_s is the threshold if the value of P is 0.25 or 0.75, and δ_{cn} is the subjective equality if P is 0.5.

Experimental results using the PEST method are exemplified in Fig. 3 to explain the above-mentioned PEST procedure. In the example, P, E_p, and R_{min} are set at 0.75, 1.0, and 0.3 µm, respectively. Also, the standard step-height δ_s and the initial comparison step-height δ_{c1}, the initial increment R_1 are 10 µm, 20 µm, and 3 µm, respectively. While the calculated result of (1) satisfies the condition given by (2), the human subject repeats the comparison of δ_s of 10 µm with δ_{c1} of 20 µm. Since after twelve trials the right side of (1) yields $0.75 \times 12 - 10 = -1$ and the result satisfies the condition given by (3), δ_{c2} is reduced to 17 µm ($\delta_{c2} = \delta_{c1} - R_1$) according to Rule #2 (incremental stimulus magnitude). As is evident from Fig. 3, the comparison step-height decreases as the trial number increases. Thereafter, δ_{c5} is increased to 12.5 µm ($\delta_{c5} = \delta_{c4} + R_4$; $R_4 = R_3 / 2$) when the condition given by (4) is satisfied for a trial block with an 11 µm step-height. In the continuous blocks, the comparison step-height is bounded because the calculated results alternately satisfy the conditions given by (3) and (4). However, the comparison step-height decreases gradually due to Rule #2. Finally the calculated R_8 satisfies the condition of (6). The terminated comparison step-height is 11.375 µm and its upper threshold is obtained from the experiment as $\Delta_U = 1.375$ µm.

In the experiments of the paper, E_p is set a constant value of 1.0 and the other values are determined according to the experiment conditions.

3. Measurement system

To measure the human finger's tactile sensation capability of recognizing fine step-heights using psychophysical experiments, a measurement system that creates step-heights of 0 to 1000 µm and presents several pairs of the step-heights to human subject's fingers according to the PEST algorithm were developed (Fig. 4). In the psychophysical experiments of this paper, the subjects touch fine step-heights in active-touch manner (Fig. 5) and passive-touch manner (Fig. 6). The step-height presentation device has the capability of controlling four parameters of the step-height presentation, i.e., the step-height, presentation velocity, presentation angle, and presentation temperature. The first three parameters are controlled by a computer that drives the wedge-shaped Z stage, the X-table and the rotary table, and the presentation temperature is controlled by the Peltier elements.

A fine step is formed between two fine finished stainless steel plates, and the height of the step is a stimulus magnitude. The stepping motor-driven Z stage slides one of the stainless

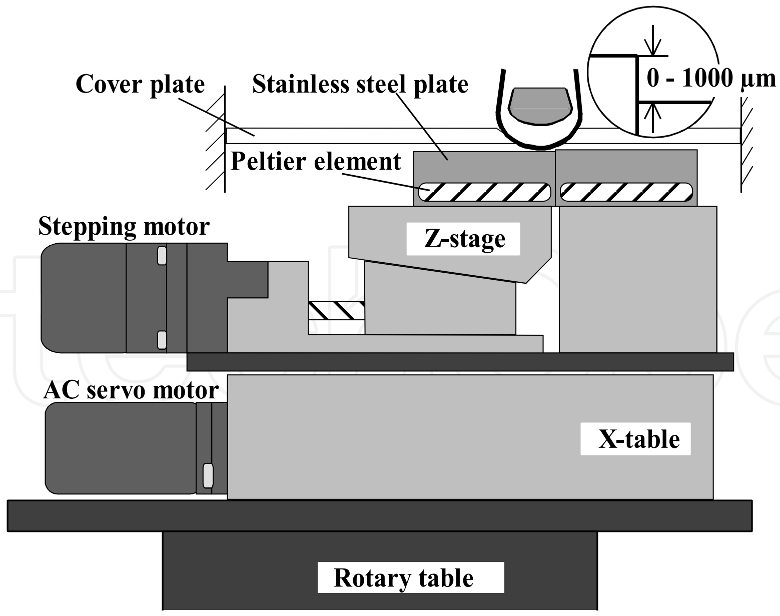

Fig. 4. Step-height presentation device.

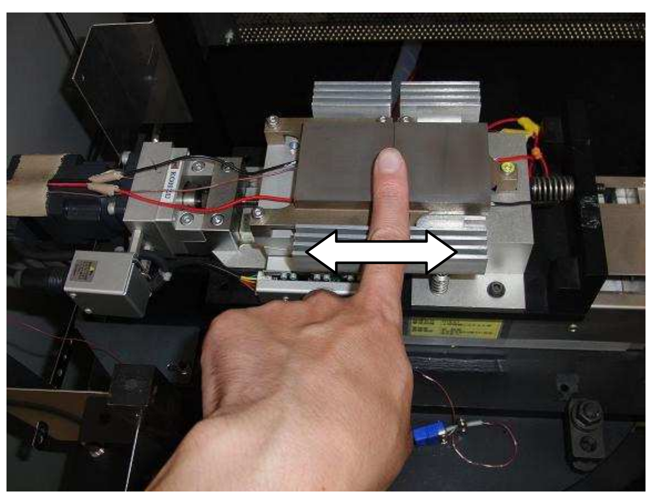

Fig. 5. Scene of psychophysical experiment of active-touch manner.

Fig. 6. Scene of psychophysical experiment of passive-touch manner.

plates vertically to control the step-height. The servo motor-driven X-table generates the presentation velocity by its reciprocating movement. The rotary table regulates the presentation angle by rotating the X table placed on it. The Peltier elements maintain, using the Peltier effect to heat or cool, the step plates' temperature by regulating the DC voltage applied to them. Here, the presentation angle of the step plates to a subject's finger is controlled as shown in Fig. 7. The motion direction of the X-table is always perpendicular to the direction of a step edge. Consequently, the presentation device is capable of presenting a fine step-height at the reciprocating velocity of 0 to 60 mm/s and the presentation angle of 0 to 180 degrees. In addition, the step plates' temperature can be controlled within the range of 8 to 50 degrees centigrade.

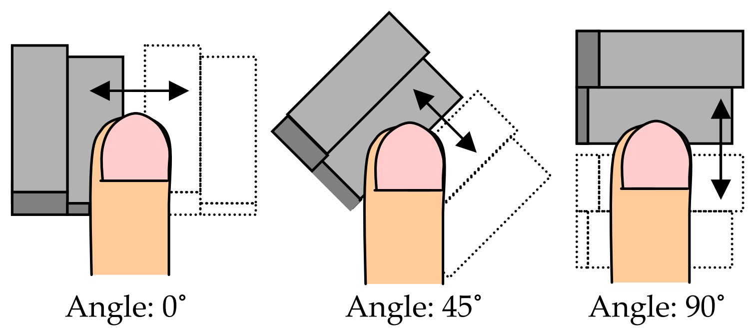

Fig. 7. Presentation angles of step.

In the psychophysical experiments using the measurement system, when the human subjects are required to judge which step-height of the presented step pair is larger, they press each of the right/left computer-mouse buttons to input the answer into the computer. The step-heights of the next trial are calculated by computer based on the PEST algorithm using the subject's answers.

In the passive-touch experiments of this paper, a cover plate with a hole like fingertip profile was installed to cover the step-height presentation device as Fig. 6 showed and the human subjects touched the step plates through the hole using their top and center of their fingertips as shown in Fig. 8. During the experiments, to prevent the sensitivity of human tactile sensation from declining, the step plates' temperature and the room temperature were kept constant approximately 37 and 26 degrees centigrade, respectively. Before the experiments the human subjects washed their hands with soap to keep them clean

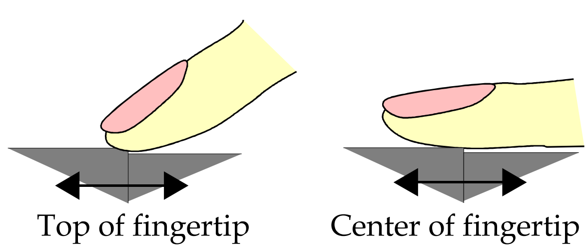

Fig. 8. Fingertip regions.

4. Experimental methods

4.1 Difference thresholds for fine step-heights in active-touch discrimination task

To measure the difference thresholds for fine step-heights in the active-touch experiments, five male subjects in their twenties of age touched and discriminated step pairs with the center of their index fingertips in active-touch manner. The subjects were allowed to touch step pairs in the 0-degree finger-motion direction as long as they wanted as choosing the motion velocity of their fingers arbitrarily. In the active-touch experiments, five step-heights of 10, 40, 70, 100 and 130 μm were used as the standard stimuli.

Table 1 shows the initial values of δ_{c1}, R_1 and R_{min} used in the PEST rules for each standard stimulus of δ_s. Each of the comparison step-heights of δ_{c1} was the value presented in the first trial block of the discrimination tasks. Also the value of P was set at 0.75 to obtain the upper thresholds. During the trials the subjects were required to press the computer-mouse button to input the answers into the computer even if they could not judge the difference between the step pair. The step-heights of the continuous trials were calculated based on the PEST algorithm using the answers and finally the upper thresholds for each standard step-height were determined.

δ_s [μm]	10	40	70	100	130
δ_{c1} [μm]	20	70	110	150	190
R_1 [μm]	3	9	12	15	19
R_{min} [μm]	0.3	0.9	1.2	1.5	1.9

Table 1. Standard step-heights and the initial values used in the PEST rules.

4.2 Difference thresholds for fine step-heights in passive-touch discrimination task

To measure the difference thresholds for fine step-heights in the passive-touch experiments, the six male subjects that had participated in the above-mentioned experiments touched and discriminated step pairs with the center of their index fingertips in passive-touch manner. The steps were moved at the reciprocating velocity of 25 mm/s and the 0-degree presentation angle using the presentation device and the subjects were allowed to touch them through the hole of the cover plate with their fingers as long as they wanted. In the passive-touch experiment, five step-heights of 10, 30, 50, 70 and 100 μm were used as the standard stimuli.

Table 2 shows the initial values used in the PEST rules for each standard stimulus. Also the value of P was set at 0.75 to obtain the upper thresholds. The discrimination tasks in the passive-touch experiment were conducted and as a result, the PEST algorithm determined the upper thresholds.

δ_s [μm]	10	30	50	70	100
δ_{c1} [μm]	20	50	80	110	150
R_1 [μm]	3	6	9	12	15
R_{min} [μm]	0.3	0.6	0.9	1.2	1.5

Table 2. Standard step-heights and the initial values used in the PEST rules.

4.3 Difference thresholds for a 10 μm step presented to the center of a fingertip at various presentation angles

To measure the difference thresholds for a 10 μm step presented to the center of a fingertip at various presentation angles, six male subjects in their twenties of age touched and discriminated step pairs with the center of their index fingertips in passive-touch manner. The magnitude of standard stimulus is 10 μm step-height and the step pairs of the standard and comparison stimuli were presented at the presentation angles of 0, 45 or 90 degrees. The steps were moved at the reciprocating velocity of 30 mm/s by the presentation device and the subjects were allowed to touch the step-heights through the hole as long as they wanted. In the passive-touch experiments, a 0-degree step of 10 μm, a 45-degree step, and a 90-degree step were used as the standard stimuli.

In the experiments, the initial values of δ_{c1}, R_1 and R_{min} used in the PEST rules were 20 μm, 3 μm and 0.3 μm, respectively. The value of P was set at 0.75 to obtain the upper thresholds. The discrimination tasks were conducted and as a result, the PEST algorithm determined the upper thresholds of the center of the subjects' fingertips.

4.4 Difference thresholds for a 10 μm step presented to the top of a fingertip at various presentation angles

To measure the difference thresholds for a 10 μm step presented to the top of a fingertip at various presentation angles, two male subjects in their twenties of age touched and discriminated step pairs with the top of their index fingertips in passive-touch manner. The step pairs of the standard stimulus of a 10 μm step and the comparison stimuli were presented at the presentation angles of 0 or 90 degrees. The steps were moved at the reciprocating velocity of 30 mm/s using the presentation device and the subjects were allowed to touch the step-heights through the hole as long as they wanted. In the passive-touch experiments, a 0-degree step of 10 μm and a 90-degree step were used as the standard stimuli.

In the experiments, the initial values of δ_{c1}, R_1 and R_{min} used in the PEST rules were 20 μm, 3 μm and 0.3 μm, respectively. The value of P was set at 0.75 to obtain the upper thresholds. As a result of the experiments, the PEST algorithm determined the upper thresholds of the top of the subjects' fingertips.

5. Experimental results and discussion

5.1 Effects of touching manner of finger

To evaluate the influence of the touching manner on the finger's fine step-height discrimination capability, the upper thresholds for the step-heights were measured in the active- and passive-touch experiments. Each human subject was tested twice for each standard step-height in the active- and passive-touch experiments and ten upper thresholds in total for each step-height were determined. Tables 3 and 4 show the upper thresholds in the active- and passive-touch experiments, respectively. At the bottoms of the tables the averages of the upper thresholds and the standard deviations are calculated.

Figure 9 describes the relationship among the touching manner, the upper threshold, and the standard step-height. The horizontal axis shows the standard step-height while the vertical axis shows the upper threshold. The threshold magnitudes of the active- and passive-touch discrimination tasks become larger as the magnitude of standard step-height increases in the range of 10 to 100 μm. It is also noticed that the threshold magnitudes for each of the step-heights are almost equal for variations of the standard step-height smaller than approximately 40 μm and that the thresholds of active-touch tasks are smaller than those of passive-touch tasks for variations of the standard step-height greater than 50 μm. The results suggest that the fingertip's tactile sense can increase the sensitivity to the step-heights by touching in active-touch manner. In addition, it could be considered that the tactile recognition module that recognizes fine step-heights of about 10 μm is different from the recognition modules for the step-heights larger than 50 μm.

Human subject	Standard step-height [μm]				
	10	40	70	100	130
A	2.7	9.2	1.8	5.9	9.4
	3.1	6.9	10.8	11.6	2.6
B	1.2	5.8	1.8	9.7	7.1
	1.9	5.8	1.8	4.1	11.6
C	4.6	4.7	13.8	13.4	7.1
	2.7	4.7	7.8	5.9	13.9
D	2.7	3.6	10.8	26.6	20.6
	4.2	10.3	12.3	13.4	16.1
E	2.7	8.1	19.8	30.9	9.4
	3.8	5.8	4.8	11.6	20.6
Ave. [μm]	3.0	6.5	8.6	13.3	11.8
SD	0.97	2.0	5.7	8.4	5.6

SD: standard deviation

Table 3. Upper thresholds for the 0-degree-presented standard step-heights discriminated using the center of an index fingertip of active-touch manner.

Human subject	Standard step-height [μm]				
	10	30	50	70	100
A	2.3	9.1	12.6	30.2	17.2
	1.9	5.4	10.3	16.8	11.6
B	0.8	6.9	8.1	4.8	9.7
	0.1	3.9	5.8	15.3	11.6
C	3.1	7.6	6.9	10.8	9.7
	1.2	2.1	4.7	3.3	9.7
D	3.8	14.4	20.4	9.3	24.7
	1.6	4.6	11.4	16.8	26.6
E	3.8	5.4	21.6	12.3	15.3
	3.8	3.1	12.6	15.3	19.1
Ave. [μm]	2.2	6.3	11.4	13.5	15.5
SD	1.3	3.4	5.4	7.1	6.0

Table 4. Upper thresholds for the 0-degree-presented standard step-heights discriminated using the center of an index fingertip of passive-touch manner.

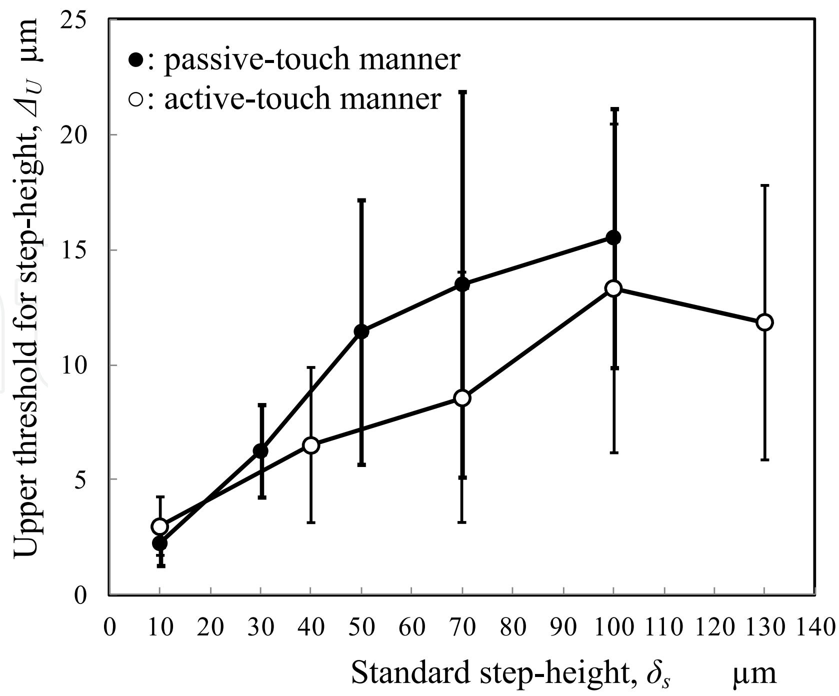

Fig. 9. Relationship among the touching manner, the upper threshold, and the standard step-height.

5.2 Effects of finger motion direction and fingertip region

To evaluate the influences of the finger motion direction and the fingertip region on the fine step-height discrimination capability, the upper thresholds for a 10 μm step-height were determined when the subjects touched the step-height presented at the presentation angles of 0, 45 and 90 degrees using the top and center of their fingertips. Here the finger's motion direction can be defined as the step's presentation angle controlled by the presentation device since it was revealed that the fingertip's discrimination capability of the step-heights of about 10 μm does not depend on the active- and passive-touch manners (Kawamura et al., 1996).

In the discrimination tasks using the center of a fingertip, each subject was tested twice for each of the standard stimuli presented at 0, 45 or 90 degrees and twelve upper thresholds in total for each presentation angle were determined, on the other hand, in the discrimination tasks using the top of a fingertip, each subject was tested four times for each of the standard stimuli presented at 0 or 90 degrees and eight upper thresholds in total for each presentation angle were determined. Tables 5 and 6 show the upper thresholds for a 10 μm step-height presented to the center and top of the subjects' fingertips, respectively. At the bottoms of the tables the averages of the upper thresholds and the standard deviations are calculated.

Figure 10 describes the relationship among the fingertip region, the upper threshold, and the presentation angle. The horizontal axis shows the presentation angle while the vertical axis shows the upper threshold. The magnitude of upper threshold measured at the center of the fingertips almost stays constant or decreases slightly for variations of the presentation angle in the range of 0 to 90 degrees. On the other hand, the magnitude of upper threshold measured at the top of the fingertips becomes smaller as the presentation angle changes from 0 to 90 degrees. It is also noticed that the upper thresholds of the top of the fingertips are smaller than those of the center and that the upper threshold for the 90-degree step presented at the top is the smallest value. Therefore, it is found that the tactile sense of the top of a fingertip is highly sensitive to a 10 μm step-height as compared with that of the center. In addition, the results point out that you can make the most of the fingertip's discrimination ability when you touch a fine step-height with the top of your fingertip moving in the motion direction of 90 degrees.

Human subject	Presentation angle [deg]		
	0	45	90
	Upper threshold [μm]		
F	3.4	2.3	6.1
	6.4	4.2	1.2
G	1.2	1.6	2.7
	4.9	3.4	1.9
H	3.8	5.3	5.7
	3.8	3.4	0.1
I	3.4	3.4	3.4
	4.2	3.8	3.8
J	3.1	2.3	1.6
	3.8	3.4	4.9
K	3.1	3.1	3.4
	2.3	3.4	2.3
Ave. [μm]	3.6	3.3	3.1
SD	1.2	0.75	2.3

Table 5. Upper thresholds for a 10 μm step-height presented to the center of an index fingertip at the presentation angles.

Human subject	Presentation angle [deg]	
	0	90
	Upper threshold [μm]	
L	1.9	0.8
	2.6	1.9
	2.6	1.5
	1.1	1.1
M	2.3	0.0
	1.1	2.3
	1.9	1.1
	3.4	1.5
Ave. [μm]	2.2	1.3
SD	0.72	0.65

Table 6. Upper thresholds for a 10 μm step-height presented to the top of an index fingertip at the presentation angles.

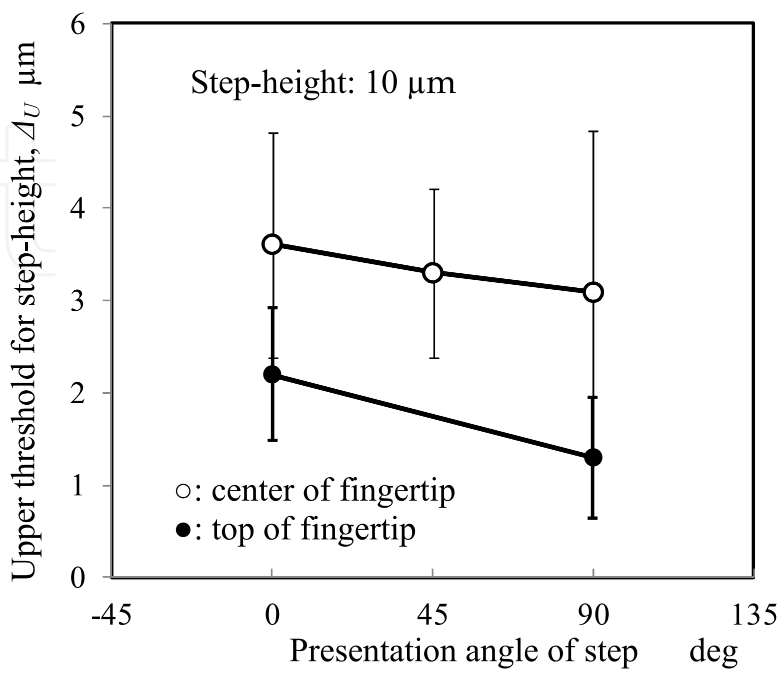

Fig. 10. Relationship among the fingertip region, the upper threshold for a 10 μm step-height, and the presentation angle.

6. Conclusion

In this study, to measure the finger's fine step-height discrimination capability the computer-controlled measurement system that presents fine step-heights of 0 to 1000 μm to subjects' fingers was developed. Using the measurement system the paper examined the effects of the touching manner of human finger, finger's motion direction, and fingertip region on the tactile recognition of fine step-heights. In the psychophysical experiments, to determine the difference thresholds and subjective equalities for fine step-heights the measurement system calculated the amounts of step-height of the step pairs by computer according to the PEST algorithm and presented the step pairs to the subjects.

First, the upper thresholds for the step-heights of 10 to 100 μm were determined in the active- and passive-touch experiments. The resulting thresholds became larger as the magnitude of step-height increased. Also the threshold of active-touch manner for each of the step-heights larger than 50 μm was smaller than that of passive-touch manner and the thresholds of the touching manners for each of the step-heights smaller than about 40 μm were almost equal regardless of the touching manners. Therefore it was found that the fingertip's discrimination ability of the fine step-heights depends on the amounts of step-height and if a step-height is larger than 50 μm, the finger's tactile sense can increase the sensitivity in active-touch manner.

Next, to investigate the effects of the finger's motion direction and fingertip region in recognizing fine step-heights, the upper thresholds for a 10 μm step-height were determined when the human subjects discriminated the pairs of step-heights presented at various presentation angles using the top and center of their fingertips. When the presentation angle of a step-height to a fingertip changed from 0 to 90 degrees, although the thresholds of the center of the fingertips almost stayed constant, the threshold for the step-height presented to the top of the fingertips at 90 degrees became the smallest value. Therefore, it was found that the tactile sense of the top of a fingertip is highly sensitive to the step-height as compared with that of the center.

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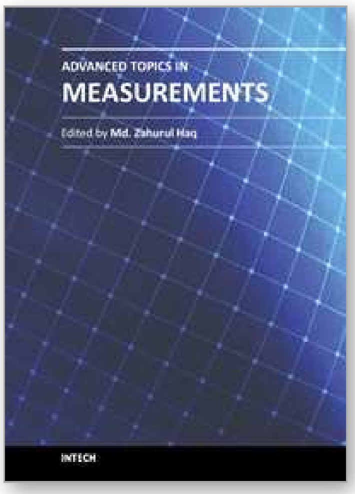

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