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Effect of Touching Manner and Motion Direction of Human Finger on Human Tactile Recognition

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Abstract*—The purpose of this paper is to investigate the effects of the touching manners and the motion directions of human finger in recognizing fine surface texture. The authors developed a measurement system to present a step-height of 10 to 1000 μm to the finger of the human subject to measure the human tactile sensation capability. The presentation device can control four parameters of the presentation, which are the step-height, the presentation velocity, the presentation angle, and the presentation temperature. Human subjects actively and passively touched and distinguished the step-heights to determine the different thresholds for step-heights. Also they passively touched and distinguished the step-heights with different motion directions of their fingers to determine the difference thresholds. As the results of the psychophysical experiments, it was found that the distinctive sensitivities of human tactile sensation in active-touch and passive-touch manners are different in discriminating between fine step-heights and that the directions of finger motion have little effect on the human tactile recognition of fine step-heights.

I. Introduction

HUMANS can detect subtle surface roughness and smoothness by touching the surface with their fingers. This human tactile sense is much more robust than the tactile sensors developed so far for robot tactile recognition. These sensors for robots still cannot recognize such fine roughness or smoothness as humans can. Therefore, it is important for engineering as well as for psychology to analyze the human tactile recognition mechanism.

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 human subject's replies to questions regarding the magnitude of stimulus.

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) [1][2]. FA II can perceive a subtle mechanical vibration. FA I or FA II can perceive a surface unevenness. SA I can perceive a pattern like Braille dots [3]. On the other hand, from psychophysical experimentations, Miyaoka et al. determined that the human tactile mechanism can detect a mechanical vibration of 0.2 μm in amplitude and a surface unevenness of 3 μm in amplitude [4][5][6]. Also, the authors found out that FA I plays an important role in discriminating magnitudes of 10 μm step-heights [7]. From these experiments, it is considered that, like the human visual sense, the human tactile sense has some kinds of module mechanisms, and it is supposed that the human tactile modules are classified into four kinds based on the magnitudes of the stimuli 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. The authors have so far been putting emphasis on the investigation of the mechanism of the fine texture recognition module.

In the previous papers [5][7], the authors determined the difference thresholds for a fine step-height of 10 μm when the human subjects actively touched fixed step-heights and passively touched moving step-heights. The difference thresholds for a 10 μm step-height in the passive-touch experiment agreed approximately with those in the active-touch experiment. Therefore, it was concluded that human capability for discriminating 10 μm step-heights does not depend on the manner in which the stimuli are touched. Also, in the subsequent paper [8], the authors concluded that when humans discriminate between two fine steps of the same height but with different velocities, they can perceive that the fast moving step-height is larger than the slowly moving step-height due to the influence of the stimulus velocity. On the other hand, the discrimination precision of the human tactile sense, which is equivalent to the sensor resolution, to discriminate between fine step-heights is scarcely affected by the difference between stimulus velocities.

In the present paper, the authors experimentally investigated the human tactile sensation capability in discriminating between the fine step-heights larger than 10 μm that had been used as the magnitude of stimulus in the previous studies and also between the step-heights presented with different presentation angles. In the first experiment, to examine the relationship between difference thresholds for step-heights in active-touch manner, human subjects actively touched and distinguished the step-heights in the range of 10 to 130 μm. In the next experiment, to examine the relationship between difference thresholds in

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passive-touch manner, they passively touched and distinguished the step-heights in the range of 10 to 100 μm that were presented at the reciprocating velocity controlled by the presentation device. In the last experiment, to evaluate the influence of the directions of finger motion, human subjects passively touched and distinguished the step-heights of 10 μm presented at the presentation angle of 0 to 90 degrees against the length of the finger controlled by the presentation device. From these psychophysical experiments, the effects of the touching manners and the motion directions of finger were investigated.

II. PSYCHOPHYSICAL EXPERIMENT

A. Subjective equality and difference threshold

Psychophysical experiment is a method to examine the relation between stimulus magnitudes and the sensitivity of human sensing mechanism. Subjective equalities and difference thresholds determined from the psychophysical experiments are important values for investigating human tactile sensation [9].

In the experiment the human subjects touch two stimuli with their fingers and try to distinguish them. One of the stimuli is the standard stimulus and the other is the comparison stimulus. The magnitudes of the standard stimulus and comparison stimulus 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 human subjects choose δ_c as stronger than δ_s is supposed to be low. Conversely, when δ_c is larger than δ_s, the proportion of the responses that human subjects choose δ_c as stronger than δ_s is supposed to be high. Figure 1 shows a characteristic curve of the proportion that a human subject chooses δ_c. The magnitudes of comparison stimulus for the proportion 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. If the standard stimulus and the comparison stimulus are presented under the same condition, the subjective equality should be equal to δ_s.

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, respectively. Moreover, the average of the upper and lower threshold, $\Delta = (\Delta_U + \Delta_L)/2$, is called the difference threshold. In addition these thresholds usually have very close values because the upper and lower thresholds measured in the same experiment are almost equal. Also the value of the ratio of the difference threshold, Δ, to the magnitude of the stimulus, 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.

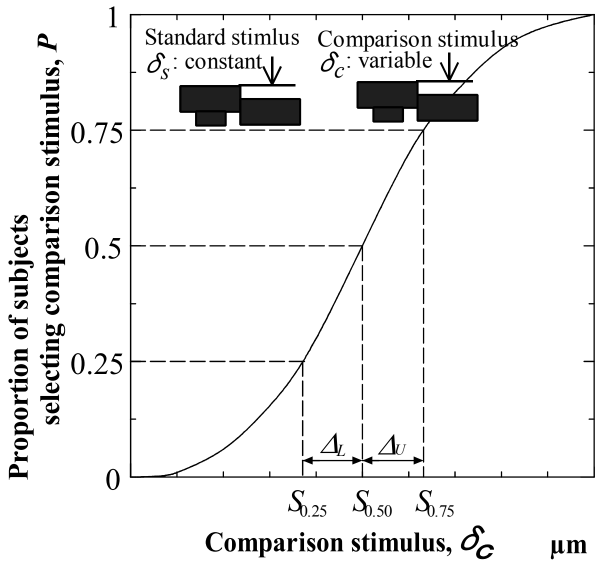

Fig. 1 An example of discrimination characteristics curve

B. PEST method

Taylor and Creelman developed the PEST (Parameter Estimation by Sequential Testing) method [10]. This is a method to determine the above-mentioned thresholds in a psychophysical experiment where the stimulus magnitude is controlled by a computer. The standard and comparison stimuli are presented in random order in each trial. The stimulus magnitude in each trial is determined based on the human subject's successive responses according to the following PEST algorithm consisting of three groups of rules.

Rule #1: Condition for changing stimulus magnitude

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 magnitude, 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 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 the comparison stimulus is varied and the trial block is incremented to the $(n + 1)$-th trial block. The comparison stimulus is decreased whenever (3) is satisfied and increased whenever (4) is satisfied. Equation (3) and (4) are given as follows:

$$E_n \leq -E_p, \quad (3)$$

$$E_n \geq E_p. \quad (4)$$

Rule #2: Incremental stimulus magnitude

The incremental width of the stimulus magnitude 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 magnitude. 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 follows:

(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 set half W_{n-1}, the incremental width in the $(n - 1)$-th trial block.
(b) If D_n and D_{n+1} are the same direction, then W_{n+1} is set 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 set 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 set 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:

$$W_n \leq W_{min} \quad (5)$$

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

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} are assumed to be 0.75, 1.0, and 0.3 μm respectively. Also, δ_s and the initial increment W_1 are presumed to be 10 μm and 3 μm, respectively. While the calculated result of (1) satisfies the condition given by (2), the human subject repeats the comparison of the standard step-height of 10 μm with the initial comparison step-height of 20 μm. Since after twelve trials the right side of (1) yields 0.75 × 12 - 10 = - 1 and the result satisfies the condition given by (3), the comparison step-height is reduced to 17 μm according to Rule #2 (incremental stimulus magnitude). 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 (4) is satisfied for a trial block with an 11 μm step-height. Therefore 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 W_n satisfies the condition of (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.

In the present paper P and E_p are 0.75 and 1.0, and W_1 and W_{min} are determined depending on experiment conditions.

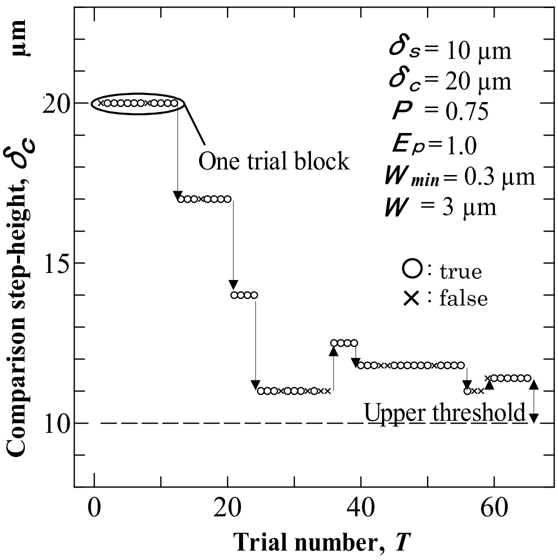

Fig. 2 An example of variation in comparison step-height calculated by the PEST algorithm

III. Measurement System

In this study, the authors developed a measurement system to present a step-height of 0 to 1000 μm to the finger of human subjects. The measurement system is shown in Figure 3. The fine step-height is formed between two fine finished stainless steel plates, and it is a stimulus magnitude. The presentation device has the capability of controlling four parameters of the presentation, which are the step-height, the presentation velocity, the presentation angle, and the presentation temperature. The first three parameters are computer controlled. The presentation device drives the wedge-shaped Z stage by a stepping motor to control the height of the step vertically, and controls the presentation velocity linearly by reciprocating movement of the servo motor-driven X-table. Moreover, the rotary table turns the X table to control the presentation angle of the step, which is always kept perpendicular to the step. The presentation device is able to present the fine step-height of 0 to 1000 μm at the reciprocating velocity of 0 to 60 mm/s at the presentation angle of 0 to 180 degrees. In addition, when human subjects can passively touch the moving fine step-height, a stainless steel plate with a hole in the center on which the fingertip is placed, similar in a size of fingertip profile, is installed to cover the step plates.

In the psychophysical experiments, the temperature of the stainless steel plates needs to be constant about 37 degrees centigrade to prevent the sensitivity of human tactile sensation from declining. In the system, the temperature of the step is controlled by regulating the DC voltage applied to the Peltier elements which, using the Peltier effect to heat or cool, maintains the stainless plates within a range of 8 to 50 degrees centigrade. In addition the room temperature was approximately 26 degrees centigrade. The human subjects washed their hand with soap to keep it clean before the experiments.

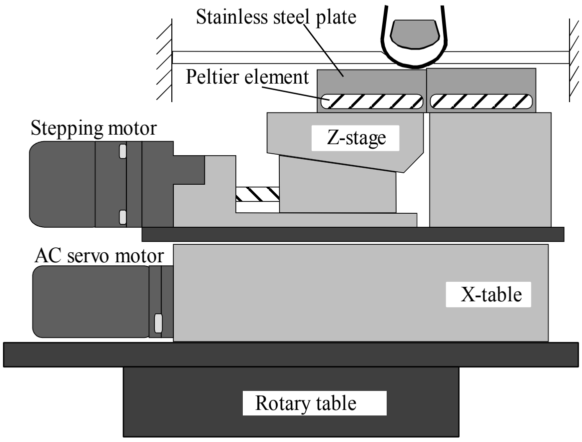

Fig. 3 Step-height presentation device

IV. EXPERIMENTAL METHOD

A. Measurement of difference thresholds in active-touching

In the previous reports, the authors determined the difference threshold in presenting the fine step-heights of approximately 10 μm to the fingers of human subjects. The aim of this experiment is to measure the difference thresholds when human subjects actively touch the fine step-heights of more than 10 μm. Five step-heights of 10, 40, 70, 100 and 130 μm were used as the standard stimulus. Six male subjects in their twenties of age actively touched the steps at the temperature of approximately 37 degrees centigrade with their index finger. They were allowed to choose arbitrarily both the motion velocity and the number of times they touched the step with their fingers.

Table 1 shows the initial values used in the PEST rules that are δ_c, W_1 and W_{min} for each standard stimulus, δ_s. Comparison step-heights for each standard step-height were presented in a trial of the PEST procedure and the subjects judged which step-height was larger. The subjects were required to press either the right button or the left button of the computer mouse to input the answer into the computer even if they were not able to judge the difference between the step-heights. The PEST algorithm based on their answer calculated the comparison step-height to be presented for the next trial. The above procedure was repeated, and as a result, one threshold for each standard step-height was determined. Consequently, the upper thresholds in active-touching were determined.

Table 1 Standard stimulus and the initial values used in the PEST rules

δ_s [μm]	10	40	70	100	130
δ_c [μm]	20	70	110	150	190
W_1 [μm]	3	9	12	15	19
W_{min} [μm]	0.3	0.9	1.2	1.5	1.9

B. Measurement of difference thresholds in passive-touching

In the above experiment the thresholds in active-touching were determined. The aim of this experiment is to measure the difference thresholds when human subjects passively touch the fine step-heights larger than 10 μm. Five step-heights of 10, 30, 50, 70 and 100 μm were used as the standard stimulus. Six male subjects in their twenties of age passively touched the steps at the temperature of approximately 37 degrees centigrade with their index finger. The steps were moved at the reciprocating velocity of 25 mm/s by the presentation device, and then the human subjects were allowed to touch them through the hole on the plate with their fingers as long as they wanted.

Table 2 shows the initial values used in the PEST rules that are δ_c, W_1 and W_{min} for each standard stimulus, δ_s. Comparison step-heights for each standard step-height were presented in a trial of the PEST procedure, and the procedure like the above active-touch experiment was repeated, and as a result, one threshold for each standard step-height was determined. Consequently, the upper thresholds in passive-touching were determined.

Table 2 Standard stimulus and the initial values used in the PEST rules

δ_s [μm]	10	30	50	70	100
δ_c [μm]	20	50	80	110	150
W_1 [μm]	3	6	9	12	15
W_{min} [μm]	0.3	0.6	0.9	1.2	1.5

C. Measurement of difference thresholds in passive-touching with different directions of finger motion

The authors assume that the motion direction of finger has an influence over the human tactile sensation capability when humans discriminate the fine step-height. To clarify this assumption, the aim of this experiment is to evaluate the influence quantitatively.

Step-heights of 10 μm with three different presentation angles were used as the standard stimulus. The motion directions of finger were defined as the presentation angle of the step against the length of the finger. The three angles were 0, 45 and 90 degrees clockwise as shown in Figure 4. The movement of the step is perpendicular to this angle.

Six male subjects in their twenties of age passively touched the steps at the temperature of approximately 37 degrees centigrade with their index finger, and then judged which step-height of the pair that has the same angle, 0, 45, or 90 degrees, was larger. The steps were moved at the reciprocating velocity of 30 mm/s by the presentation device. The human subjects were allowed to touch the step-heights with their fingers as long as they wanted.

In this experiment, δ_c, W_1 and W_{min}, the initial values used in the PEST rules, were 20 µm, 3 µm and 0.3 µm, respectively. The step-heights were presented in a trial of the PEST procedure, and the procedure like the above experiment was repeated, and as a result, one threshold for each presentation angle was determined. Consequently, the upper thresholds for 10 µm presented in passive-touching with different presentation angles were determined.

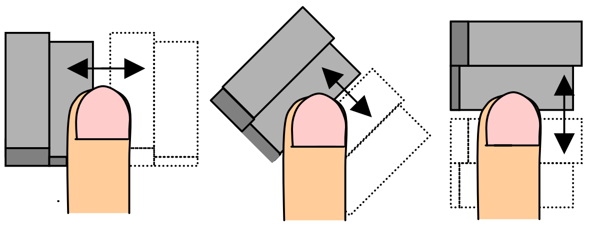

Fig. 4 Presentation angles of the stimulus

V. Experimental results and Discussion

A. Effect of the touching manner of finger on human tactile recognition

The upper thresholds for discriminating between step-heights were determined in the active-touch and passive-touch experiments. Each human subject was tested twice for each standard step-height to determine ten upper thresholds in total. Table 3 and 4 show the averages of the upper thresholds for each human subject in the active-touch and passive-touch experiments. In addition, the upper thresholds of human subject F in the passive-touch experiment were excluded because they were remarkably separated from the averages of the other upper thresholds.

The authors have previously reported that the thresholds for δ_s = 10 µm in the active-touch and passive-touch manners are in the range of 2 to 3 µm. In the present experiment the averages of thresholds for δ_s = 10 µm calculated from the values in Table 3 and 4 are 2.9 µm in the active-touching and 2.2 µm in the passive-touching, and they are almost equal to the previously reported values. Therefore, we confirmed that the measurement system could measure the thresholds precisely in these experiments.

Figure 5 demonstrates the relationship between the upper thresholds and the standard step-height in the active-touch and passive-touch experiments. The horizontal axis shows the magnitudes of standard stimuli while the vertical axis shows the upper thresholds. The upper thresholds for the step-heights in the range of 10 to 100 µm become larger as the magnitude of standard stimulus increases. It is also noticed that the upper thresholds in the active-touching and passive-touching are almost equal for variations smaller than approximately 40 µm and that the upper thresholds in the active-touching are smaller than those in the passive-touching for variations larger than 50 µm. Now we can say that humans try to increase the sensitivity of the human tactile sensation by actively touching the step-heights. Also we might say that the tactile recognition module that recognizes the fine step-height of about 10 µm is different from the module for the step-height larger than 50 µm.

Table 3 Upper threshold in active-touching

Human subjects	Standard stimulus [µm]				
	10	40	70	100	130
A	2.9	8.1	6.3	8.8	6.0
B	1.6	5.8	1.8	6.9	9.4
C	3.6	4.7	10.8	9.7	10.5
D	3.4	6.9	11.5	20.0	18.4
E	3.3	6.9	12.3	21.3	15.0
F	2.7	7.5	6.8	17.2	21.8
Ave. [µm]	2.9	6.7	8.3	14.0	13.5

Table 4 Upper threshold in passive-touching

Human subjects	Standard stimulus [µm]				
	10	30	50	70	100
A	2.1	7.3	11.4	23.5	14.4
B	0.4	5.4	6.9	10.0	10.6
C	2.1	4.6	5.8	7.0	9.7
D	2.7	9.5	15.9	13.0	25.6
E	3.8	4.3	17.1	13.8	17.2
F	13.2	44.8	28.3	29.5	24.7
Ave. [µm]	2.2	6.2	11.4	13.5	15.5

The averages are excluding F.

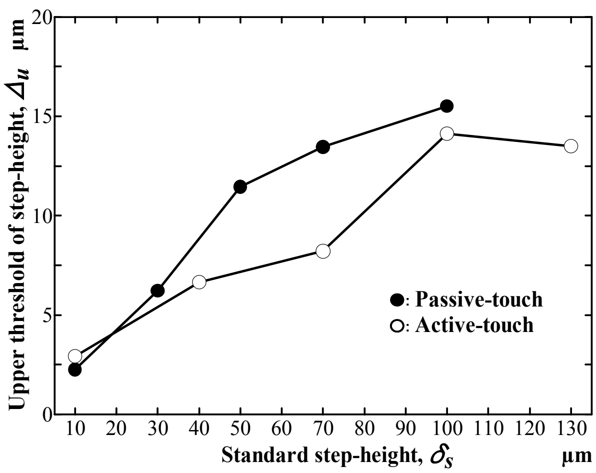

Fig. 5 Upper threshold in active-touch and passive-touch

B. Effect of the direction of finger motion on human tactile recognition

The upper thresholds for the step-height of 10 μm passively presented at the angle of 0, 45, or 90 degrees were determined. Each human subject was tested twice in each motion direction of the finger to determine six upper thresholds in total. Table 5 shows the averages of the upper thresholds for each human subject in each motion direction of finger. Figure 6 also shows the relationship between the upper thresholds and the motion directions of finger. The horizontal axis shows the motion directions of finger while the vertical axis shows the upper thresholds.

The upper thresholds for variations in the motion direction of finger of 0 to 90 degrees are almost constant. Therefore, it was found that the discrimination precision of human tactile sense of 10 μm step-height stays constant regardless of the finger motion. Now we can say that the finger motion has little effect on the tactile recognition of fine step-heights about 10 μm.

Table 5 Upper threshold and motion direction of finger

Human subjects	Finger motion direction [deg]		
	0	45	90
A	4.9	3.3	5.1
B	3.1	2.5	2.3
C	3.8	4.4	2.9
D	3.8	3.6	3.6
E	3.4	2.9	3.3
F	2.7	3.3	2.9
Ave. [μm]	3.6	3.3	3.4

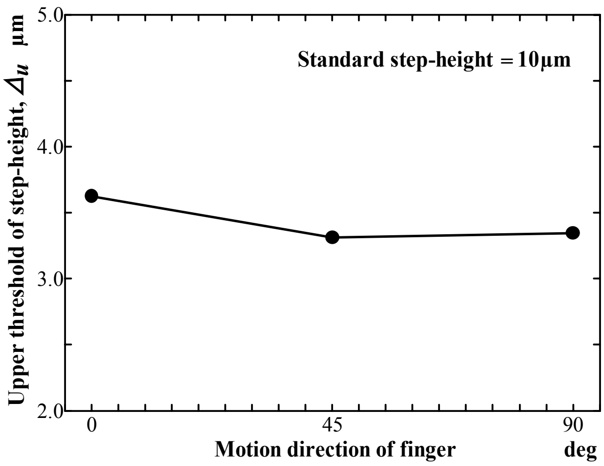

Fig. 6 Relationship between upper threshold and motion direction of finger

VI. CONCLUSION

In this paper, the difference thresholds of fine step-height were measured in psychophysical experiments. The effects of the touching manners of finger and the directionality of finger motion on the ability of the human tactile sense in discriminating the subtle surface roughness were examined quantitatively.

First, the upper thresholds for discriminating between step-heights of 10 to 100 μm in the active-touch and passive-touch experiments were determined. The resulting thresholds become larger as the magnitude of step-height increases. Moreover, for the step-heights larger than 50 μm, the upper thresholds in active-touching were smaller than those in passive-touching. Therefore it was found that the distinctive sensitivity of human tactile sensation in active-touch manner is higher than in passive-touch manner in discriminating between step-heights larger than 50 μm.

Next, the upper thresholds for a 10 μm step-height were determined when human subjects discriminated between the step-heights presented with the different angles. It was found that the upper thresholds are almost constant for variations of the presentation angle. Therefore, the authors concluded that the directions of finger motion have little effect on the discrimination precision of human tactile sense of fine step-heights about 10 μm.

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