Proposal of Tactile Inspection Conditions for Valid Defects Detection Focusing on Haptic Perception with Active Touch

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Abstract. Tactile inspection is a task for detecting minute irregularities of several tens of micrometers and is one of the tasks performed by human senses. However, the detection of defects in tactile inspection has not been evaluated quantitatively. Therefore, this study aims to examine the factors that affect the detection of defects in tactile inspection by focusing on the haptic perception with active touch and to propose inspection conditions for the valid detection of defects based on the experimental results. Specifically, defect height, defect size, and the control force applied by the subject are used as the experimental factors, and their effects on the detection of defects are examined. Moreover, it was found that the detection rate increases with the increase of the defect features and that the strengths of the effect on the detection rate are in the order of defect height, defect size and control force of the subject. Based on the above, we proposed that tactile inspection is effective in detecting defects with heights greater than 15 μm and that the control force of approximately 7.0 N is suitable for defect detection.

Keywords: tactile inspection, haptic perception, detection sensitivity, active touch

1. INTRODUCTION

Automation of tasks in industrial manufacturing is now advancing continuously. Similar advances have also occurred in the inspection process, such as the automatic visual inspection by image processing technology. However, due to the complexity of the object shape and the shortening of the product life cycle, work by humans is still essential in the inspection process. Tactile inspection is one example of this type of human inspection that is used for detection of molding defects, dents, and convex defects caused by coating of foreign matter such as dust and is performed by touching the surface of a product.

The most important goal in the inspection process is to detect defective products; therefore, it is necessary for the inspectors to maintain high inspection accuracy. Unfortunately, due to the maintenance of working posture for long hours and the repetition of the inspection operations, tactile inspection gives rise to risks of upper limb disorder and a lowering of inspection accuracy. Thus, to decrease the upper limb load in tactile inspection, the effects of object orientation and the direction of wrist joint have been investigated in the previous study (Yukinawa *et al*., 2013, 2014).

Tactile inspection is also used for detecting minute irregularities of several tens of micrometers (Sano *et al*., 2005); however, a long time is required to acquire the skill necessary for this type of inspection. This leads to a problem of uneven inspection results caused by the difference in the skill of the inspectors. In one example, the inspectors detect the defects based on the subjective decision of whether they feel as lack of uniformity by touching softly. The need to reduce the skill difference between the inspectors has motivated the development of a haptic device that amplifies the tactile stimuli and the study of factors affecting the inspection accuracy (Sano *et al*., 2005). A "tactile contact lens" has been developed on the basis of the mechanism that the leverage by the stockinette stitch of cotton work gloves enhances the perception of minute irregularities. Furthermore, Kleiner (1987) has revealed that the crack detection rates of novice and experienced inspectors were affected by crack width, probe-tip diameter and the contribution of vision.

In tactile inspection, a defective product is distinguished from a good product by actively touching the product. Therefore, it is necessary to focus on human tactile perception in order to investigate the detection of defects in tactile inspection. Tactile perception is classified as passive touch and active touch. Passive touch is the sense obtained by touching something without intentional motion (Ooyama *et al*., 1994). The stimulus threshold of passive touch is approximately 6 to 7 μm in the ball of the finger (Lindblom, 1976). Conversely, active touch is the sense obtained by searching actively (Ooyama *et al*., 1994). In a general tactile inspection, irregularities of the surface of the product are detected with active touch. Nevertheless, few studies have focused on the features of active touch in tactile inspection.

Therefore, this study aims to examine the factors that affect the detection of defects in tactile inspection by focusing on active touch. Specifically, we conduct experiments considering the convex heights and the sizes of the defects and the control force of the subjects as the experimental factors and examine their effects on the detection of defects. Furthermore, based on the experimental results, we aim to propose the valid inspection conditions for the detection of defects.

2. EXPERIMENT

2.1 Experimental task

As the experimental task, the subjects were asked to inspect an object by touching it with the tips of the fingers of the right hand fingertips without using the thumb and in the sitting posture in order to distinguish whether the object has a defect. Laminated paper with dimensions of 240 × 420 mm^2 and a thickness of 180 μm shown in Figure 1 was used as the inspection object. Convex defects are created by cutting thin films out in a circle and inserting them between the papers and the laminate films. This allows us to reproduce minute convex defects caused by painting over dust in the painting process, as defect models with minute convex height. The defect is located in a central location in squares A, B, or C with dimensions of 40 × 60 mm^2 on the inspection object. In addition, an inspection object without defects was created.

The subjects touched from the start point to the end point of the inspection object for approximately 5 s. Then, if the subjects detected the defect, they chose the location of the defect from among squares A, B, or C. If the subjects did not detect the defect, they declared the object to be defect-free. The experimental layout is shown in Figure 2.

2.2 Experimental factors

2.2.1 Convex height of the defects

Using the results of a preliminary experiment designed based on the previous study, three different convex heights were chosen. It was clarified that it is difficult to detect the defects with heights smaller than 5 μm. Therefore, the convex heights of the defects were 10, 15, and 20 μm.

2.2.2 Defect size

The defects were circular, and their size was defined by the diameter. A preliminary experiment using four subjects found that there was no difference in the detection rate of defects with diameters larger than 4.5mm. Therefore, three different diameters of 1.5, 3.0, and 4.5 mm were used.

With respect to the defect shape, there are various types of defects such as scratches and dents in manufacturing industries. However, when the defect size become small, the defect shape does not need to be considered and all defects can be summarized as circles (points). The defect shape was fixed as a circle because this experiment targeted defects that were small and difficult to detect. However, additional consideration is necessary regarding the effects of the defect shape on the detection rate.

2.2.3 Control force of the subjects

The control force was defined as the power that the subject applied to the inspection object in a vertical direction. In the preliminary experiment comprising four subjects, it was clarified that the control force required for the detection of a defect with small features is approximately 3.0 N and the control force required for the detection of a defect with large features is approximately 11.0 N. Furthermore, measurements of any control force of the subjects performed in the previous study found that the control force applied by the subjects is 7.0 N on the average (Yukinawa *et al*., 2013, 2014). Therefore, three different control force magnitudes of 3.0, 7.0, and 11.0 N were used.

In addition, the control forces of the subjects in this experiment were measured by the load cell (WEF-6A500-10-RC5, WACOH-TECH Inc.) attached to the back of the inspection object.

2.3 Experimental procedure

Ten male graduate and undergraduate students were used as the subjects in this experiment. The mean and standard deviation for the age, height, and body weight of the subjects were 21.7 ± 1.6 years, 172.1 ± 4.7 cm and 65.7 ± 9.8 kg, respectively. Prior to the experiment, the subjects received a sufficient explanation of the overall goals and the method of the experiment and then practiced to familiarize themselves with the experimental task.

In this experiment, the experimental tasks were repeated five times for ten conditions: nine conditions for the defect features (the convex heights of three levels and the sizes of three levels) and a condition without the defects for each of the three levels of the control force. Therefore, the total of 150 tasks experimentally performed by each subject. In addition, to eliminate the effect of the order, the orders in which the samples with different conditions were examined were randomized for each subject.

The detection rate of the subjects in the experiment was calculated according to equation (1) for each feature of the defects and was used as an evaluation index.

$$\text{detection rate[\%]} = \frac{\text{the number of detected defects}}{\text{the number of defects with same feature}} \times 100 \qquad (1)$$

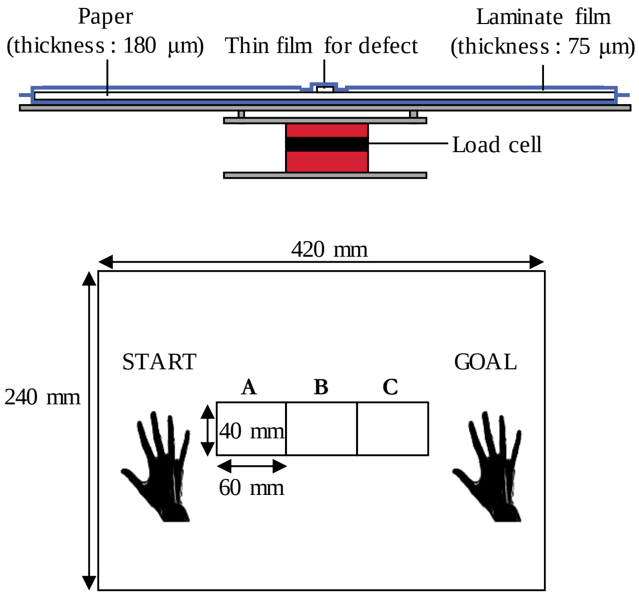

Figure 1: Inspection object

Figure 2: Experimental layout

3. RESULTS

3.1 Experimental results for the feature quantity of the defects

First, the detection rates for each convex height of the defect are shown in Figure 3. Analysis of variance found significant differences in the main effect of the convex height of the defects. Moreover, as a result of the multiple comparisons (Bonferroni’s test) as the subeffect test, it was found that the results for 10 μm differed significantly from the results for 15 μm and 20 μm. This indicates that the detection rate varies with the convex height of the defects.

Second, the detection rates for each size of the defect are shown in Figure 4. Analysis of variance found significant differences in the main effect of the defect size. Moreover, as a result of the multiple comparisons (Bonferroni’s test) as the subeffect test, significant differences were observed among all levels of the defect size. This indicates that the detection rate varies with the defect size.

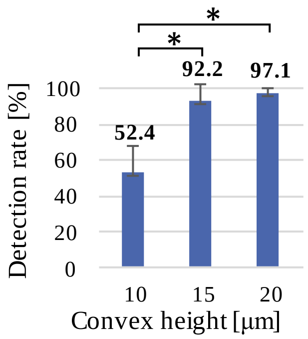

Figure 3: Detection rate for each convex height of defect

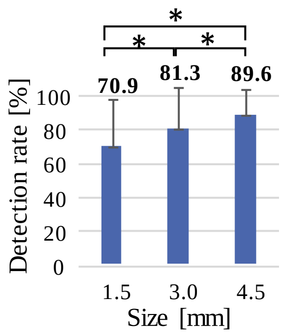

Figure 4: Detection rate for each size of defect

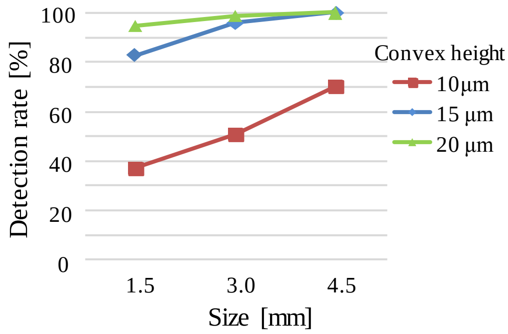

Figure 5: Relationship between convex height and size

Table 1: Mean values for each level of control force of subjects [N]

		subject 1	subject 2	subject 3	subject 4	subject 5	subject 6	subject 7	subject 8	subject 9	subject 10
3.0 N	A	2.93	3.23	3.24	3.37	2.84	2.85	3.11	3.19	2.47	3.26
	B	3.23	2.84	3.31	3.58	2.73	2.75	3.10	3.11	2.41	3.18
	C	3.39	2.79	3.24	3.53	2.55	2.57	3.21	3.14	2.36	3.24
7.0 N	A	6.56	7.17	6.75	6.73	6.99	7.50	6.87	6.80	6.50	6.97
	B	7.11	7.03	6.98	7.06	6.99	7.29	7.29	7.02	6.77	7.15
	C	7.52	6.83	6.94	7.35	6.95	6.98	7.48	6.99	6.88	7.27
11.0 N	A	11.15	11.40	10.62	11.06	11.11	10.77	10.66	10.45	11.21	11.13
	B	11.38	10.93	10.78	11.52	10.92	10.72	10.56	10.53	11.39	11.22
	C	11.33	10.67	10.79	11.80	10.69	10.46	10.43	10.63	11.74	11.21

Third, the relationship between the convex height and the defect size is shown in Figure 5. It was found that the detection rate increases with the increase of the defect characteristics such as the height and the size. Moreover, for the increase in the size of the defects with lower heights, the change in the detection rate tends to increase. In other words, this indicates that the effect of a change of the defect size has on the detection rate varies depending on the convex height of the defects.

3.2 Experimental results for the control force of the subjects

The mean values for each level of the control force of the subjects are shown in Table 1. It was found that the mean values of the control force of each subject are controlled within a range of ± 1 N from each level of the control force.

Additionally, the detection rates for each control force of the subjects are shown in Figure 6. Analysis of variance shows significant differences in the main effect of the control force of the subjects. Moreover, as a result of the multiple comparisons (Bonferroni's test) as the subeffect test, the result for 3.0 N were shown to differ significantly from the results for 7.0 and 11.0 N. This indicates that the detection rate varies with the control force of the subjects.

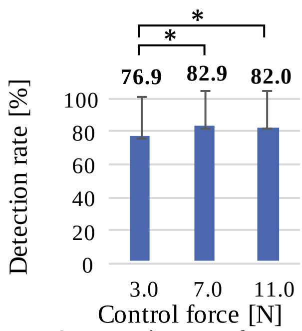

Figure 6: Detection rate for each control force of subjects

4. DISCUSSION

4.1 Effects of each experimental factor on the detection rates

First, we examine the effects of the change of the convex height of the defects on the detection of the defects. The experimental results indicate that the detection rates for the convex height of 10 μm were significantly lower, whereas the detection rates for 15 μm were not significantly different from those of 20 μm. The mechanical stimuli received in tactile organs can be represented as a deformation of the skin (Nakatani *et al*., 2016). Furthermore, it is considered that the skin is dented in the direction vertical to the object by touching the object with convex height. Therefore, it appears that the experimental results described above are due to the deformation of the skin by the change of the convex height (that is, the stimulus amount to the skin) reaching a threshold value.

Second, we examine the effects of the change of the defect size on the detection of the defects. Significant differences were observed among all levels of the defect size and detection rate tended to increases with increasing diameter. It is considered that the deformed area of the skin changes with the changes of the defect size. In addition, the Meissner corpuscle and the Merkel cell receiving the mechanical stimulus exhibit three characteristics: 1) they are distributed at a high density in the tip of the finger. 2) their receptive fields are small circles with diameters of approximately 2–4 mm. 3) their sensitivity is sharply lower in the outside of the receptive field (Ooyama *et al*., 1994) (Katou *et al*., 2007). Therefore, if the deformed area is small because the size of the defect is small, the number of the receptors that are fired with the deformation of the skin decreased. This appears to result in a low detection rate.

Finally, we examine the effects of the change of the control force of the subjects on the detection of the defects. A previous study has shown that the contact area of the object and the skin increases with the increase of the control force applied to the object (Fujita *et al*., 2000). Similarly, in this experiment, it was found that the contact area of the defect and the skin increased with increasing the control force. Therefore, the number of the receptors that are fired with the deformation of the skin increased and the detection rate also increased. Furthermore, it was found that the detection rate for the control force of 3.0 N was significantly lower. The previous study indicated that the contact area of the object and the skin increases with increasing the control force. However, the increase was logarithmic rather than constant. Therefore, for the control force of more than 7.0 N, the observed difference between the detection rates became small because of the decreasing rise in the contact area.

4.2 Valid tactile inspection conditions for defects detection

4.2.1 Effect of experimental factors on detection rate

It was found experimentally that the detection rate varies with the defect characteristics and the control force of the subjects. However, to propose suitable tactile inspection conditions for the detection of defects, it is necessary to consider the extent to which each experimental factor affects the detection rate. Therefore, to examine the extent to which defect characteristics and the control force of the subjects affect the detection rate, a multiple regression analysis was performed. The independent variables were the convex height of the defects, the size of the defects, and the control force of the subjects; the dependent variable was the detection rate. The resulting standard partial regression coefficients of each independent variable are shown in table 2. The values range in decreasing order from the convex height of the defects, to the size of the defects, and finally to the control force of the subjects. In other words, the convex height of the defects has the greatest effect on the detection rate. Moreover, the regression equation obtained by the multiple regression analysis is shown in (2). It can be seen that the detection rate rises with increases in the quantitative features of the defects and the control force of the subjects.

Table 2: Standard partial regression coefficients of each independent variable

independent variables	partial regression coefficients	standard partial regression coefficients
size of defects [mm]	5.4614	0.2116
convex height of defects [μm]	4.1243	0.7665
control force of subjects [N]	0.3892	0.0359

Adjusted $R^2 = 0.9823$

$$\begin{aligned}&\text{detection rate}[\%] = \\ &+4.1243 \times \text{convex height of defects} \\ &+5.4614 \times \text{size of defects} \\ &+0.3892 \times \text{control force of subjects}\end{aligned} \tag{2}$$

4.2.2 Proposal for valid inspection conditions

The factors that affect the detection of defects can be classified into those related to defect characteristics and those related to the inspectors. Here we propose the valid tactile inspection conditions for the detection of defects for each factor on the basis of the experimental results.

First, the factors related to defect characteristics are discussed. From the experimental results, it is seen that the detection rate rises with increases in the quantitative defect characteristics. In particular, as seen from the multiple regression analysis results, the convex height of the defects has the greatest effect on the detection rate. Specifically, because the detection rate for convex heights greater than 15 μm is relatively high, tactile inspection is considered to be effective for such defects. In addition, because the experimental results show that the detection rate rises with increasing defect size, tactile inspection is considered to be effective for relatively large defects.

Second, the factors related to the inspectors are discussed. From the experimental results, it is seen that the detection rate with a control force of 3.0 N is lower than those with control forces of 7.0 and 11.0 N. Therefore, since the detection rate decreases when in sufficient tactile force is applied to the inspection object, it is desirable to use a tactile force of approximately 7.0 N. Moreover, there is a need to consider both the change in detection rate when the control force further, and the muscle load of the inspectors when the control force is excessive.

5. CONCLUSION

This study examined the factors that affect the detection of the defects in tactile inspection by focusing on the haptic perception with active touch. Specifically, experiments with defect height, defect size and control force of subjects as the experimental factors for the tactile inspection task were performed. In addition, based on the experimental results, we proposed inspection conditions for valid detection of the defects in tactile inspection. In particular, we classified the factors that affect the detection of the defects in tactile inspection based on the defect characteristics and based on the inspectors. Moreover, we proposed conditions for valid inspection for each factor.

However, in the actual tactile inspection process, it is common to inspect by using the entire palm of the hand rather than only using the part of the hand as in this study. Furthermore, in this study, the arrangement of the defects was not considered. Consequently, to apply the inspection conditions proposed in this study to the actual inspection process, it is necessary to add the extra experimental factors in the consideration of the actual inspection environments.

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