Control strategies in human pinch motion to detect the hardness of an object

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ABSTRACT

Human pinch is a motion to perceive an object's hardness as well as a motion to hold an object. Numbers of studies have been carried out on human pinch motion to understand how human applies force to maintain an object against gravity using friction. However, no study has been performed to analyze the pinch motion for the hardness detection of an object. The understanding of the hardness detecting pinch motion is expected to help developing artificial reality devices.

In this study, the applied force, finger displacement and contact area were measured in the pinch motions with five different objects. The objects were transparent to allow the contact area analysis, and with the same texture by putting polyvinyl film on them. Two of the objects were made of gelatin and the three were made of silicon rubber. Ten volunteers were required to answer the harder object from the two different objects presented in sequence without visual information. The task was repeated five times for each object in random sequence. The pinch motion for the first object was analyzed. The applied force, finger displacement and contact area were normalized by each maximal value.

The applied force to the harder object was higher as expected. The difference of the applied force between the hard and the soft object was 84%. The difference of the displacement was 91%. In contrast to them, the difference of the contact area was 26%. The first finding in this study was that the contact area is almost constant despite of the hardness difference in the pinch motion to perceive the hardness.

The next question was how human controls contact area constant without sensing the hardness in advance. The slopes of the force, the displacement and the contact area were analyzed. The calculated values showed the same tendency as the peak value. It suggests that the control of the contact area is attained without feedback mechanism. The equilibrium point hypothesis was introduced into this experiment. The imaginary displacement was calculated with the measured fingertip and the object hardness. The difference of the imaginary displacement was 29%. It appeared that human pinches object with equilibrium point tactics to perceive the hardness of the object.

1. INTRODUCTION

"Precision grip" has been studied, which is a pinch motion using thumb and index finger to hold a small object. Johansson et al (1984) investigated the effect of the tactile information on precision grip [1]. Kinoshita et al (1997) studied the effect of the tangential torque [2]. The objective of these studies was to understand the mechanism of the precision grip to hold or pick up an object. The main interest was to understand how human controls the grip force to obtain the adequate friction force for holding the object against gravity.

On the other hand, the pinch motion has another functional role that is the detection of the hardness of an object. It is required to display hardness by controlling the reflection force against finger pads in the field so-called virtual reality of tele-existence [3,4]. Understanding the human pinch motion to detect the hardness is required to develop the hardness display devices for those applications.

Few studies have been performed on the pinch motion with an elastic object. Mai (1991) reported the pinch force error while a subject pinched two objects having different hardness with both hands [5]. Van Doren (1995) explained the mechanism of that error using equilibrium-point model [6]. However, the task in these studies was to pinch an object at required force, not to perceive the hardness of an object.

The hardness is perceived by sensing both the applied force and the deformation of the object, while the deformation is sensed from the change of the fingertip pressure and the finger span. That means the hardness detection is an "active sensing" task which is based on the pinch motion. Therefore, it is important to understand the control strategy of the pinch motion, in order to clarify the mechanism of the hardness perception. Regarding to the study on the analysis of the human pinch motion for hardness perception, the hardness judgement experiment [7] was performed by Srinivasan (1995) to evaluate the role of the tactile and kinesthetic informa-

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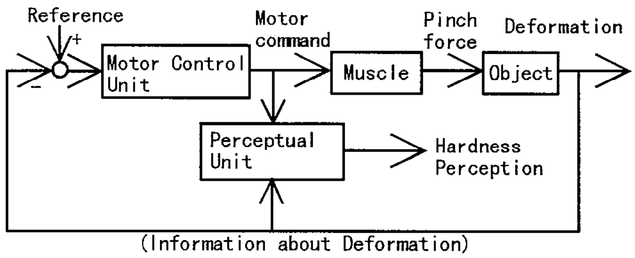

Figure 1 Model of the hardness cognition in pinch motion.

tion. No study has been performed on the pinch motion itself.

This study was planed to reveal the control strategy in human pinch motion for hardness detection. The pinch force, finger displacement and fingertip contact area were measured during the hardness judgement tasks. This paper describes the "constant contact area hypothesis" arose from the experimental results, and describes that experimental results by using "equilibrium point model" proposed by Feldman [8].

2. MODEL OF HARDNESS COGNITION

Hardness can be defined as the ratio between the deformation and the applied force. It is required to sense both informations in order to recognize the hardness. The force can be sensed as the "efferent copy" of the motor command in addition to the skin receptor information. The deformation of the object can be perceived as the somatosensory information from muscle afferents and as the tactile information from the skin receptors.

In addition to these signal pathways, it is obviously necessary to control the pinch force, because the hardness detection is an "active sensing" task. A model of hardness cognition as shown in figure 1 was assumed. This model is based on the idea of feedback control. It is desirable to apply higher force as much as possible within the object's limitation, in order to detect the hardness with accuracy. If the same force is applied to a soft object and a hard object, the soft object might be broken or the hardness of the hard object can not be exactly detected. However, human controls the force with the hardness of the object. The question was how human manages the pinch force with the object's hardness. Therefore, the feedback mechanism was occupied in the initial model.

The question is what is the reference input as the information about the object deformation. Because the reference input is independent from the object, the deformation information, which is equal to the reference input, will be a signal that is not affected by the hardness of the object. The experiments were conducted to discuss the essential information in the hardness perceiving pinch motion.

3. MATERIALS AND METHOD

Experimental system

An experimental system shown in figure2 has been developed to measure the pinch force, the thumb displacement and the contact area during the pinch motion. The pinch force was detected by the two strain gauges on the steel plate on which the specimen was attached. The thumb displacement was measured as the displacement of the string which was glued on the thumbnail. The images of the contact area were recorded by a CCD camera and a VCR. The recorded images were sampled as a 512 x 512 bit map images using a video-input board. The contact areas were computed after the images were converted into binary images at every sample time. The resolution of the contact area in the utilized condition was 0.012 square-millimeters.

The experimental specimens were three silicon rubbers and two gelatins that are highly transparent. The specimens were cut in a cylindrical form with 48mm diameter and 10mm height. A vinyl chloride film was placed on the specimens to unify the textures of

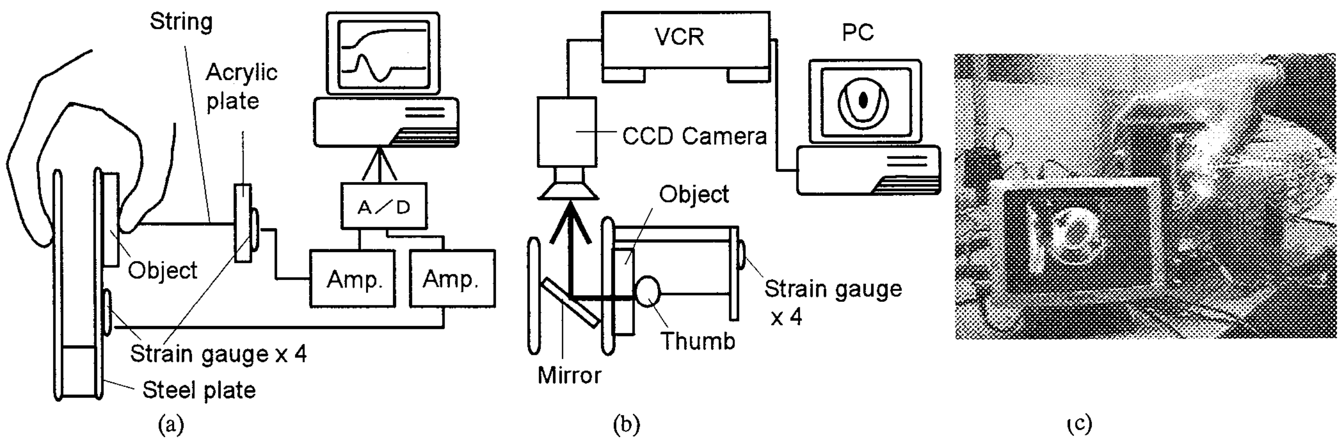

Figure 2 Experimental system to measure the pinch force, thumb displacement and contact area during pinch motion. (a) side view, (b) top view, (c) set-up.

the specimens. The finger span between the thumb and the index finger was 60mm.

The hardness of the specimens were defined as the ration of the force and the displacement while a 13mm diameter cylinder was pressed to the objects. The hardness of the specimens were 21, 100, 690, 2070, 5280 g/mm.

Experimental conditions

Ten male volunteers, ages 21-24 years, were requested to answer the harder object from the sequentially presented two specimens. In each trial, the subject was required to pinch the object twice. One additional trial was allowed on the subject's request. The all combinations of the hardness, including the same hardness, were examined five times at random sequence. Therefore, the measurement was performed 100 times per subject. The subjects answered the harder objects correctly in all trials. The visual information was not provided. The following results and the discussions are about the first specimen, because some subjects did not complete the pinch motion in the second specimen especially the hardness was obviously different.

Measured indexes

An example of the measured pinch force, thumb displacement and the contact area are shown in figure 3. The peak values were calculated for both the first and the second pinch.

Because the thumb displacement includes both the thumb deformation and the object deformation, the object deformation was calculated from the object hardness property measured in advance and the applied force. The peak values were averaged for each specimen.

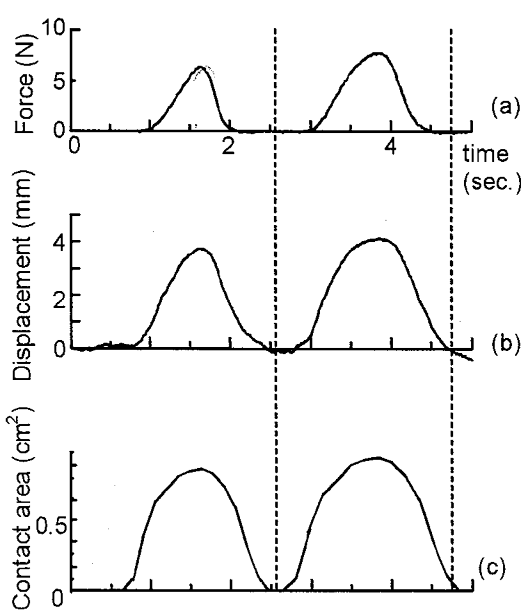

Figure 3 The measured pinch force, thumb displacement and contact area.

Results

The peak values of the pinch force, the calculated object displacement and the contact area are shown in figure 4. The values were normalized by each maximum. The same trends are observed in the first pinch and the second pinch.

The observed trends were reasonable that the subject pinched the harder object with higher pinch force but the object was less deformed. The variation of the force, displacement and the contact area were 91%, 84% and 26% of the each maximum in the first pinch, 89%, 86% and 29% in the second pinch.

The contact area less changed with the hardness of the object. It was experimentally demonstrated that human pinches an object until the contact area reaches particular value independent from the hardness of the object, while perceiving the hardness of an object.

The reference input of figure 1 appeared to be the contact area. If, the contact area is controlled with feedback control strat-

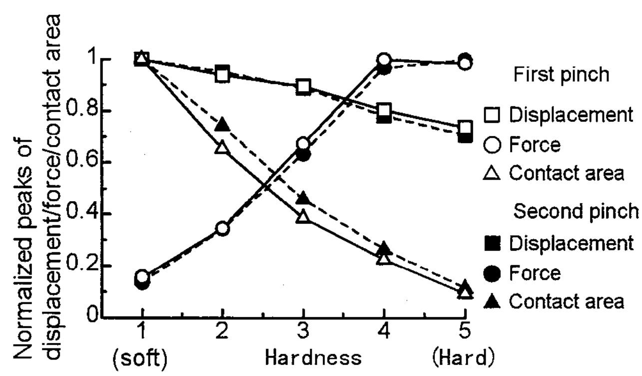

Figure4 The pinch force, object displacement and contact area during the pinch of five objects. Values are normalized by each maximal values. The object displacement was calculated from the precedently measured hardness of the object and the measured pinch force.

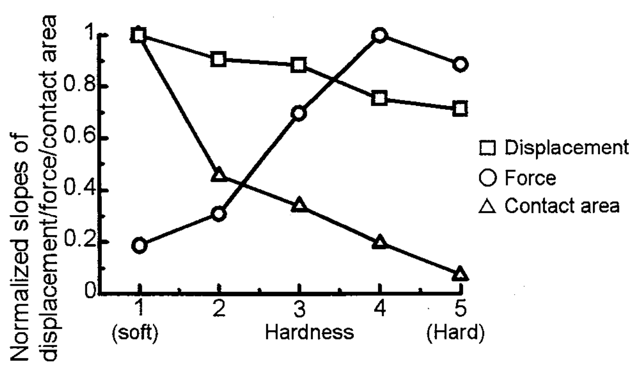

Figure5 The slopes between 10% and 90% of the pinch force, object displacement and contact area during the pinch of five objects.

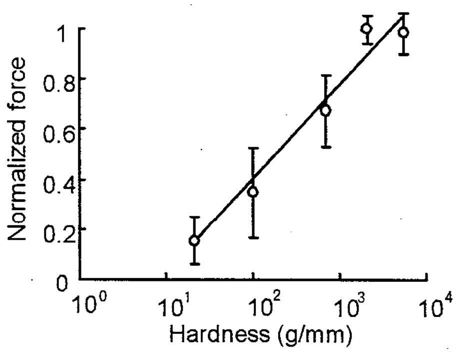

Figure 6 The relationship between the hardness of the object and the applied pinch force.

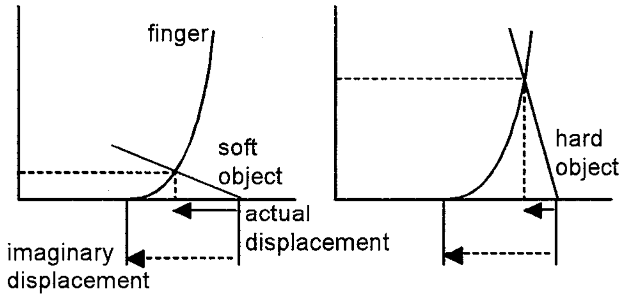

Figure7 Change of the object displacement described by the equiriblium point model.

egy, there must be a difference in the transient response of the contact area, and the difference of the transient force must be less.

The slopes of the force, displacement and the contact area, detected in the first pinch motions are shown in figure 5. The trends are similar to the trends of the peaks. It appears that the pinch motion is controlled without feedback of the perceived hardness. It was suggested that the human pinches the object with open-loop control strategy while detecting the hardness of an object.

Discussion

Meaning of constant contact area

As shown in the previous section, human pinches an object with constant contact area while perceiving the hardness the object. Physiologically, the constant area is equivalent to the constant number of the exciting skin receptors. Therefore, the hardness of the object can be perceived from only the receptor firing rate without counting in the number of the exiting receptor. Therefore, the hardness perception task is simplified by controlling the contact area constant. It appears that the "constant contact area" is to reduce the central load in perception.

The relationship between the object hardness and the force is represented in figure 6. It is observed that the force is proportional to the logarithm of the hardness. The relation means that the receptor firing rate represents the logarithmic hardness of the object. The human sensations such as auditory sensation are known to be logarithmic. The logarithmic property of the hardness detection appears to be natural.

As shown in the previous section, this logarithmic property is supposedly attained by open-loop control strategy. The effect of the finger mechanical property is discussed by applying the equilibrium point model proposed by Feldman [8], because the fingertip hardness has been reported as exponential [9].

Equilibrium point model

The equilibrium point model is based on the idea that the central command shortens the natural length of the muscle that is modeled as a spring. The muscle contractile force is indirectly defined as the force generated by the expanded spring. In this model, joint position is determined as the balance point of the antagonistic pair of springs. The joint position is controlled by changing the natural length of a muscle by the central command. In other words, central nervous system controls displacement not the muscle force. That displacement is called imaginary displacement.

Van Doren extended the equilibrium point model to describe the pinch of an elastic object. The mimetic diagram changing the position with the same imaginary displacement is described in figure 7. The imaginary displacement changes the finger position, however the object deformation is different because the fingertip is also deformed. Therefore, the imaginary displacement is equal to the sum of the finger deformation and the object deformation. The imaginary displacement in the experiments was calculated using the measured hardness of the objects and the finger. The finger hardness was modeled using an exponential function as already reported [9].

The calculated imaginary displacement is shown in figure 8. The measured finger displacement is also shown because the

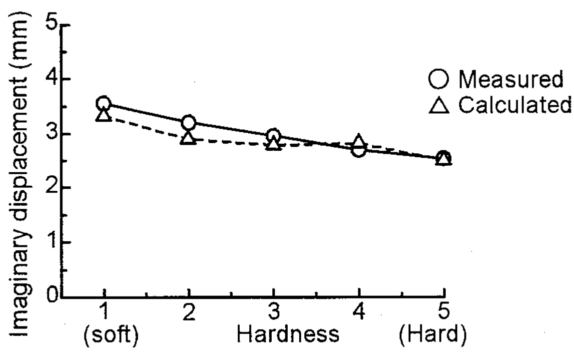

Figure 8 The calculated imaginary displacement based on the equilibrium point model and the measured thumb displacement.

measured finger displacement includes both the finger and the object deformation. The imaginary displacement should theoretically agree with the measured finger displacement.

The measured thumb displacement and the calculated imaginary displacement agreed well as shown. The object and the thumb deformation appear to be properly calculated. The variation of the calculated imaginary displacement was 28.6%. The "constant imaginary displacement control strategy" described the "constant contact area" well, because the variation of the imaginary displacement was considerably less than that of force (91%). The decrease of the imaginary displacement with the increase of the hardness comprises that there is some effect of "constant force strategy" in addition to the imaginary displacement tactics.

Conclusions

The human pinch motion to perceive the hardness of an object with unknown hardness was analyzed. It was revealed that 1) human tends to pinch an object with constant contact area regardless the hardness of the object; 2) the "constant contact area" tactics allows to perceive the hardness from only the steady state force as the firing rate of the tactile receptors; 3) the "constant contact area" appears to be attained by using "constant imaginary displacement" tactics. It is expected to develop a system which detects the pinch force and controls the fingertip contact area as a hardness display device.

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