Electronics and Communications in Japan, Part 2, Vol. 87, No. 11, 2004
Translated from Denshi Joho Tsushin Gakkai Ronbunshi, Vol. J85-D-II, No. 11, November 2002, pp. 1733–1740

Control Strategies in Human Pinch Motion to Perceive the Hardness of an Elastic Object

Kinya Fujita

Faculty of Technology, Tokyo University of Agriculture and Technology, Koganei, 184-8588 Japan

SUMMARY

This paper considers human pinch motion to perceive the hardness of an elastic object. The pinch force, the displacement of the object, and the contact area are measured, and the control rule for the pinch motion is examined experimentally. Pair comparison tasks for hardness are tried for 10 subjects, using five different elastic objects of different hardness. It is found that the displacement changes for 91% of the maximum value, and the force changes for 84% of the maximum value, depending on the difference of the elastic constant. But the change of the contact area is 26%, and is less related to the elasticity. Calculating the imaginary displacement based on the equilibrium point control hypothesis, the change due to the hardness is 29%. Consequently, it is suggested that in pinch motion to perceive hardness, the imaginary displacement is maintained constant and the contact area is maintained almost constant. Electron Comm Jpn Pt 2, 87(11): 28–37, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecjb.20126

Key words: pinch motion; hardness; perception; motion control; imaginary displacement.

Contract grant sponsor: Supported in part by a Ministry of Education and Science Grant.

1. Introduction

Among human motions to pinch an object, the motion of pinching a small object, in which the thumb and the index finger are mostly used, is called the precision grip. There have been many studies of this motion.

Johansson and Westling investigated the relation of the motion to the sensory information obtained at the fingertip [1]. Kinoshita and colleagues investigated the effect of the torque in the tangential direction [2]. There is also a study by Kinoshita and colleagues in which the development of the adjustment function is examined [3].

In these studies, however, the pinch motion is used to *lift* or to *hold* the object. The essential interest of this study is how humans generate a pinch force that provides necessary and sufficient friction to hold the object against the force of gravity.

On the other hand, there are cases in which the pinch motion is performed as a contact operation to perceive the hardness of the object. In artificial reality sensation [4] or tele-existence, it is required to represent the elasticity by presenting a reactive force to the fingertip [5]. In order to develop such a device efficiently, it will be effective to analyze the mechanism of perception of hardness through the human pinch motion and to identify the rules governing it.

There are a few studies that analyze the pinch motion for elastic objects. Mai and colleagues [6] and Van Doren [7] reported the force difference when the subject tries to pinch two objects of different hardness with the same force, and attempts an explanation based on the equilibrium point control hypothesis. However, these studies sought to analyze the task in which the subject pinches the object with a specified force, not to analyze the human pinch motion to perceive hardness.

The perception of object hardness by the pinch motion is composed of perceptions of two different kinds of information: the force applied to the object and the deformation of the object due to the change of the fingertip position. In other words, it is a problem of active sensing, which makes use of the contact motion. Thus, it seems important in the analysis of the perception mechanism to investigate the control strategy used in applying the force to the object, that is, the control rule of the pinch motion. The only studies in this direction, however, are a discrimination experiment for objects with different hardness [8] and an experimental study of the problems in hardness presentation using a finger force presentation device [9], conducted by Srinivasan and LaMotte. There has been no study of the motion itself.

Consequently, the purpose of this study is to analyze the motion control rule in pinch motion for perceiving hardness. The task of discriminating the hardness of an elastic object is posed to the subject, and the pinch force, the displacement of the object, and the fingertip contact area are measured during the pinch motion. It is found that the rate of change is the least for the fingertip contact area, suggesting that the contact area is maintained almost constant.

By analyzing the transient response of the motion, it is experimentally revealed that the control strategy to maintain a constant contact area is open-loop control without feedback, and that the contact area constant rule can be accounted for by an imaginary displacement control hypothesis using the equilibrium point model. These results are reported in this paper.

2. Model for Control of Pinch Motion and Hardness Perception Mechanism

When an elastic object such as rubber is pinched by the fingertips and a force is applied in the direction normal to the contact surface, the object is perceived as soft if the deformation relative to the applied force is large, and as hard if it is small. In other words, humans seem to perceive the hardness of elastic objects on the basis of information related to the force applied by the fingertips and the deformation of the object.

When the task of hardness perception for an elastic object is considered as a task of perception of the ratio between the force and the deformation, the model shown in Fig. 1 can be conceived as the simplest model for the hardness perception mechanism in which the two variables

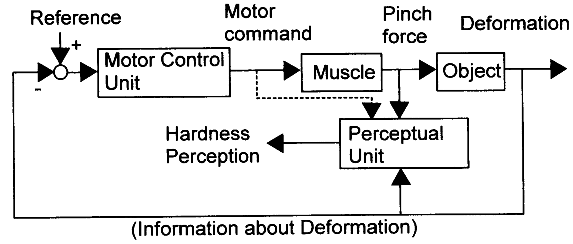


Fig. 1. Primitive model of hardness perception mechanism of elastic objects by pinch motion.

are perceived and their ratio is determined. It is a model in which the hardness is perceived by using two kinds of information. One is the information related to the pinch force, such as the firing frequency of the fingertip pressure receptors and the efferent copy of the motion command. The other is information related to deformation, such as the pressure distribution pattern of the fingertip and the inherent sensation of the change of the finger joint angle.

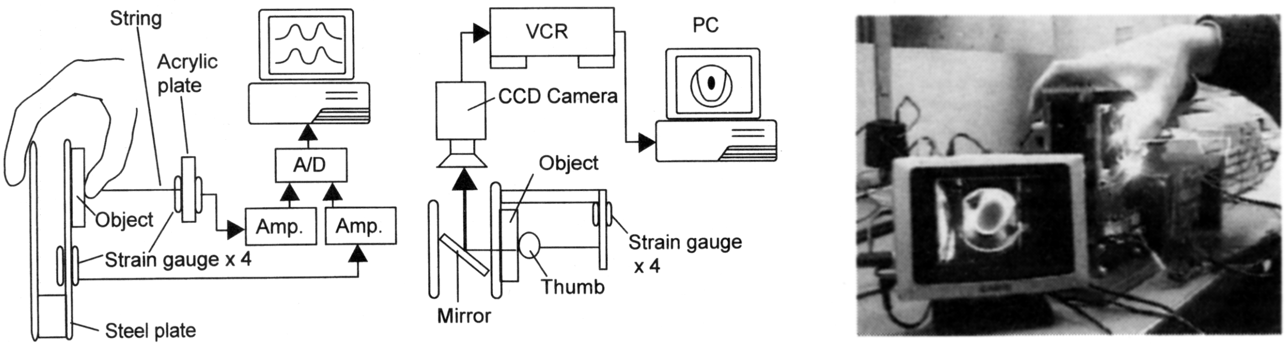
The correspondence between hardness perception for elastic objects felt by humans and the physical variables is not clear. In studies using the force presentation device, we see that the sensation scale for hardness is clearly proportional to the value obtained by the logarithmic transformation of the reactive force per unit displacement [5]. Consequently, in this study, the reactive force per unit pushing displacement of the elastic object is used as the measure of hardness, and is simply called the hardness of the elastic object.

It should be noted that human perception has a discrimination threshold. In order to perceive accurately the hardness of the elastic object, it is desirable that a sufficiently large pinch force be applied. Unless the pinch force is adjusted according to the hardness of the elastic object, however, soft objects with a low elasticity limit will be destroyed. Consequently, a feedback control mechanism is assumed in the perception model of Fig. 1, in which the deformation of the object is perceived and the pinch force is controlled. In the next and later sections, we experimentally examined such a control strategy in which the pinch force is adequately generated according to the object.

3. Method of Experiment

3.1. Experimental system

In this study, the pinch force, the displacement, and the contact area are measured as indices of the pinch motion. For this purpose, the system shown in Fig. 2 is constructed. The objects for pinch motion must be highly



(a) (b) (c)

Fig. 2. Schematic diagram of the experimental system to measure the contact force, thumb displacement, and contact area of the thumb fingertip. (a) Side view; (b) top view of the system; (c) experimental setup.

transparent while providing different hardnesses, since the contact area is measured by image processing. Five different samples, namely, two kinds of gelatin and three kinds of silicone rubber, are used. The objects are cylinders 48 mm in diameter and 10 mm thick. In order to assure that the material feeling is uniform, a polyvinyl chloride film is applied to the surface.

The pinch force is measured by using a bridge composed of four strain gauges, which are placed on the front and rear surfaces of an iron plate to which the object is fixed. (One of each pair of gauges is used for temperature compensation, and is placed perpendicular to the distortion direction.) In order to measure the contact area, the image of the contact between the thumb and the object is viewed by a CCD camera and is recorded on a video recorder. An image with a size of 512 × 512 pixels is stored off-line through the image board in the computer. The area is determined by using the binarized image. The area resolution in this imaging condition is 0.012 mm^2.

The displacement of the thumb is determined by using a strain gauge to measure the bend of the acrylic substrate due to the displacement of a string connected to the back of thumb, as shown in Fig. 2. The displacement measured by this method includes the displacements of both the thumb and the object. Consequently, it differs from the distance that the object is pushed by the thumb, that is, the displacement of only the object. Consequently, as a preliminary procedure, the elasticity of the object is measured, and the displacement of the object is calculated from the pinch force by making a correction based on the contact area. The measured displacement, which includes the deformation of thumb and the deformation of the object, is used in verification of the imaginary displacement control hypothesis based on the equilibrium point model.

The displacement x of the object is calculated as follows. When a pushing force F is applied to the object to be pinched by using a rigid body of surface area S_0, the relation between F and x is assumed to follow approximately the relation

$$F = f(x) \tag{1}$$

When the contact area in pinching the object changes from S_0 to S, the pressure applied to the object is multiplied by S/S_0. Consequently, the displacement x of the object when pinched is expressed by

$$x = f^{-1}(F) S_0 / S \tag{2}$$

The hardness characteristic $f(x)$ of the experimental sample is measured by pushing the load cell to the object using a micrometer. The two kinds of gelatin exhibited nonlinear characteristics, even in the range of the thumb force applied by the subject. Consequently, approximation by a quadratic function was applied. The three kinds of silicon rubber exhibited linear characteristics. Consequently, the ratio between the pushing force and the displacement was calculated. When the area of contact between the load cell and the object was 130 mm^2, the relation between the pushing force and the displacement in the experimental samples is approximately 210, 1100, 6900, 21,000, and 53,000 N/m, respectively. The quadratic functions were used for the two kinds of gelatin samples; the above values are for a displacement of 1 mm.

3.2. Experimental conditions

In this study, we wish to stabilize the contact position of the object so that the accuracy of the measured contact area is improved. For this purpose, we performed an experiment in which the index finger is touched to the side of the iron plate opposite to that contacted by the thumb, and only the thumb moves when the pinch force is generated. The subject is instructed to compare the hardness by pinching the object in this state, and the thumb motion is analyzed. In other words, the result of the analysis is not of the pinch motion: two fingers are not moved at the same time, but instead one of the fingers is fixed.

In a paired comparison task presented to the subject, two kinds of objects are presented by the experimenter. Then, the subject performs the pinch motion for hardness perception and declares which of the two is harder. The comparison is performed for all combinations except for the same hardness (20 cases). The order of presentation is random. The subject is instructed not to watch his finger during the experiment. Only a single incorrect answer for hardness discrimination of five levels of hardness occurred in the whole experiment. In other words, the discrimination task was relatively easy. The subjects were 10 healthy males 21 to 23 years old. The subjects were instructed to pinch each object two or more times.

When the order of hardness of the two presented objects was obvious, the subject sometimes did not pinch the second object with sufficient pinch force. Consequently, only the first pinch motion is analyzed in this study.

3.3. Evaluation index

Figure 3 shows an example of the temporal change of the contact area and other indices. For these curves, the peak values and the rate of increase in the rise period (from 10% to 90% of the peak value) are calculated as the evaluation indices. In addition, in the first and second pinch motions, the displacement of the object, the force, and the contact area at the time when the pinch force reaches a maximum, are measured for each object as the peak time values. The results are normalized to the respective maximum values.

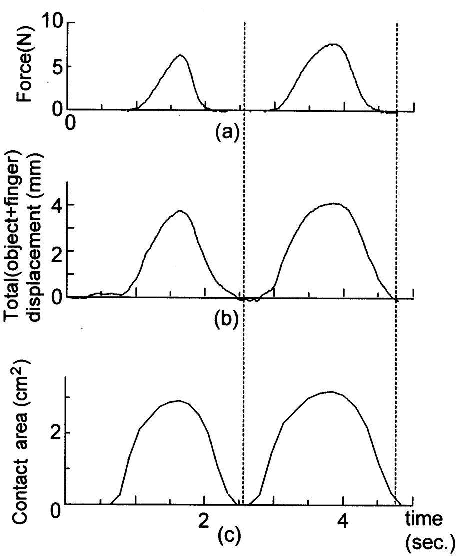


Fig. 3. Example of the measured (a) pinch force, (b) total (object + finger) displacement, and (c) thumb contact area.

4. Experimental Results

4.1. Peak-time value

The peak-time values in various trials are compared. Since there is no correlation to the hardness of the object touched in the previous trial, it is concluded that the history has no effect on the pinch motion. Figure 4 shows the result

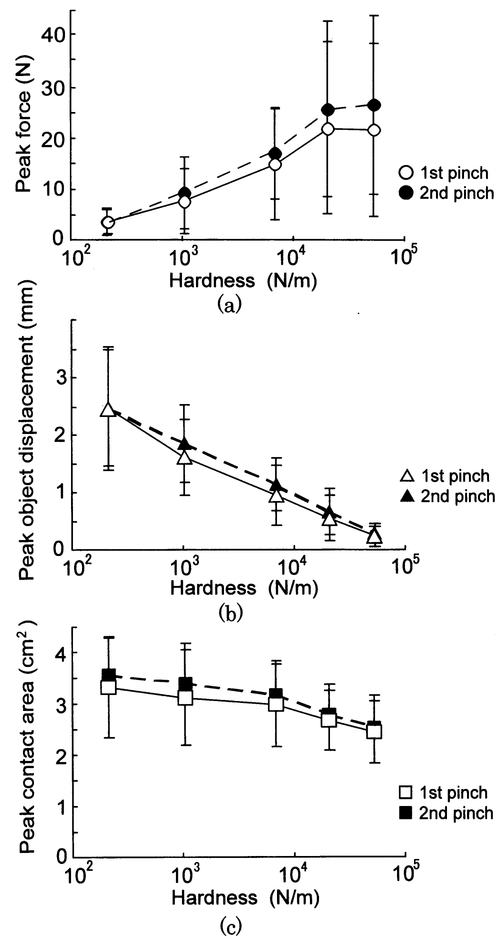


Fig. 4. Peak values of (a) pinch force, (b) object deformation (calculated), and (c) contact area. The error bars are the standard deviations.

of averaging four pinch motions. The standard deviation is large due to individual differences of the pinch force. As a general tendency, the peak-time values are higher in the first pinch motion than in the second for the pinch force, the object displacement, and the contact area. It is conjectured that the first pinch motion is a preliminary hardness perception, and the second is a well-prepared perception.

Figure 5 is the result obtained when the peak-time values of each index are summed and normalized to the respective maximum values. The solid line is the result for the first pinch motion, and the dashed line is the second. A control is provided so that a larger pinch force is applied as the object hardness is increased. It is noted that the object displacement calculated on the basis of the hardness characteristics of the object decreases with the hardness of the object, even though a larger force is applied. Thus, the peak-time value of the contact area is slightly decreased.

Although there is a slight difference in the peak-time values between the first and second pinch motions, the tendency is almost the same when normalized to the maximum value of each index. In other words, it appears that the same control strategy is probably used. Examining the difference between the maximum and minimum values in the first pinch motion, the result is 91% for the object displacement, 84% for the force, and 26% for the contact area. The difference due to the difference of hardness in the second pinch motion is 89% for the object displacement, 86% for the force, and 29% for the contact area.

In contrast to the difference due to the hardness, which is 91 and 89% for the object displacement and 84 and 86% for the force, the difference of the contact area is small, being 26 and 29%. It appears that in the pinch motion to perceive the hardness, the subject tends to apply the pinch force until a constant contact area is realized, regardless of the hardness of the object. The tendency for the rate of change of the contact area to be small compared to the object displacement and the pinch force is the same for both gelatin and rubber. Since the tendency is also observed in the first pinch motion, where no a priori knowledge is available, it appears likely that the control for the constant contact area is open-loop control without feedback control.

4.2. Inclination in the rise period

We wish to examine whether the tendency for there to be constant contact area, regardless of the hardness, is due to saturation of the contact area due to the shape of the fingertip, or the result of the motion control strategy. For this purpose, the rise behavior of each index is analyzed. If the contact area simply saturates in the soft object, becoming equal to the case of the hard object, the contact area in the soft object will rise more rapidly than in the hard object, becoming constant near the peak, since the contact area will saturate more quickly.

Consequently, the inclination and the average rise time in the rise period (from 10% to 90%) are calculated for each index. Since the first and second pinch motions are not completely separated in some subjects, only the result of analysis for the first pinch motion is shown in Fig. 6.

As in the case of the peak-time value, the change of the inclination of the contact area due to the hardness is smaller than for other indices, and there is no tendency that suggests saturation of the contact area. The average rise time for each object is 0.83, 0.89, 0.78, 0.85, and 0.78 s in decreasing order of softness, with the average for the whole being 0.83 s. In other words, there is no correlation to the object hardness. In addition, the peak-time pinch force changes markedly with the object hardness. Consequently, it is inferred that the pinch force rather than the saturation changes by some mechanism according to the object hardness, reflecting the control strategy of the pinch motion control system.

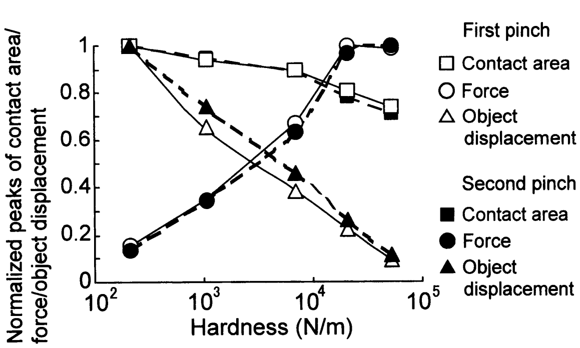


Fig. 5. Normalized peak values of pinch force, thumb displacement, and thumb contact area normalized.

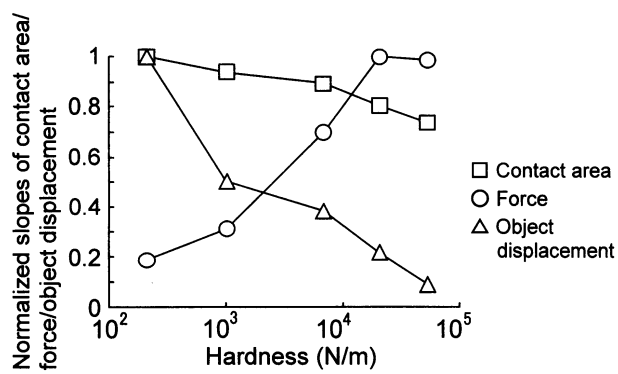


Fig. 6. Normalized slopes of pinch force, thumb displacement, and thumb contact area.

5. Discussion

5.1. Implication of contact area constant control rule

It was found that the contact area at the peak of the pinch motion is almost constant, regardless of whether the object is hard or soft. This can be interpreted as in Fig. 7. When the object is hard, a large force is applied and the fingertip is deformed to increase the contact area. When the object is soft, a small force can deform the object to increase the contact area, completing the pinch motion.

The constancy of the contact area implies physiologically that the same number of pressure receptors fire. However, since the applied force differs, the firing frequency differs. Thus, ignoring the effect of the self-perception sensation, for example in the muscle spindles, the perception of the receptor firing frequency at the peak of the pinch motion is equivalent to the perception of hardness.

Figure 8 shows the relation between the pinch force, normalized to the maximum value for each subject, and the hardness of the object. The straight line in the figure is the regression line. Since the pinch force is almost proportional to the hardness after logarithmic transformation, it is not necessary to calculate the hardness from the ratio of two data, that is, the force and the deformation. We see that the hardness after logarithmic transformation is perceived if the pinch force at the state when the contact area is constant is perceived. It is conjectured from this fact that contact area constant control serves to reduce the processing load in the central nervous system, in the sense of physiological reasonableness.

In pinch motion for hardness perception of an elastic object, the pinch force is not applied beyond the point at which the contact area is increased and reaches a constant value. This implies that the hardness can be perceived if the dynamic change of the contact area is represented until it reaches the constant value. In other words, there is a possibility that various hardness sensations can be produced if the pinch force is detected and the contact area of the fingertip is controlled, so that the rate of increase of the contact area as a function of the pinch force is adjusted.

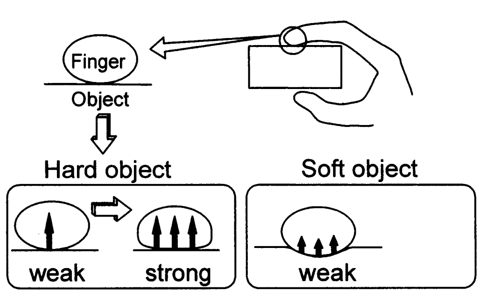


Fig. 7. Diagram of hardness detective pinch motion for objects with different hardness.

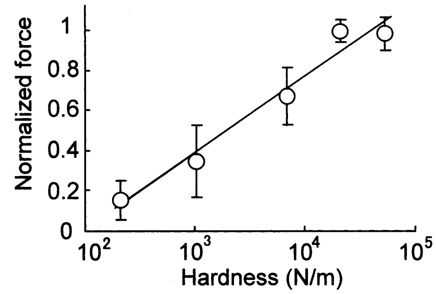


Fig. 8. The relationship between the hardness of the object and the applied pinch force (normalized for each subject).

As artificial reality devices to represent the hardness, force feedback devices and other devices in which the displacement of the fingertip is detected and the reactive force to the fingertip is controlled have been tested [9]. However, this approach has the problem that the hardness in passive contact cannot be represented. The hardness presentation system with contact area control has the possibility of solving the problem in the imaginary sense, since the displacement is not directly utilized. A system based on this idea is under development [10].

5.2. Analysis of initial pinch motion

In this study, we have observed that in pinch motion for hardness perception a large force is applied to hard objects and a small force is applied to soft objects. If this control of the pinch force is due to feedback control based on the perceived hardness, then we may expect the muscle contraction force at the initial period before perceiving the hardness—the force exerted on the object by the fingertip—is independent of the object hardness.

Consequently, we examine whether or not pinch motion is performed by force feedback control by comparing the rate of change of the force at the initial period of the pinch motion (10 to 13% of the peak value). In order to exclude the effect of pinch force variation due to individual subjects, the force for each subject is normalized to the maximum pinch force. Figure 9 shows the averaged results. The average length of the initial period is 0.22 s, and the required time is not correlated with the object hardness. In contrast, the rate of change of the force is 79%, which obviously depends on the hardness.

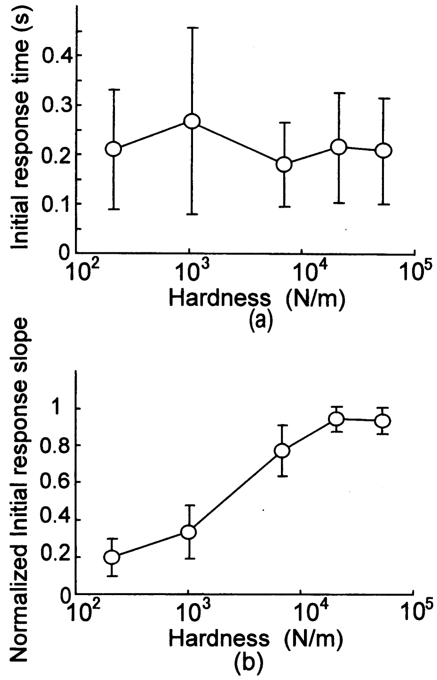


Fig. 9. (a) Response time and (b) normalized slope of force during initial phase of pinch motion (10 to 30% of peak force).

In general, we know that a brain wave component called P300 with a latency of 300 ms occurs prominently in tasks involving perception. If the pinch force is controlled on the basis of perceived hardness, a time longer than several hundred milliseconds will be required before the result of hardness perception is reflected in the pinch force, with a further delay for propagation through the motor nervous system and for the response of the muscle. But the time required for the initial pinch motion is 0.22 s on average, which is not sufficient time to perceive the hardness and control the pinch force.

Even in such a short time, however, the pinch force changes greatly depending on the hardness. In addition, the time required for the pinch motion is almost constant regardless of the object hardness. These facts indicate that the pinch motion is performed by the same control rule regardless of the object hardness. Thus, open-loop control rather than feedback control of the pinch force based on the perception of the object hardness provides an adequate interpretation of pinch motion for perception of hardness.

5.3. Hypothesis of constant imaginary displacement

In this section we consider the strategy of open-loop control, where a pinch force depending on the object hardness is applied without using feedback of hardness information. We introduce below the hypothesis of constant imaginary displacement control for the pinch motion, as proposed by Van Doren [7] on the basis of Feldman's equilibrium point model [11]. In the equilibrium point model, control commands for human motion are output not in terms of force, but in terms of the imaginary displacement of the principal muscle of motion.

The model is based on the following idea. Human muscle has elastic properties, and the joint has antagonistic muscles—flexors and extensors. Consequently, the actual displacement, that is, the joint angle, is determined as the equilibrium point between the forces generated by the two elastic elements (the flexor and extensor muscles). Van Doren extended this idea to the relation between the finger and the object. He asserted that the force and the actual displacement differ depending on the object hardness, even when the intent is to pinch the object with the same force, because the imaginary displacement output by the central nervous system is kept constant. Figure 10 shows a schematic diagram of this idea.

The straight line rising to the left represents the elastic characteristic of the object. The X segment represents the initial position of the object surface. Displacement in the negative direction from the initial position represents pushing into the object. When pushed, the object generates a reactive force according to its elastic properties.

Similarly, the exponential curve represents the nonlinear elastic characteristic of the finger. The X segment represents the imaginary fingertip position as controlled by the central nervous system. The positive displacement from the imaginary fingertip position is the displacement by the deformation of the underside of the finger. The pinch motion is realized by setting the imaginary fingertip position inside the object, as shown in the figure. The fingertip also generates a reactive force according to the deformation from the imaginary fingertip position.

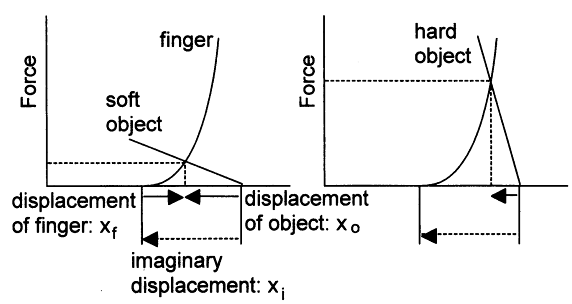


Fig. 10. Pinch motions with constant imaginary displacement control strategy for objects with different hardness.

The imaginary displacement control hypothesis asserts that the equilibrium point between the two is the actual position of the fingertip, that is, the position of the object surface. Thus, the imaginary displacement x_i is given as the sum of the finger displacement x_f and the object displacement x_0:

$$x_i = x_f + x_0 \tag{3}$$

Applying the imaginary displacement control hypothesis, when the elastic properties of the object vary as in Fig. 10, the reactive force and the displacements of the finger and the object at equilibrium vary, even if the imaginary displacement is the same. This accounts for the experimental result that the displacement varies according to the object hardness without the use of feedback control.

When the hardness characteristics of the finger and the object are known, the displacements of the finger and the object can be determined on the basis of their respective hardness characteristics if the reactive forces generated by the two are given. In this study, the hardness of the object is measured beforehand. As regards the finger characteristics, an acrylic plate used as a rigid sample is attached to the experimental device. The pinch force and the displacement of the finger are measured for 10 subjects participating in the analysis of the pinch motion. In accordance with the report of Hajian and Howe [12], the result is approximated by an exponential function as in Fig. 11. Based on this finger hardness characteristic and the pinch force measured in the experiment, the displacement of the finger is calculated, and the imaginary displacement in each trial is estimated.

The displacement measured by the displacement measurement unit of the experimental device used in this study includes the displacement of the finger and the displacement of the object. Consequently, it is considered the same as the imaginary displacement obtained by calculation. Figure 12 summarizes the imaginary displacement and

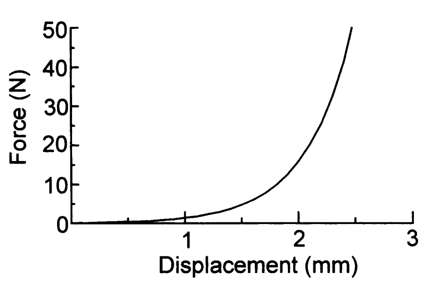


Fig. 11. Property of fingertip hardness model based on measured data.

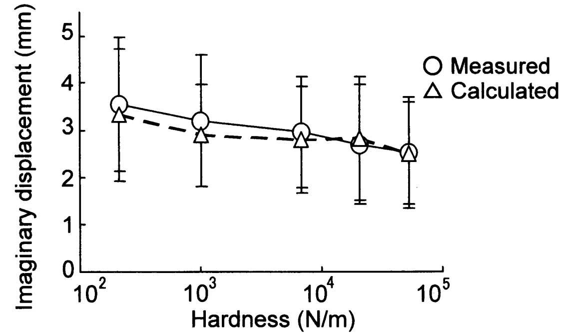


Fig. 12. Calculated imaginary displacement and measured displacement including both object and finger deformation.

the experimentally obtained imaginary displacement, including the finger and the object.

The imaginary displacement agrees well with the actually measured displacement, indicating the validity of the calculated imaginary displacement. The rate of change of the estimated imaginary displacement is 29%, which is nearly the same as that of the contact area. Thus, the fact that the finger contact area remains almost constant regardless of the hardness is accounted for by assuming that the imaginary displacement is kept constant in the imaginary displacement control model.

The imaginary displacement, which is the sum of the displacements of the object and the finger calculated from the respective elastic characteristics, agrees well with the actually measured displacement including both the object and the finger. This indicates the validity of the object displacement calculated by Eq. (2).

To summarize, the following observations have been made.

(1) Pinch motion is performed on the basis of a constant command (constant imaginary displacement) from the central nervous system.

(2) Because of the nonlinear hardness characteristics of the finger, the contact area at force equilibrium is maintained constant.

(3) Since the contact area is maintained constant, the hardness of the object can be estimated by using the force alone, regardless of the displacement.

Figure 13 shows the suggested model for the above hardness perception mechanism. The result is interesting, since it implies that the burden on the central nervous system is reduced doubly, in the sense of control and perception, by the nonlinear physical characteristic of the

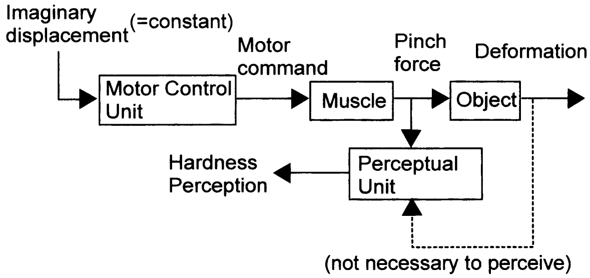


Fig. 13. Model of hardness perception mechanism obtained in this study.

finger hardness and the imaginary displacement control mechanism.

6. Conclusions

In this study, pinch motion is analyzed for the case in which a human perceives the hardness of an object of unknown hardness by touching the object with a finger. A series of interpretations is obtained in which the pinch force is applied to the object by the imaginary displacement constant control. Thus, the hardness of the object can be recognized by using only the pinch force, since the contact area is almost constant.

Problems for the future include further detailed analysis of the hardness perception mechanism, such as the case in which the contact surface is not planar, and investigation of the application of the results presented in this paper to artificial reality devices.

Acknowledgment. This study was supported in part by a Ministry of Education and Science Grant, for which the author is grateful.

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AUTHOR

Kinya Fujita (member) received his B.S. degree from the Department of Electrical Engineering, Keio University, in 1983, and completed the doctoral program in 1988. After serving at Sagami Institute of Technology, the Faculty of Medicine at Tohoku University, and the Faculty of Engineering at Iwate University, he became a Researcher in Neural Science Division, University of Alberta. He has been an associate professor on the Faculty of Engineering at Tokyo University of Agriculture and Technology since 1999. He is engaged in analysis of human motion control mechanisms, and in the development and evaluation of application systems, such as force sensation presentation devices, analysis of erect posture control systems, and functional electrical stimulation. He holds a D.Eng. degree, and is a member of the Japan MEBE Society, Biomechanism Society, Society of Instrument and Control Engineers, Japan Virtual Reality Society, Human Interface Society, and IEEE.