A Tactile Display using Ultrasound Linear Phased Array

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Abstract

We developed a new tactile display using acoustic radiation pressure. The display can produce a 1 mm diameter focal point and 2 gf total force. By steering the focal point using a linear phased array, the display creates various spatiotemporal patterns of pressure distribution on the skin precisely. We carried out experiments on "tactile apparent movement" with the tactile display and found that tactile apparent movement is evoked quite stably even if the successive stimuli are not vibration but indentation.

Key words: tactile display, ultrasound, acoustic radiation pressure, apparent movement

1. Introduction

Compared to other sensations like vision and auditory sensation, the mechanism of tactile perception is not revealed enough. One of the reasons for that is that it is difficult to fabricate experimental setups which provide various kinds of sufficiently fine tactile stimuli. In recent years, many tactile displays have been proposed and developed [1]. However, these tactile displays are designed only for specific purposes, for example, Braille displays or producing particular textures [2]. Therefore, they are not always appropriate for other purposes, especially for experiments on general features of human tactile perception.

It is generally accepted that understanding the basic mechanism of human perception contributes not only to science itself but also for designing practical applications. For example, the audible frequency range determines the sampling rates for audio applications. As for tactile perception, we still need much more knowledge which can provide sufficient design requirements for designers of tactile interfaces.

Our study is based on both scientific and practical interests. The goal is to develop a device which can control spatiotemporal patterns of stress field precisely on the skin with high spatial and temporal resolution compared to human tactile perception, in order to both clarify the mechanism of human tactile perception and produce real tactile feelings as an interface for virtual reality.

We have proposed a tactile display using acoustic radiation pressure [3][4]. In previous studies, we confirmed that the prototype display could produce a 1 mm diameter focal point and the temporal property was sufficient for precise tactile stimulations. Based on the previous studies, we developed a new tactile display. The basic principles and features of the tactile display are described in sections 2, 3 and 4.

One of the outstanding features of our display is that it can produce various spatiotemporal patterns of pressure distribution precisely. For example, the focal point is swept along the finger while the pressure is kept at a constant value. This feature is quite useful especially for investigating tactile perception of moving objects.

Related to tactile perception of moving objects, "tactile apparent movement" is widely known as an interesting tactile illusion. This phenomenon is interesting from both theoretical and practical perspective. To understand the proper condition for the emergence of tactile apparent movement will help to clarify the tactile perception of motion. This in turn will give the designer of haptic devices the design criteria for producing real tactile feeling. We carried out experiments on tactile apparent movement and acquired the results that contradict the generally accepted view that tactile apparent movement is not induced by nonvibratory stimuli stably. The details of the experiments are described in section 5.

2. Method

The display uses ultrasound to exert pressure on the surface of the skin. When we apply ultrasound to the surface of the object, it generates a force called acoustic radiation pressure that pushes the object in the direction of the sound propagation. The acoustic radiation pressure exerted on the surface of the object is given as

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where P is the acoustic radiation pressure exerted on the surface, α is a coefficient determined by the reflection property of the surface of the object, E is the energy density of ultrasound near the surface, p is the acoustic pressure, ρ is the density of the sound medium and c is the sound velocity.

As Dalecki pointed out [5], acoustic radiation pressure is useful for investigating tactile perception. Equation (1) means that the acoustic radiation pressure is proportional to the energy density of ultrasound. Therefore, by controlling the spatiotemporal pattern of the energy density of ultrasound, various spatiotemporal patterns of pressure distribution are produced.

A popular way of controlling the spatial distribution of the intensity of ultrasound is to use a linear phased array. A linear phased array consists of small ultrasound transducers and can produce a variable focal point. By steering the focal point at a much higher speed than human perception, the display creates various spatiotemporal patterns of pressure distribution on the surface of the skin.

3. System

Fig.1 shows the schematic drawing of the tactile display. The system consists of a linear array transducer, a driving circuit and water bath. The water bath was filled with water. Water was used as a medium for ultrasound.

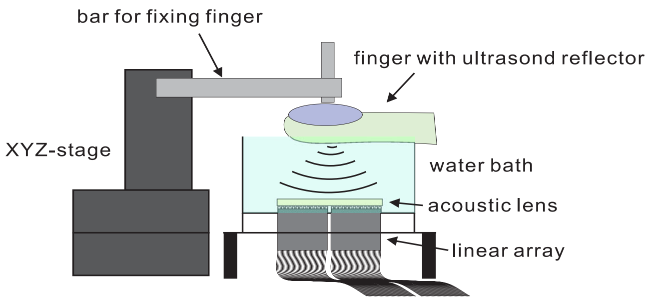

Fig.1 Schematic drawing of the tactile display.

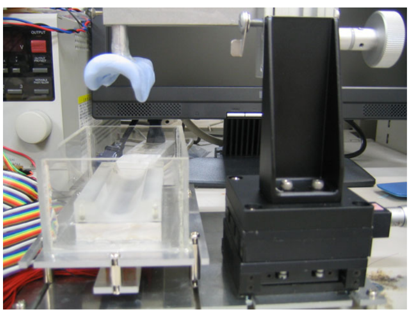

Fig.2 Photograph of the tactile display.

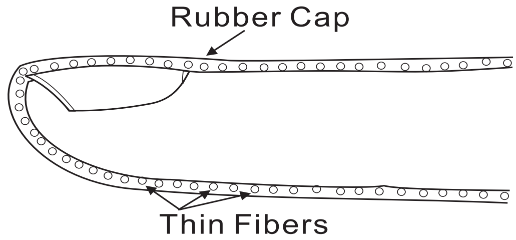

Fig.3 Cross section drawing of the finger cap for reflecting ultrasound

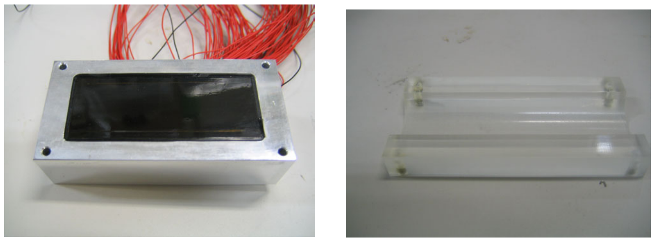

Fig.4 Photograph of the linear array transducer: Left: 120 channel linear array transducer, Right: cylindrical acoustic lens made of acrylic plastic

Users put their fingers on the surface of the water. When psychophysical experiments were conducted, the subjects fixed their fingers and adjusted the position of their fingers with the XYZ stage. Users wore finger caps for reflecting ultrasound. The cross section drawing of the finger cap is shown in Fig.3. The finger cap created an air gap between the subject's finger and a rubber cap to reflect ultrasound. The finger cap was thin enough for subjects to perceive various tactile sensations.

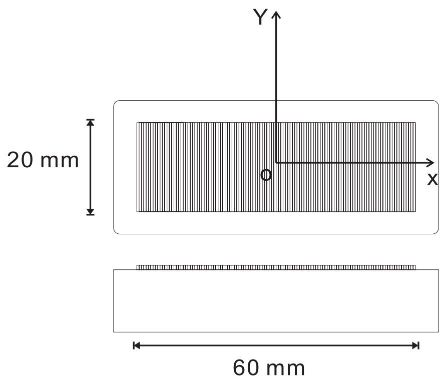

Fig.5 Schematic drawing of the linear array transducer: Top view and side view

We used the linear array transducer (Nihon Denpa Kogyo Co., Ltd.) especially designed for high-power driving using PZT. The power limit is given by the maximum electrical field to maintain polarization of the PZT and the maximum temperature as the Curie temperature. In order to avoid the temperature rising, the PZT pieces were attached on a thermally conductive material. The total number of the PZT pieces was 120 but only 60 channels in the center were used during the experiments. The resonant frequency of the PZT transducer was 3 MHz. The length and width of each PZT piece was 20 mm and 0.445 mm, respectively. The PZT pieces were arranged at 0.5 mm. A semi-cylindrical acoustic lens was attached to the surface of the linear array transducer so that the ultrasound from each PZT piece was converged on a single focal point. The focal length of the lens was 30 mm.

The driving circuit included signal delay circuits implemented with 4-bit counters. The signal for each transducer was controlled so that ultrasound from each PZT transducer converged along an x axis.

4. System Specification

In this section, we show the basic properties of our tactile display in terms of temporal characteristics and spatial resolution. The acoustic radiation pressure at a single focal point was measured by a point-aperture pressure sensor. In measuring the acoustic radiation pressure, an ultrasound beam was focused on a fixed focal point just above the device center at 30 mm from the device surface.

4.1 Temporal Characteristics

Fig.6 shows the intensity of the acoustic radiation pressure at a focal point changing sinusoidally. The acoustic radiation pressure was modulated by Pulse Width Modulation. The frequency of the pulse train was set to 10 kHz because high-frequency (higher than 1 kHz) vibration of the skin is normally imperceptible for humans but can induce tactile sensations when amplitude modulation is applied in the low-frequency region [6]. The graph in Fig.6 was the waveform filtered by a low-pass filter. The cut-off frequency of the filter was 10 kHz. The frequency of the resultant wave was 100 Hz.

The gain-frequency characteristics between 20 Hz and 1 kHz is shown in Fig.7 The frequency characteristics curve is not perfectly flat because of the dynamics of the ultrasound medium, but the fluctuation of the gain is within 5 dB from 20 Hz to 1 kHz.

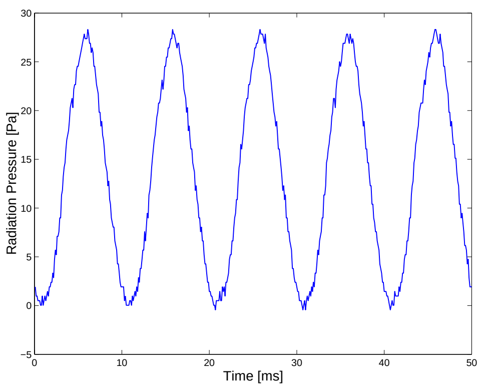

Fig.6 Sinusoidal wave of observed acoustic radiation pressure: Horizontal axis means time [ms]. Vertical axis means the observed acoustic radiation pressure [Pa]

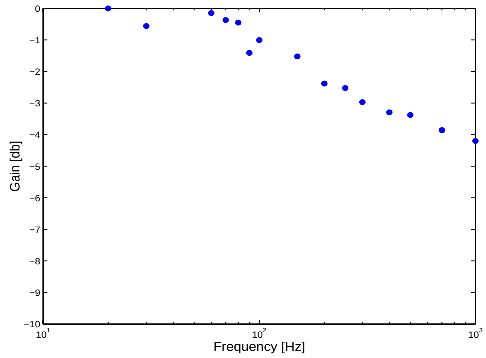

Fig.7 Gain-frequency characteristics of acoustic radiation pressure: Horizontal axis represents frequency of modulated radiation pressure [Hz]. Vertical axis represents dB gain

4.2 Spatial Resolution

Next we show the spatial distribution of the acoustic radiation pressure for a single focal point. We defined x-y coordinates as in Fig.5. The acoustic radiation pressure was measured from -2.5 mm to 2.5 mm for both x and y.

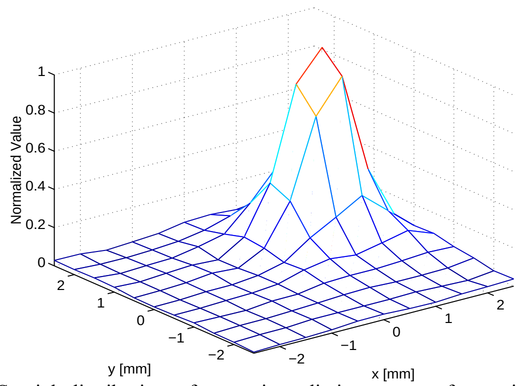

Fig.8 Spatial distribution of acoustic radiation pressurefor a single focal point (3D plot)

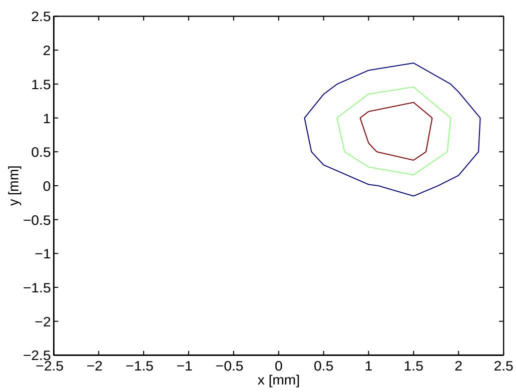

Fig.9 Spatial distribution of acoustic radiation pressure for a single focal point (contour plot): Each line represents 25%, 50%, 75% of the peak value, respectively.

The results are shown in Fig.8 and Fig.9. Fig.8 is a 3D plot of the measured spatial distribution of the acoustic radiation pressure. Z-axis in Fig.8 is the pressure obtained at each point normalized by the largest value in the data (i.e. the value at the focal point). Fig.9 is a contour plot of the same data. The diameter of the focal region is estimated as 1 mm when we define the focal region as the area in which the obtained pressure is higher than the half value of the pressure at the peak.

5. Experiments on Tactile Apparent Movement

The experiments on tactile apparent movement carried out with the tactile display are described in the following section. First, the previous studies on tactile apparent movement are discussed. The details of the experiments and the results are described in subsections 5.2 and 5.3.

5.1 Tactile Apparent Movement

"Tactile Apparent Movement" is one of the famous tactile illusions. When two or more discrete points on the skin are vibrated successively, the stimuli are recognized as if a single vibrating point is stroked over the skin.

Historically, the phenomenon was first reported by Von Frey and Metzner (1902). When they conducted successive two-point stimulation experiments, subjects described stimulation such as stroking the skin. Later, Hulin (1927) found that when he used two successive indentations as tactile stimuli, the percentage that tactile apparent movement was perceived by subjects reached only 63.7 % even at the optimal conditions [7]. However, in the 1960s, several studies showed that tactile apparent movement was clearly perceived when vibratory stimuli were employed instead of simple indentations. Sherrick [8] and Kirman [9] showed that optimal conditions for vibrotactile apparent movement were determined by interstimulus onset interval and stimulus duration.

The study of this interesting phenomenon has importance not only for the understanding of human tactile perception but also for determining the design requirements for tactile interfaces. For example, if we can produce a "stroking" feeling without actual stroking, from the viewpoint of designing tactile interfaces, that means it is not necessary to fabricate a particular mechanism for sliding a stimulating point. For the designers of tactile displays, the most important concern is if there are any differences between actual stroking and tactile apparent movement in terms of the quality of the perceived motion.

However, there are no studies in which apparent movement was compared with actual stroking in a precisely controlled manner. In many studies on tactile apparent movement, subjects judged whether the given stimuli were continuous or discrete based on their subjective opinions. One of the reasons why this comparison has not been done is that it's difficult to fabricate apparatuses for these kinds of experiments. But our tactile display can easily produce both stroking stimuli and stimuli on discrete points while applied pressure is precisely controlled.

Another factor that should be taken into consideration is that previous studies on tactile apparent movement didn't use nonvibratory stimuli. As described above, while vibrotactile stimulus clearly evokes tactile apparent movement, it has been said that tactile apparent movement induced by nonvibratory stimulation (i.e. indentation) is not a stable phenomenon. However, we think that in order to apply tactile apparent movement to practical tactile displays and also to clarify the perception of moving objects, sensation of motion should be separated from vibratory sensation.

We carried out experiments on these two points. Actual stroking without vibrations along the finger was compared with successive indentations on three points on the finger. The details of the experiments are described in the following section.

5.2 Experiment

Two types of stimulation were employed and compared. One type of stimulation was called "Stroking"(STR). In STR, after applying a gradually increasing force for 250 ms at the starting point A, the focal point was moved continuously along the subjects' finger from the starting point A to the endpoint B while the force at the focal point was kept at a constant value (i.e. no vibrations were applied), then applied force was gradually decreased to zero for 250ms at the end point B. The applied force during sweeping was fixed to 1.2 gf.

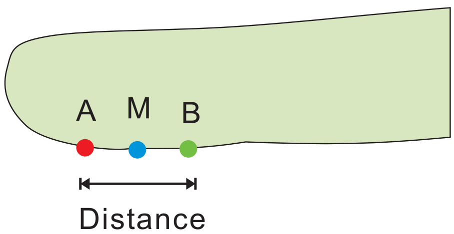

Fig.10 The position of each point on the finger pad. The starting point A is located at the center of the finger pad. The position of the end point B is determined by the parameter "Distance". M is the midpoint of the line segment AB.

Another type of stimulation was called "3 points"(3PT). In 3PT, after applying a gradually increasing force for 250 ms at the starting point A, the force was applied only to the three points on the finger; the starting point A, the middle point M and the end point B. The point M was located just at the center between A and B. The pressure at each point was changed so that the center of the applied force moved at the same velocity and that the total amount of applied force was kept at 2 gf. The reason why the applied force was different from that of

STR is that when the applied force in STR was equal to that in 3PT, subjects could distinguish STR from 3PT not by the quality of perceived motion but by the perceived intensity of the stimulation. After moving the focal point to B, applied force was gradually decreased to zero for 250ms at B. Fig.11 explains how the applied force at each point was changed.

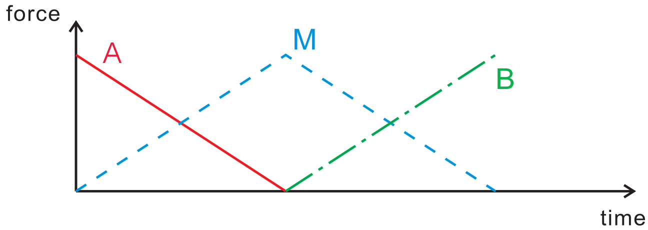

Fig.11 Schematic drawing of time dependent force at each stimulation point in 3PT type stimulation. The solid, dashed and dash-dot lines represent forces applied to A, M and B, respectively. Note that the total amount of force is always kept at the same value and that the center of the force is moved at the constant velocity

The parameter "Distance" (*D*) means the distance between the starting point A and the end point B. *D* of 10, 15 and 20 mm were chosen. Another parameter "Time for Motion" (*TM*) indicates the time required for the focal point to move from A to B. *TM* of 20, 40 and 80 ms were used. In one experimental session, a particular set of *D* and *TM* was chosen and examined.

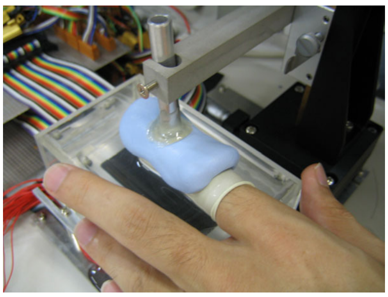
Fig.12 Photograph of the experiments

Subjects sat and placed their left index fingers on top of the tactile display. The position of the finger was adjusted by XYZ stage so that the center of the finger pad was on the starting point A.

First, the subjects were exposed to one type of stimulation S_1 and then, after 1 sec interval, another type of stimulation S_2 was applied. The subjects were asked whether S_1 and S_2 were the same type of stimulation or not. The answer was chosen from "yes" or "no." A combination of S_1 and S_2 (S_1, S_2) was chosen from all possible sets: (STR, STR), (STR, 3PT), (3PT, STR), (3PT, 3PT). Within any one experimental session, the order of the four sets of stimulation was randomized but the number of times each set of stimulation was presented was equal. In this experimental procedure, the percentage of correct answers reaches 50% if the subjects can not distinguish the two types of stimulation.

Nine experimental sessions were carried out for each subject in order to examine all possible combinations of *D* and *TM*. For each session and each subject, the percentage of correct answers was recorded.

5.3 Results

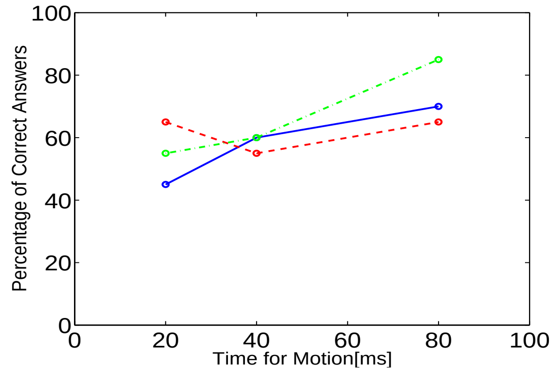

Fig.13 The results of the experiment for *D* = 10 mm. The solid ine represents the results on Subject A. The dash-dot line is for Subject B. The dashed line is for Subject C.

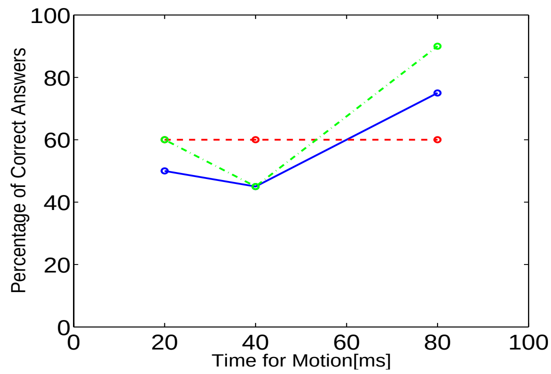

Fig.14 The results of the experiment for *D* = 15 mm

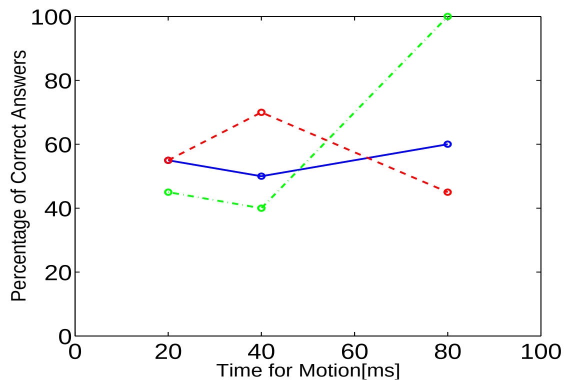

Fig.15 The results of the experiment for *D* = 20 mm

Fig13, 14 and 15 show the percentage of correct answers for each *TM*. Vertical axis means the percentage of correct answers. Horizontal axis means "Time for Motion" (*TM*). Fig.13, 14 and 15 are for *D* = 10, 15 and 20 mm, respectively. Except for Subject C (red dashed line), the graphs seem to have similar tendency. Interestingly, the graphs are independent from *D*. In other words, the graphs are dependent on *TM* itself rather than the velocities which are estimated from *D* and *TM*. The graphs indicate that subjects could not distinguish actual stroking from successive indentations on three points at *TM* less than 40ms. In other words, at *TM* less than 40 ms, tactile apparent movement was evoked even if the stimulations were successive indentation without vibrations and the sensation of movement was indistinguishable from actual stroking

6. Discussion

Though there was a difference between STR and 3PT in terms of the perceived intensity of stroking, we succeeded in inducing the sensation of motion quite stably even by nonvibratory successive stimuli. It has been said that it is difficult to induce tactile apparent movement by successive indentations, however the phenomenon is clearly observed when vibrotactile stimuli are employed instead. One of the possible explanations for this interesting finding is the perception of high frequency vibrations by Pacinian corpuscles.

In our experiments, when 3PT type stimulation was applied, in other words, when successive indentations were applied while the applied pressure was precisely controlled, no high frequency vibrations were induced. Actually no subjects reported vibratory sensation during the 3PT type stimulation. In this case, we can say that the signals from Pacinian corpuscles were always “OFF” during the course of the stimulation.

In comparison, Kirman[9] used 100 Hz bursts as vibrotactile stimuli which were supposed to activate Pacinian corpuscles. According to his data, under the optimal conditions for tactile apparent movement, the required interstimulus onset interval was shorter than the stimulus duration at a single stimulating point. (For example, according to his paper, if the stimulus duration at a single point was 100 ms, the best interstimulus onset interval was 90 ms.) That means that before the stimulus at the first point finished, another stimulus was applied at the second point: two successive stimuli overlapped under the optimal conditions. In this case, Pacinian corpuscles were always activated during the stimulation. In other words, the signals from Pacinian corpuscles were “ON” during the course of the stimulation

Compared to the above two cases, successive indentations produced with a conventional experimental setup would induce high frequency vibrations only at the onset of each indentation, which would activate Pacinian corpuscles and make subjects feel each tap. However, both in our case and Kirman’s case, the signals from Pacinian corpuscles didn’t include any information on the onset of the stimulus. Therefore, it is possible to infer that the information on the onset of stimulus detected by Pacinian corpuscles is one of the reasons that the subjects could distinguish between successive indentations and stroking, and prevented them from perceiving tactile apparent movement.

7. Summary

In this study, we presented a new tactile display using acoustic radiation pressure. The temporal properties and spatial resolution of the display were quite good and could produce 2 gf total force. We also carried out experiments on tactile apparent movement with the tactile display and found that it is possible to induce tactile apparent movement quite stably by successive indentation and that the sensation of tactile apparent movement is indistinguishable from that of actual stroking.

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