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# INVESTIGATION OF VHI AFFECTED BY THE DENSITY OF MECHANORECEPTIVE UNITS FOR VIRTUAL SENSATION

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***Abstract- The velvet hand illusion (VHI) is an innovative tactile illusion that enables a human to perceive a velvety sensation by gently rubbing the hands on both sides of wire mesh string through a frame. In order to enhance tactile displays presentation ability, VHI's mechanism is applied through a series of psychophysical experiments. In this paper, we have investigated the effects of several physical parameters on intensity variation of VHI in subjects' fingers and fingertips, such as wire distance D and a dimensionless ratio of wire stroke r to wire distance r/D in passive touch based on psychophysical experiment. We obtain D = 45 mm and r/D ≈ 1 as optimum values for VHI intensity for wire distance***

***and the ratio, respectively. Furthermore, as the result of comparison between the present result and the previous result for palm, we conclude that a combination of mechanoreceptive afferent units, SAI, SAII and FAI, are involved in VHI. VHI mechanism is induced when movement of wires is accepted through FAI under constant compressive stimulus for SAI and no shearing force for SAII. This result indicates that VHI can be generated by normal pin matrix type tactile displays because no stimulation of SAII is required.***

**Index terms: Tactile displays and sensors, Virtual sensation, Velvet hand illusion, Psychophysical experiment, Mechanoreceptive afferent units.**

## I. INTRODUCTION

The virtual reality (VR) concept, occasionally called virtual environments, has attracted scientists' attention for a few decades. VR technology allows a human to perceive and experience sensory contact with a nonphysical world. To date, application of VR has expanded to a range of studies including education, business, medical care, entertainment, CAD/CAM and robotics. From the standpoint of robotics, the haptic devices seem to be indispensable tools with the most effect on VR. They utilize both tactile and force sensory information because haptic perception in VR enables humans to produce an interaction with their environments in daily life.

Tactile displays, which are a human-machine interface, are one of the critical parts of haptic devices in making the virtual environment appear as a real environment. There are many significant types of experimental tactile displays, such as mechanical vibratory pin arrays [1], surface acoustic waves [2], pin arrays driven by a pneumatic actuator [3], piezoelectric actuator arrays [4] and a new spherical haptic device equipped with unlimited work space [5]. However, these studies have endeavored to generate pressure distribution to emulate the tactile sensation of a human's fingers touching a virtual object. Despite these attempts, there is enormous difference between virtual and real tactile sensation because the tactile display does not generate relative motion between the finger surface and the display pad, which prevents the sensation of real touch. In previous work, we have developed a tactile display that capable of generating pressure and slippage stimuli to enhance the reality generated by tactile displays [6]. Although the tactile display can enhance edge detection precision, the reality generated by the display is not always satisfied. Hence, we are attempting to develop new tactile displays using tactile illusions so that the human brain perceives the virtual objects as real ones regardless of lack of relative motion on the tactile display.

Many early studies of tactile illusion, which generates an erroneous perception of touch, concentrated on investigating whether there were tactual analogous phenomena of commonly reported geometric optical illusion [7]. In contrast, more recent studies have been directed toward achieving illusory phenomena that arise when humans perceive either the real world or virtual environment via haptic interfaces [8]. Although there are several types of tactile illusions such as Aristotle's illusion, which is a classic shape illusion [9], fishbone illusion [10], comb illusion [11] and velvet hand illusion (VHI) [12]-[14], we expect VHI exhibited in a science museum in San Francisco (http://exs.exploratorium.edu/exhibits/velvet-hands/) would be appropriate for application to the tactile display because it produces virtual feel of texture such as velvetiness sensation in the human's hands [12]. In VHI, a person gently rubs his/her hands together on both sides of mesh wires strung through a frame in a grid pattern. We focus on several effective parameters of VHI strength because an illusion's strength refers to magnitude changing in the human perception. Thus, in the previous study we have proposed that VHI could be applied to a future tactile display capable of presenting virtual feeling with variable intensities of the parameters [13].

Here, we review the literature on VHI. As above mentioned, studies have shown that VHI produces velvetiness, softness sensation. The strength of the velvetiness sensation generated by VHI depends on several parameters of stimulation. Mochiyama *et al*. concluded that VHI was sensed in the area between two wires on the surfaces of joined hands [12]. Ohka et al. found that the intensity of VHI depended strongly on the distance between the two wires, so that increasing wire distance led to increasing strength of VHI perception [13]. In addition, the intensity of VHI caused by passive touch was considerably stronger than that caused by active touch. These studies have also shown that the strength of VHI intensity depends on the ratio of wire strokes to wire distance.  This ratio caused the strongest VHI occurred when the ratio almost equals one ($r/D \approx 1$; $r$ and $D$ are wire movement stroke and wire distance, respectively). Eventually, the strongest VHI occurred at a particular frequency relative to wire motion. Consequently, the results represented a combination of mechanoreceptive afferent units (SAI and SAII units), which are necessities for designing a tactile display using VHI [14]. These results also suggest that VHI can be controlled by manipulation of various aspects of the external mechanical simulation using a tactile display [15].

However, the previous studies investigated intensity of VHI on the palm of the human hand. Since the population of mechanoreceptive afferent units is variable in different parts of human hand skin [16], we expect identification of the mechanoreceptive afferent unit for VHI using this characteristic: if we compare the present result with the previous one, we can identify the mechanoreceptive afferent unit for VHI because mechanoreceptors' populations of palm is sparse, meanwhile at fingers-and-fingertips is dense. Therefore, it is important for VHI study to investigate variable intensity of VHI in additional parts of the hand skin.

In this study, we focused on variation of VHI intensity on fingers and fingertips based on several different conditions. As the feeling of an illusion is an event that occurs in the individual mind, psychophysical experiments using Thurstone's method of paired comparison are conducted to measure the intensity of VHI perception. To conduct the experiments, we prepared several wire frames so that they were fixed on a motorized *x*-table with reciprocating motion to cause the subject to feel passively. First, we investigate the effects of variation in wire distance on intensity of VHI in passive touch. Second, we survey the relationship between wire stroke movement and intensity of the illusion. Finally, we introduce a possible combination of mechanoreceptive afferent units with a main role in VHI sensation in fingers and fingertips. Furthermore, we will design a new tactile display based on the results.

## II. MECHANORECEPTIVE AFFERENT UNIT

For later discussion, we summarize characteristics of mechanoreceptive afferent units in this section because they closely relate to VHI sensation.

A mechanical stimulation or pressure on the skin surface can activate tactile receptors, which are called mechanoreceptors. Four types of mechanoreceptive afferent units have been found. They number 17,000 units scattered throughout the glabrous skin layers of the human hand. They classified into two types of fast adaptation units, FAI and FAII units; and two types of slow adaptation units, SAI and SAII units [17]. Each of the mechanoreceptors, known as the Merkel disk (SAI), Meissner corpuscle (FAI), Pacinian corpuscle (FAII) and Ruffini ending (SAII), is particularly sensitive to a category of mechanical stimulation as shown in Table 1 [18]-[21].

SAI responds best to steady compressive pressure. In addition, it is highly sensitive to points, edges and curvature such as Braille dots, when a person explores an object or surface with his/her hands. This means that it enables tactile acuity. Furthermore, it responds to extremely low frequency of less than 5 Hz. SAII detects sustained downward pressure and particularly the lateral skin stretching that occurs on the skin surface. However, a single SAII is incapable of generating tactile sensation; hence to detect a stimulus, more than a single SAII must be stimulated [19].

FAI responds to low frequency normal vibration from about 5 to 50 Hz (flutter) while an object makes contact with the hand. In contrast, FAII responds best to high frequency normal vibration from about 50 to 700Hz (buzz) [18]-[20]. In addition, a study conducted on tangential vibration by Miyoka et al. found that the FAII receptor responds to high frequency from about 100 to 350 Hz, whereas the tangential vibration has no effect on FAI receptors [21].

Table 1. Mechanoreceptors: summary of features and associated function [17]-[21]

| **Mechanoreptive afferent unit population (Corresponding mechanoreceptor)** | **Maximum feature sensitivity** | **Primary function** |
|---|---|---|
| SAI (Merkel disk) | Sustained pressure, very low frequency (< 5Hz), spatial deformation | Texture perception, detect points, edges and curvature |
| FAI (Meissener corpuscle) | Temporal changes in skin deformation (5-50 Hz), motion | Low-frequency vibration |
| FAII (Pacinian corpuscle) | Temporal changes in skin deformation (normal vibration: 50-700 Hz) & (tangential vibration: 100 - 350 Hz ) | High-frequency vibration |
| SAII (Ruffini ending) | Lateral skin stretch | Finger position, stable grasp |

Table 2. Density of mechanoreceptive afferent units in three different parts of human hand (unit/cm$^2$) [16]

| **Mechanoreptive afferent unit** | **Palm** | **Finger** | **Fingertip** |
|---|---|---|---|
| SAI | 8 | 30 | 70 |
| SAII | 18 | 17 | 16 |
| FAI | 25 | 40 | 130 |
| FAII | 10 | 10 | 22 |

VHI is generated by both normal and tangential stimuli on the surface of hand skin simultaneously because the VHI does not occur for single hand touch. The normal pressure is generated by compressing the fingers, and it leads to generating stress on the finger skin layers. The tangential stimulus is generated through the stroking of wires on the skin surface while the wires are moved between the fingers [14]. The combination of stimuli leads to activating mechanoreceptors in the fingers or fingertips. Our final objective is to determine what combination causes the velvetiness perception in the brain as the subjects reported in the previous experiments.

In 2002, Johansson et al. showed that the mechanoreceptors are always working together to inform us about different sensations. They gave the example of opening a door with a key. Feeling the shape of the key requires the SAI units (or likely FAI units), and grasping and preventing the key from slipping involve the SAII and FAI units. Finally, the FAII notifies us that the key has hit the end of the keyhole [22]. Moreover, Johansson and his colleagues also showed that density of mechanoreceptive afferent units is variable in different parts of the hand as shown in Table 2 [16]. Therefore, it could be assumed that not only a combination of mechanoreceptive afferent units evoked with VHI but also difference in density of mechanoreceptors is influences on tactile sensation.

## III. PSYCHOPHYSICAL EXPERIMENT

### a. Experimental Apparatus

We mentioned that VHI occurred not only when touching a wire grid but also two adjacent wires [12]. Based on the authors' subjective judgment, VHI sensation occurring with two parallel wires is stronger than that with a wire grid. The apparatus shown in Fig. 1 is used in the present study. The frame is made of acrylic board; two piano wires 0.8 mm in diameter are strung through the frame. A bolt and nut are used for generating sufficient tension in the wires.

In all experiments, the primary contact area was the fingers (phalanxes) and fingertips, with occasional contact occurring in the distal palm and no contact off of the fingertip. Although a few subjects were able to sense VHI in the distal palm, the majority reported that VHI sensation occurred on both the whole area of their middle and proximal phalanxes and fingertips as shown in Fig. 1.

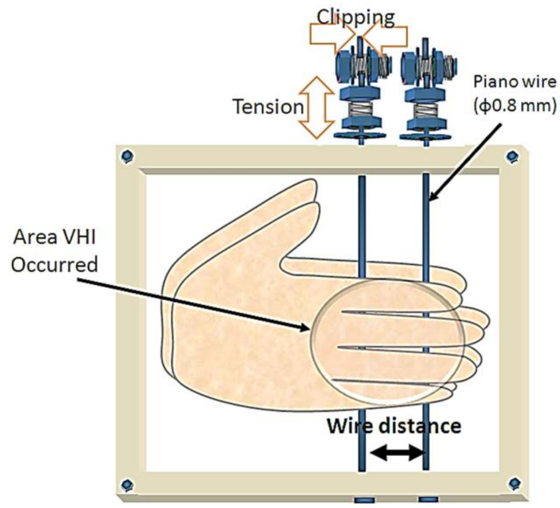
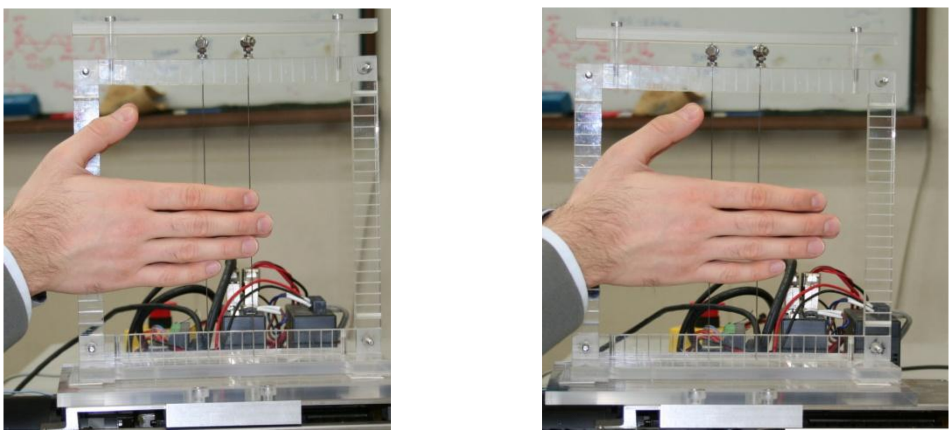



**Figure 1.** Experimental setup



a. Forward movement b. Backward movement

Figure 2. Scene of psychophysical experiment

In this experiment, we adapted five wire distances ($D$) of 15, 25, 35, 45 and 55 mm. The minimum wire distance ($D$ = 15 mm) was selected based on a process of trial and error, revealing that wire distances such as $D$ < 15 mm were too small to generate the velvetiness sensation. We also selected the maximum wire distance ($D$ = 55 mm) based on length of a typical person's middle finger, which is roughly 70 - 80 mm. For the experiment to be successful, when the wires move between the subject's hands, both wires should not leave the fingertips and not travel into the distal flexion crease. The relationship between fingers and wires is shown in Fig. 2. Even if the frame moves forward and reaches the terminal of forward motion, the wire is not off of the fingertip; if the frame moves backward and reaches the terminal of backward motion, the wire does not contact the distal palm. Thus, maximum wire distance adapted is less than the length of middle finger.

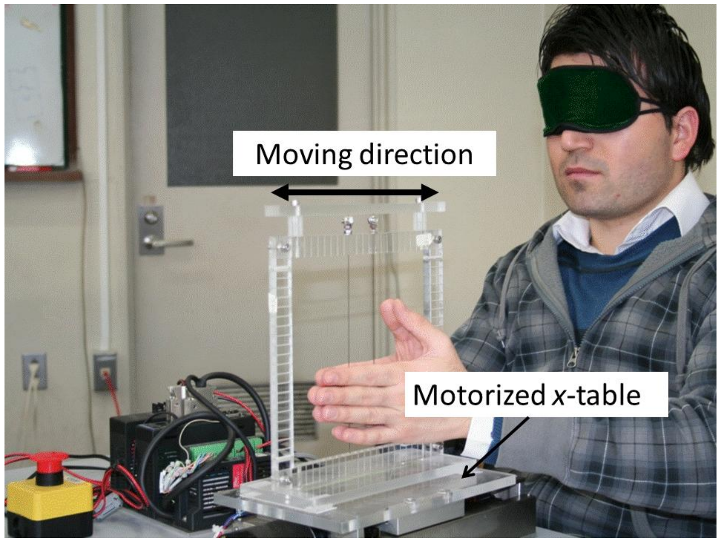


Figure 3. Scene of psychophysical experiment

All psychophysical experiments are examined in passive touch, which means a human subject does not move his/her hands, and the frame is moved instead. The frame is fixed on a motorized *x*-table and moved with reciprocation motion, while the subject's hands are without motion as shown in Fig. 3. The motorized *x*-table can be programmed for various stroke distances using software (MAXP01, Oriental Motor Co. Ltd.). The average of temperature and humidity for the first and the second experiment were 27.2 °C and 70%, and 22 °C and 43%, respectively.

b. Thurstone's Paired Comparison Method

Although measuring the strength of an illusion is the goal of this study, it is extremely difficult to ascertain the strength because the perception of an illusion is an event that occurs in the individual mind. In order to investigate such difficult measurement, psychophysics method is use since it is very effective to survey the relationship between physical stimuli and the sensation and perception. There are several psychophysical experimental methods to measure events in the mind. Since Thurstone's method of paired comparison is one of the key psychophysical experiments and is the one most frequently employed to collect data based on comparative judgments [23], we employed it in this study.

For generating stimuli combinations of Thurstone's method of paired comparison, in the experiment we introduced five values of a parameter as stimuli to make a league table as shown in Table 3(a). The first column and row show stimuli in the table. Relationships between the first and second stimuli are shown in Table 3(b). In the experiments, human subjects report judgments based on comparing two different stimuli. For example, pair numbers #18 and #8 in Table 3(a) refer to a comparison between stimuli 4 and 3. If the human subject feels stimulus 4 is stronger than stimulus 3, the number of wins is recorded in the column of #18. If matching of stimulus 4 versus 3 is done 10 times and stimulus 4 wins the match 6 times, 6 and 4 are written in the cells of #18 and #8, respectively. Since, in every comparison, the subject compares two different stimuli, there are twenty trials in Table 3(b).

| | *Stimulus* 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| *Stimulus* 1 | ------- | *Pair* #1 | #2 | #3 | #4 |
| 2 | #11 | ------ | #5 | #6 | #7 |
| 3 | #12 | #15 | ----- | #8 | #9 |
| 4 | #13 | #16 | #18 | ----- | #10 |
| 5 | #14 | #17 | #19 | #20 | ----- |

(a) League table

| *Pair Number* | *First Stimulus Number* | *Second Stimulus Number* |
|---|---|---|
| #1 | 1 | 2 |
| #2 | 1 | 3 |
| #3 | 1 | 4 |
| #4 | 1 | 5 |
| #5 | 2 | 3 |
| #6 | 2 | 4 |
| #7 | 2 | 5 |
| #8 | 3 | 4 |
| #9 | 3 | 5 |
| #10 | 4 | 5 |
| #11 | 2 | 1 |
| #12 | 3 | 1 |
| #13 | 4 | 1 |
| #14 | 5 | 1 |
| #15 | 3 | 2 |
| #16 | 4 | 2 |
| #17 | 5 | 2 |
| #18 | 4 | 3 |
| #19 | 5 | 3 |
| #20 | 5 | 4 |

(b) Relationship between two stimuli included in each pair

Table3.Comparison tables for method of paired comparison

In actual tests, the pairs of stimuli were presented randomly to avoid unintentional selection bias. Thus, each subject responded to three sets of twenty (60 trials total), which are performed for each subject. The Thurstone's paired comparison method is relied on for constructing psychological interval scales. Therefore, after all experiments are conducted, for each stimulus choice probability *p* is obtained from the results.

c. Human Subjects

Five healthy male volunteers in their twenties participated in this study as human subjects. In each trial, the subject pressed his both hands together with normal force. They had to judge between two stimuli and selected the stimulus that produced the stronger VHI sensation on their fingers and fingertips. Since the experiments were adapted based on *within subject design*, all subjects had to contribute to two distinct series of psychophysical experiments. One of them was for examining the effects of variation of wire distance on the strength of VHI sensation. The other was for testing the effect of stroke movement distance on VHI intensity.

## IV. EXPERIMENTAL PROCEDURE RESULTS

a. Experiment 1: Optimum Wire Distance

First, to obtain the optimum condition of wire distance, we surveyed the effects of various wire distances ($D$) on intensity of VHI sensation. Thus, we adopted five wire distances, $D$ = 15, 25, 35, 45 and 55 mm. The stroke $r$ and the velocity of wire movement $V$ were held at constant values, $r$ = 35 mm and $V$ = 100 mm/sec (mean velocity of reciprocating motion) in all experiments, respectively. In the previous study, when the dimensionless ratio of wire stroke to wire distance was almost one, the strongest VHI was perceived [14]. Therefore, we selected wire stroke at 35 mm to have an up-and-down range of quantities around a numerical value of one for the ratio ($r/D \cong$ 0.6, 0.8, 1, 1.4 and 2.3).

The experimental results are shown in Fig. 4. It is obvious that the intensity of VHI increases significantly from wire distance $D$ = 15 mm to 45 mm. In contrast, the intensity of VHI decreased steeply from wire distance 45 mm to 55 mm. Accordingly, we concluded that the optimum value of the experiment is $D$ = 45 mm to cause the strongest VHI intensity. If $D$ = 45 mm is used to calculate the ratio $r/D$, the ratio causing the maximum VHI intensity is 0.8, which is close to one.

b. Experiment 2:Influence of $r/D$ on VHI

Subsequently, we performed Experiment 2, of which the goal was investigating the relationship between wire stroke and wire distance for interpreting VHI mechanics. While wire distance is changed in Experiment 1, movement stroke is changed in this experiment. For this purpose, a series of experiments was conducted for five movement strokes, $r$ = 18, 27, 36, 45 and 54 mm, related to a constant value of wire distance $D$ = 45 mm. We obtained the dimensionless ratio of wire stroke to wire distance, $r/D$ = 0.4, 0.6, 0.8, 1 and 1.2. The velocity of the motorized $x$-table in the experiment was also at the constant value $V$ = 100 mm/sec.

The experimental result is shown in Fig. 5. This result shows that increased amount of the ratio from 0.4 to 1 leads to significantly raising the intensity of VHI. On the other hand, this expansion is saturated from $r/D$ = 1 to 1.2 and the variation becomes almost constant. As mentioned, although maximum VHI intension is caused at around $r/D \cong 1$, variation in $r/D$ causing the maximum VHI intensity is slightly different between the controls of Experiment 1 (control $D$) and Experiment 2 (control $r$).

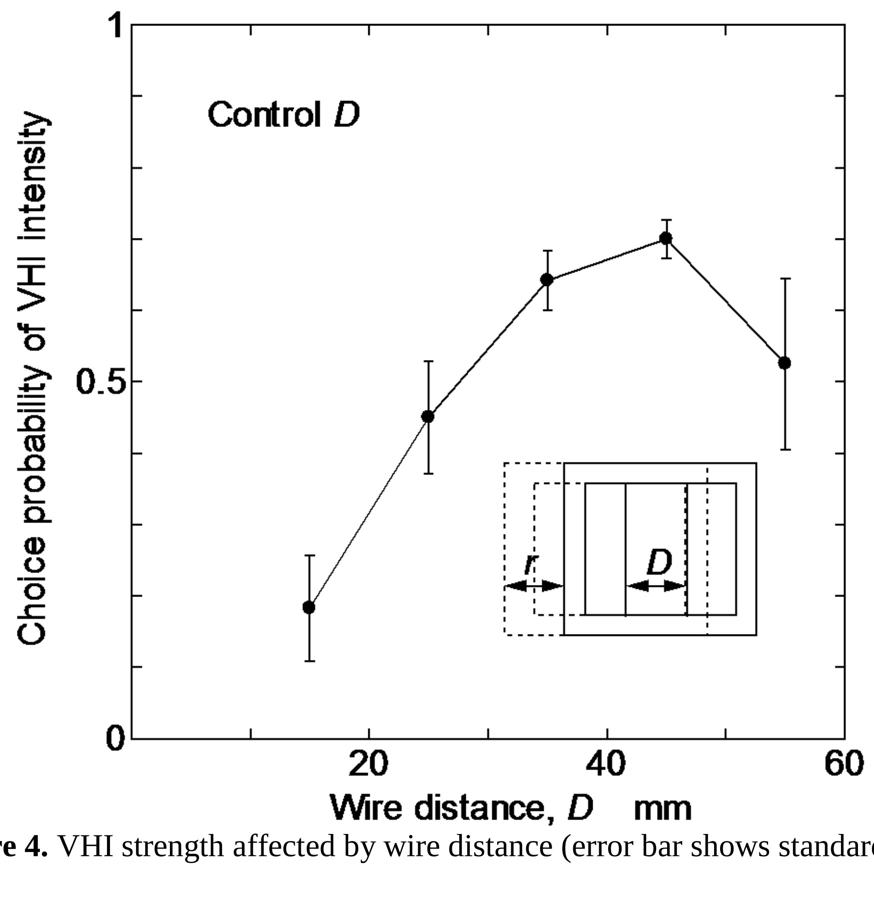



**Figure 4.** VHI strength affected by wire distance (error bar shows standard error)

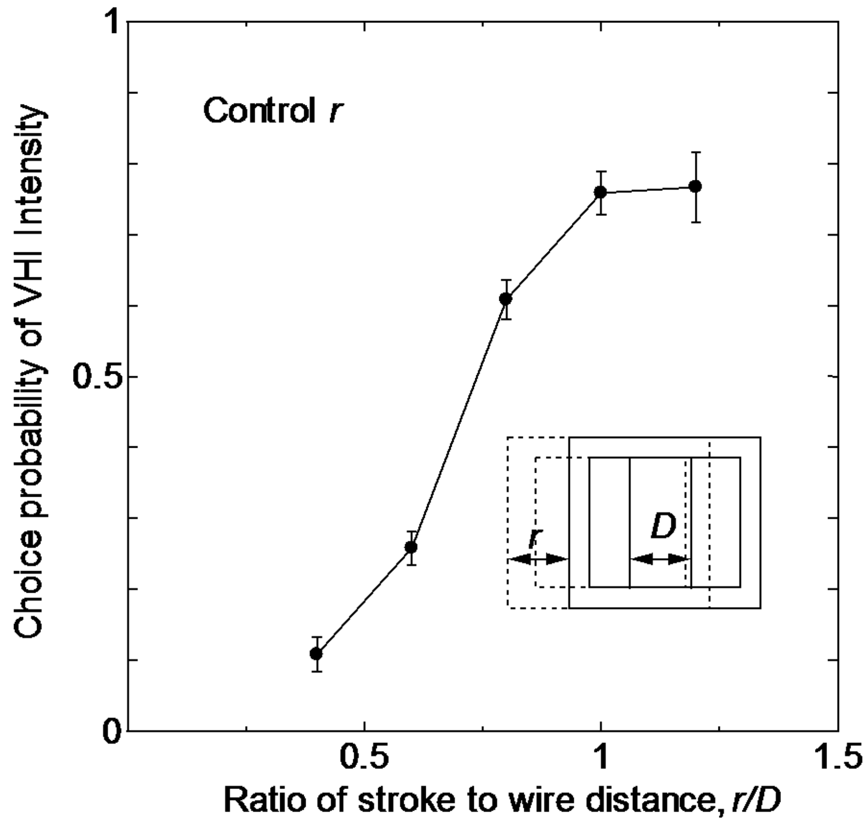



**Figure 5.** VHI strength affected by ratio of stroke to wire distance (error bar shows standard error)

## V. DISCUSSION

### a. Combination of Mechanoreceptive Afferent Units

We will consider what combination of mechanoreceptive afferent units evokes VHI. Primarily, we assume that FAII does not function at relatively low frequency because in the previous study, the optimum frequency for VHI was obtained at 50 Hz [14]. Thus, there is no need to consider FAII effect on VHI because VHI occurs in the relatively low frequency condition in the following discussion; FAII captures high frequency vibration as shown in Table 1.

First, we examine the dependence of VHI on the region between two wires and movement distance. The experimental results ensure that the strongest VHI is generated when the wire stroke is almost equal to wire distance ($r/D \cong 1$) from Figs. 4 and 5. The intensity of VHI is proportional to movement distance $r$ in the region of $r/D < 1$. This result confirms the mechanism of VHI assessed on the palm in the previous study by the authors [16]: the velvetiness feeling of

VHI is proportional to the movement of the area sandwiched by wires *r* when $r/D < 1$; it decreases with increasing *r* when $r/D > 1$; it becomes the maximum when $r/D \cong 1$.

Next, we consider the fact that the condition inducing maximum VHI intensity is almost the same in both palm and fingers. According to Table 2, although SAII has similar density in both palm and fingers, SAI and FAI have largely different density. In spite of the large density difference of mechanoreceptive afferent units, the condition invoking maximum VHI intensity is almost the same in both palm and fingers. This means that mechanoreceptive afferent units' density is not so important for generating VHI. Since retrieving the contact pattern requires high density of mechanoreceptive afferent units, simple tactile feeling received on either the whole palm or fingers, such as compressive and no skin stretching feeling, is important for VHI.

Since VHI does not occur without pressure caused by joining the hands, sensing ability for compressive pressure is primarily important. We assume that the compressive pressure is detected by SAI because SAI units are more sensitive to steady pressure than FAI units. Since VHI is invoked when compressive pressure is applied on the palm or fingers and there is no skin stretching feeling because of no relative tangential movement between the two joining hands, VHI is induced under that SAI receives the compressive pressure with no SAII activation. Yet no SAII activation also has meaningful to perceive VHI.

On the other hand, FAI units are four times more sensitive to dynamic skin deformation than SAI units [20]. Therefore, the wire motion seems to be detected by FAI and not SAI units. This means that FAI plays a role as a trigger for invoking VHI sensation via the information of moving wires, which induces a feeling of contact area movement. However, VHI intensity is reduced by extremely large stimulus of wire motion because VHI decreases with increasing *r* when $r/D > 1$.

Furthermore, as referred to in the previous chapter, variation in $r/D$ causing the maximum VHI intensity is slightly different between controls of *D* and *r*. While the maximum VHI intensity is caused at $r/D = 0.8$ in the experiment controlling *D* (Experiment 1), maximum VHI intensity is saturated from $r/D = 1$ to 1.2 in the experiment controlling *r* (Experiment 2). Since greater $r/D$ in Experiment 2 causes longer stimulation time, the velvetiness feeling generation requires sufficient stimulation time. This corresponds to our subjective feeling about the velvetiness sensation, which emerges after a little time delay.

Finally, we introduce the conditions for generating VHI: while compressible pressure sensed by SAI is applied to the palm or fingers, constant tangential stress sensed by SAII does not occur in spite of wire movement sensed by FAI. We suppose that the velvetiness feeling is caused by active SAI and non-active SAII and that FAI plays a role in triggering the feeling. Although we drew similar conclusions in previous studies, the contributions of SAI, SAII and FAI have become clearer via this study. Consequently, VHI sensation does not independently occur in unreceptive afferent units but in the brain because the condition composed of active SAI, non-active SAII and active FAI is handled by the brain.

b. New Tactile Display

Based on the results, we will design a new design of tactile display in this section. According to the results, no SAII stimulation is required because skin stretching feeling is not important. Since skin stretch feeling is not required for VHI, we do not need to use a special actuator such as one used in the pressure-slippage-generation tactile mouse [6].

Although compressive force stimulus is required, this stimulus is easily generated by keeping a contact with human skin and a plane surface. After making a palm contact with a plane surface, VHI is appeared if not moving it on the surface and appropriate trigger stimulus is added.

The abovementioned combination of stimuli can be generated by the common pin matrix type tactile display [4][6]. However, the generation of the appropriate trigger stimulus is yet unknown. Consequently, any new design of tactile display is not needed for VHI but the conventional pin matrix type display can be adopted as the tactile display. In the future work, we will investigate the way of generating appropriate trigger stimulus using the pin matrix type display.

## VI. CONCLUSIONS

In this study, we investigated the strongest VHI for several different conditions in fingers and fingertips using psychophysical experiments with Thurstone's method of paired comparison. In the results of the experiments, wire distance $D$ = 45 mm is the optimum value for generating the largest velvetiness sensation. Furthermore, the strongest VHI occurred when the stroke was almost equal to the wire distance ($r/D \cong 1$). In addition, evaluation of the density of mechnoreceptive units in different parts of the hand showed that SAI, FAI and SAII play crucial roles in the perception of VHI, whereas FAII did not have any effect on VHI sensation based on the previous studies. This result indicates that VHI can be applied by normal pin matrix type tactile displays because no stimulation of skin stretch feeling (SAII) is required.

Although this study could introduce the mechanism for combination of mechnoreceptive afferent units' activity related to VHI, we believe that the obtained results are not sufficient to prove the mechanism. This means that while we distinguished the combination of mechanoreceptive afferent units that are part of the answer to the VHI mechanism, the coteries that are activated in the human brain also play a role in determining its mechanism. This study did not concentrate on the human brain and how it reflects VHI. In future work, a functional Magnetic Resonance Imaging (fMRI) study will allow us to investigate which brain regions play a role in VHI.

## VII. ACKNOWLEDGMENT

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