The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Virtual Active Touch II: Vibrotactile Representation of Friction and a New Approach to Surface Shape Display

Sho Tsuchiya, Masashi Konyo, Hiroshi Yamada, Takahiro Yamauchi, Shogo Okamoto and Satoshi Tadokoro

***Abstract*— The tactile display for handheld devices requires compact hardware and useful applications. To satisfy these points, we have proposed the concept of 'Virtual Active Touch' that implements virtual exploration with a cursor on a screen through a pointing-stick-type tactile interface. The objective of this study is to present three-dimensional shapes on a two-dimensional screen without force feedback devices. It is possible to present three-dimensional shapes such as a bump using a lateral force [1]. In order to represent human perception of geometric surface shape, instead of the lateral force, we use the cutaneous sensation of friction that occurs when a human finger strokes object surfaces. First, we confirmed that the Virtual Active Touch interface could present cutaneous sense of friction. Second, we evaluated the perception of surface height in the context of bumped shape induced by the friction display. The experimental results agreed with our expectation that faster and longer increases in friction sensation were perceived as higher bumped shapes.**

I. INTRODUCTION

Many handheld devices; such as mobile phones, PDAs, and portable media players; have become popular in our life. Haptic interaction with them is expected to enhance their usability and provide strong impressive experiences. To popularize such haptic interaction, more compact hardware and more useful applications must be developed.

Recently, touch screens with vibratory tactile feedback have been developed for handheld devices and several commercial mobile phones have employed them. For example, Immersion Corp. has developed tactile feedback technology with vibrations of touch screens [2]. However, actuation of the entire screen has limitation to produce richer tactile information because large area and heavy mass of the screen restrict controllability. On the other hand, Luk et al. [3] have developed a handheld tactile display using a compact tactile stimulator known as STRESS2 [4], which produced discrete lateral skin stretches. The stimulator was attached on a slider-type controller located on the side of the handheld device. The tactile feedback was generated in response to movement of the finger placed on the controller. The objectives of their study were to deliver haptic icons as just symbolic information.

We have proposed the concept of 'Virtual Active Touch' to overcome the size and weight limitations of a haptic device [5]. This concept is implemented by applying a tactile feedback function to a pointing-stick-type interface as illustrated in Fig. 1. The pointing-stick is operated by the fingertip and generates tactile feedback. The cursor on the

S. Tsuchiya, M. Konyo, H. Yamada, T. Yamauchi, S. Okamoto and S. Tadokoro are with the Graduate School of Information Sciences, Tohoku University, 6-6-01 Aramaki Aza Aoba, Aoba-ku, Sendai, 980-8579, Japan {tsuchiya, konyo, yamada, yamauchi, okamoto, tadokoro}@rm.is.tohoku.ac.jp

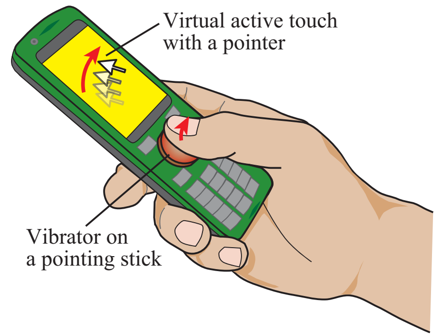

Fig. 1. Concept of virtual active touch[5]

screen can perform virtual exploration as a substitute for the finger without actual hand movement. This approach makes the tactile stimulator much smaller than the touch-screen type while providing richer tactile sensation because a smaller stimulator can generate complex waveforms rapidly. Our question was whether Virtual Active Touch could produce the same tactile sensation as actual hand exploration. We have already confirmed the performance of Virtual Active Touch for perceiving roughness [5]. Psychophysical experiments showed that Virtual Active Touch delivered perceived roughness identical to that provided by tactile interfaces involving actual hand exploration. However, the suitability of Virtual Active Touch for other sensations is not yet established. In this second report, we verify the perception of friction through Virtual Active Touch.

This study also proposes a new approach to inducing human geometric shape perception using the proposed friction display. Conventional tactile displays have attempted to reproduce the tactile sensation itself and the tactile quality. In contrast, our main target is the reproduction of the kinesthetic sensation induced by the tactile sensation. In particular, we aim to reproduce human perception of geometric surface shape induced by the cutaneous sensation of friction. The perception of geometric shape is regarded as kinesthetic information [6]. Robles-De-La-Torre and Hayward [1] determined that lateral force between the skin and the surface is the main cue in perceiving geometric shape through active touch. If any tactile sensation can substitute for the lateral force in shape perception, we can present three-dimensional shapes on a two-dimensional screen without force feedback devices. The shape display can be applied to representing GUI icons such as a button and a slider, 3D-maps, movement of shapes, *etc*. Such technology would drastically expand the range of tactile applications, compared with conventional quality-oriented tactile displays.

In this study, a friction display method using vibratory stimulation as we have proposed [7] is applied in support of the above concept. This display method provokes the sensation of friction using tactile vibrations instead of lateral force. The vibratory stimulation is generated in response to stick-slip transitions between the skin and the surface depending on hand exploration speed and normal force. We expect that cutaneous friction sensation can replace lateral force in shape perception.

The objective is to verify the possibility of tactile-induced shape perception using the friction display through Virtual Active Touch. We confirm the potential of our new approach to presenting three-dimensional surface shapes via tactile sensation. To use the friction display through Virtual Active Touch, we confirm that the friction displaying method [7] can be applied in Virtual Active Touch.

In this paper, we first give an overview of the proposed friction display method and local modifications. Next, we describe two types of experimental apparatus to evaluate the friction display through Virtual Active Touch. Finally, we evaluate tactile-induced shape perception by changing friction sensations.

II. FRICTION DISPLAY BY VIBRATORY STIMULI

We use a vibrotactile display method that presents friction sensations to users [7]. The method focuses on stick-slip contact of finger skin with an object. The method delivers friction sensations by controlling activity of FA II type tactile receptors at the moment of stick-to-slip transition using high frequency vibrations more than 200 Hz, which are selected to fit the frequency response characteristics of the FA II type receptor. We use the same stick-slip friction model in the previous paper and improve a waveform of vibratory stimuli to produce more natural friction sensation.

A. Stick-slip Friction Model

The stick-slip phenomena of the contact between finger skin and object surface were simulated by a 1-DOF vibration model with Coulomb friction, shown in Fig. 2. The model approximates the dynamic characteristics in the shear direction of a finger pad surface in contact with a flat object. The model involves stiffness k, mass m and viscosity c. The finger contacts a flat object with a normal force N, and lateral friction force F. The velocity of the object is V, and $\dot{x}(t)$ is the finger velocity. The contact state of the finger (stick or slip) was calculated based on this model. Motion equation when stick-to-slip transitions occur is expressed as

$$m\ddot{x} + c\dot{x} + k(x - x_0) = \mu_s N, \quad (1)$$

where x_0 is the position of the object when the spring is in its natural length and μ_s is the static friction coefficient. Since the finger pad is sticking with the flat object in its sticking phase, both the finger pad and object move at a constant velocity V and $\ddot{x}$ is equal to zero. The details of the simulation are described in the literature [7].

Stick-slip phenomena depend on the stiffness and the difference $\Delta\mu$ between the static friction coefficient μ_s and the kinetic friction coefficient μ_k. For example, stick-slip phenomena are less likely to occur with smaller $\Delta\mu$. In order to observe the phenomenon with smaller $\Delta\mu$, the model requires smaller V and higher N.

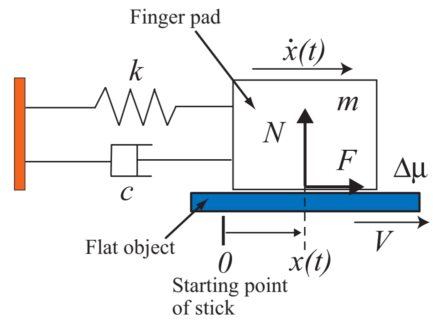

Fig. 2. 1-DOF vibration model of stick-slip motion

The parameters (k, m, c) in the friction model affect the frequency of the stick-to-slip transition. We set these parameters so that the frequency of the model was close to that of a real finger pad in contact with a flat acrylic board, which was measured by filming the contact with a high-speed camera. The selected parameters values were as follows: $k = 2.0$ [N/mm], $m = 1.0 \times 10^{-6}$ [kg], and $c = 1.0 \times 10^{-5}$ [Ns/mm].

B. Control of Vibratory Stimuli

Fig. 3 shows the approach to controlling vibratory stimuli for simulating friction sensations adopted in this report. The finger pad is given vibratory stimuli according to the timing of the stick-to-slip transitions calculated with the stick-slip friction model. We improved a waveform to have a gradual increase of vibratory amplitude at the moment of stick-to-slip transitions, while the previous report had a step increase which cause ragged surface sensation.

The intensity of FA II type receptors' activities is controlled by modulating the amplitude of the applied voltage. The maximum amplitude A of the voltage applied to a vibrator is proportional to elastic energy due to the spring. From the equation (1), the elastic energy at the moment of stick-to-slip transition is expressed as

$$A = B(\mu_s N - c\dot{x}), \quad (2)$$

where B is constant. The amplitude increases as the static friction coefficient μ_s or the normal force N in the friction model increase. The vibration frequency is constant at 300 Hz. After switch from the stick state to the slip state, the applied amplitude increases linearly for 5 ms and then decreases for 30 ms in a quadratic form.

Fig. 4 shows waves of applied voltage (the normal force N= 0.5 or 2.0). Both the amplitude of the applied voltage and the period of the stick-to-slip transition are influenced by N.

III. EXPERIMENTAL APPARATUS

A. Two Types of Tactile Interface

In this research, in order to examine whether or not friction sensations can be presented using Virtual Active Touch, a pointing stick that can deliver tactile sensations has been developed. This pointing stick is an interface which

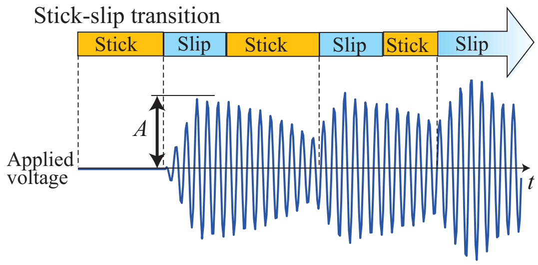

Fig. 3. Control of vibratory stimuli

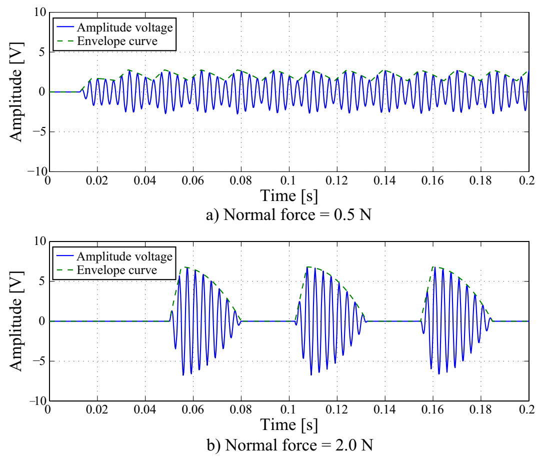

Fig. 4. Waveforms of the vibratory stimulation corresponding to normal force changes.

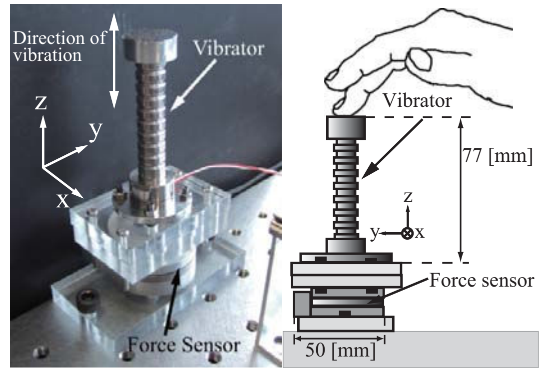

Fig. 5. Pointing-stick-type interface

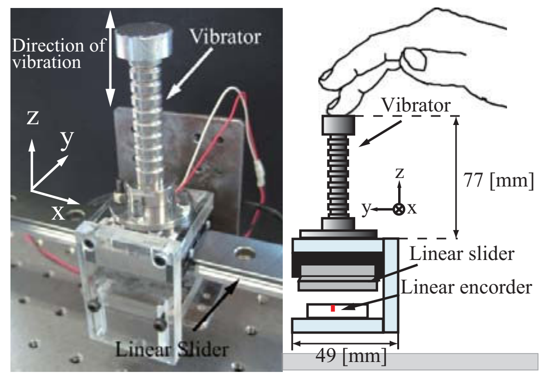

Fig. 6. Linear-slider-type interface

manipulates a cursor on a computer screen by a force input. This interface is named the Pointing-Stick-Type (PS-type) interface. Note that the objective of this study is to confirm the validity of Virtual Active Touch. Therefore, we gave more importance to the performance of the experimental equipment than to miniaturization. We use a vibrator that has sufficiently large output force (800 N) and a sufficiently precise force sensor to perform the pointing operation. However, in our past study [7], a thin-model piezoelectric vibrator was enough to generate stimuli for practical purposes.

Next, in order to compare friction sensation by PS-type to actual touch movement, a Linear-slider-type interface (LS-type) that allows a user to move his finger in a straight line has been developed. The LS-type had the same kind of vibrator and the same approach to control of vibratory stimuli as the PS-type. Therefore the effect of input motion could be determined.

B. Pointing-Stick-Type Interface

The PS-type is shown in Fig. 5. When an operator applies a tangential force with his fingertip to the x-axis, the cursor on a computer screen moves according to the applied force. In addition, according to the speed of the cursor and the force along the z-axis, vibratory stimuli are presented to the finger of the operator.

A contact shoe was installed on top of the vibrator to provide an adequate contact area between the fingertip and the vibrator. The shoe was circular with a diameter of 20 mm and a thickness of 10 mm. A six-axial force sensor (BL-AUTOTECH, MINI2-10) was installed beneath the vibrator to measure the tangential force along the x-axis and the normal force along the z-axis applied to the vibrator.

We employed a linear transformation between the applied force $f(t)$ and the cursor velocity $v(t)$. The transformation equation is expressed as

$$v(t) = \alpha f(t), \tag{3}$$

where α is the gain. $v(t)$ corresponds to V in Fig. 2. The computation frequency for calculating the cursor velocity was 1 kHz. The gain α used in this paper is 316 [mm/Ns] on the basis of a preliminary experiment. In the preliminary experiment, a participant stroked a virtual object at constant cursor velocity and the constant normal force. The participant adjusted the gain so that the vibrotactile sensations presented by the PS-type were similar to the vibrotactile sensations presented by the LS-type. Three male participants aged between 20 and 30 performed the tasks. We used the mean of the gains adopted by participants.

C. Linear-Slider-Type Interface

The LS-type is shown in Fig. 6. When the operator places his finger on the vibrator and moves his hand along the linear guide, the cursor on the computer screen moves and tactile stimuli are presented to the operator's finger on the basis of the cursor velocity and the force along the z-axis. The vibration actuator was installed on top of the linear slider, and was moved along the x-axis with touch movement. The linear guide could slide along the x-axis over a range of approximately 200 mm. The position of the vibrator on the slider was measured by an optical encoder with a spatial resolution of 0.4 μm. The force along the z-axis was measured by a force sensor (VISHAY, 1004) installed below the linear slider. There was a contact shoe as in the PS-type. The velocity of the cursor controlled by the LS-type was equal to the actual hand velocity measured by the encoder. The computation frequency required for calculating the cursor velocity was 1 kHz.

D. Vibrator

The vibratory actuators used for the presentation of friction sensations were piezo stack actuators (NEC/TOKIN, AHB800C801FPOLF). The relationship between the applied voltage and the displacement of the vibrator was linear, as shown in Fig. 7. The figure shows the voltage-displacement plot of the vibrator when it was actuated with a frequency of 300 Hz, the frequency used in experiments.

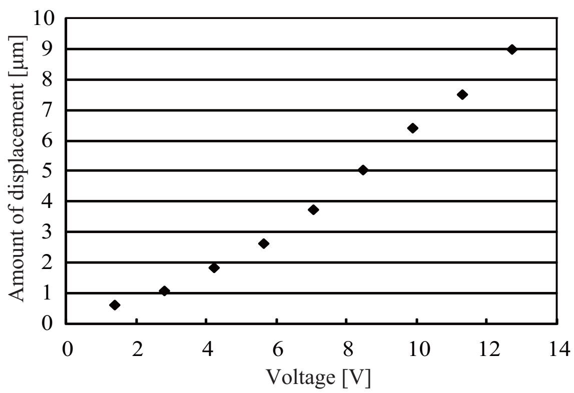

Fig. 7. Amplitude-frequency characteristics on 300[Hz]

E. Visual Stimuli

The image used as a visual stimulus in the experiments should be of a familiar object such that the every experimental subject can imagine its actual dimensions. Otherwise, the subjects would not consider the tactile stimuli to be natural. In our experiments, we used the image of a brick as shown in Fig. 8. Its dimensions as observed on a computer screen were 120 mm $\times$ 60 mm. The cursor manipulated by the interface was a 6-mm-square. When the cursor slid on the brick, vibratory stimuli were displayed through the tactile interfaces.

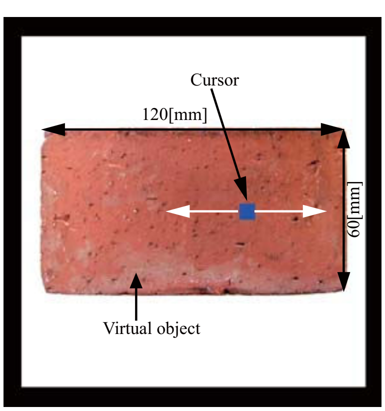

Fig. 8. Visual stimuli

IV. EVALUATION OF FRICTION SENSATION THROUGH VIRTUAL ACTIVE TOUCH

We estimated whether or not a friction sensation was presented by Virtual Active Touch. We compared the friction sensation presented by the PS-type to that of the LS-type.

A. Task and Procedure

The experiments were performed with both the PS-type and the LS-type apparatus. The sensory magnitudes of the perceived friction were evaluated as two parameters (the static friction coefficient μ_s and the difference between the two friction coefficients $\Delta\mu$) in the stick-slip friction model were changed. Magnitude estimation method was applied to evaluate the two types of interface. Participants were asked to assign an arbitrary number to quantify the subjective strength of the friction sensation after stroking a virtual object on a computer screen within 30 seconds. Ten values of μ_s were selected from 0.375 to 0.6 at intervals of 0.025. Three values of $\Delta\mu$ = 0.1, 0.2, 0.3 were applied. Thus, one set of friction conditions contained 10 $\times$ 3 combinations. A participant evaluated one set (30 trials) on both the PS-type and the LS-type with a short break. The ordering of the parameter value combinations was random. In this experiment, the normal force N had a constant value of 2 N, the average force along the z-axis when human stroke objects. The participants wore headphones through which pink noise was played to mask the sounds generated by the vibrator. Five men and one woman aged from 20 to 40 performed the tasks.

B. Experimental Result

The magnitudes of perceived friction were calculated as the geometric average of the normalized ratings of all participants. Fig. 9 and Fig. 10 show the normalized results for the two types of apparatus.

According to Fig. 9, the LS-type successfully increased the perceived friction as the static friction coefficient μ_s increased. This result agrees with a related study [7]. Therefore, the LS-type presents the same friction sensation as in the related study.

According to Fig. 10, the PS-type successfully increased the perceived friction as the static friction coefficient μ_s increased as well as the LS-type did. Therefore, the PS-type presents friction sensation. However, the increases of perceived friction from the PS-type were smaller than from the LS-type. There is a possibility that the difference between these two tendencies was influenced by some factors, such as a weight of vibrator. But, it appears certain that the gain α of the transformation from the applied force to the cursor velocity influences perceived texture in the first report [5].

Correlation coefficients between the PS-type and the LS-type on for $\Delta\mu$ series were calculated. Correlation coefficients for $\Delta\mu = 0.3, 0.2, 0.1$ were $r = 0.595, 0.869, 0.616$. In particular, the correlation coefficient for $\Delta\mu = 0.2$ was higher than those for $\Delta\mu = 0.3, 0.1$.

As a result, although the sensitivity with perceived friction increased as the friction coefficient increased in the PS-type was different from that of LS-type, the ability of

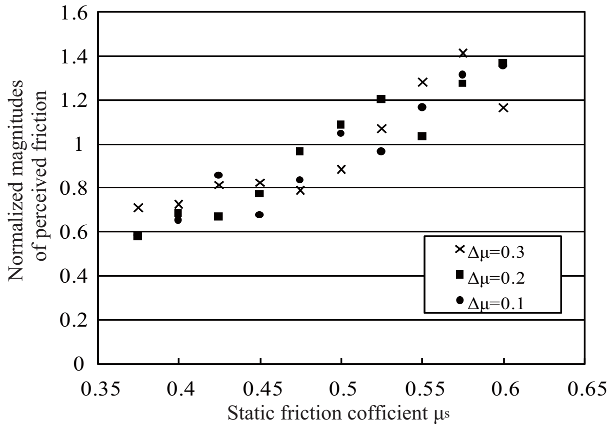

Fig. 9. Perceived friction for LS-type

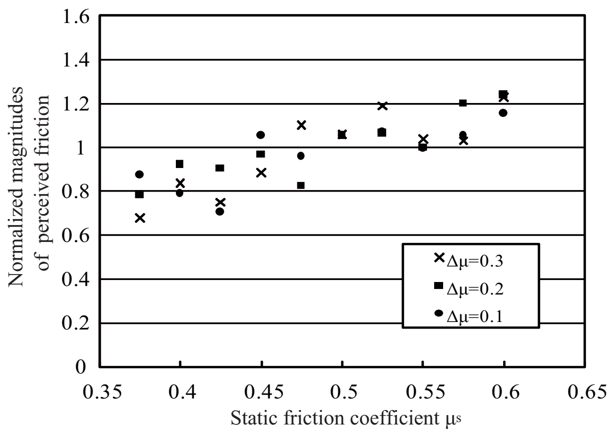

Fig. 10. Perceived friction for PS-type

Virtual Active Touch to present friction sensations using the suggested method for synthesizing vibratory stimulation was confirmed.

V. EVALUATION OF SURFACE SHAPES PERCEPTION BY FRICTION SENSATION

A. Purpose

We examined the possibility of presenting geometric shapes by changing the friction sensation as an example of kinesthesia induction by tactile perception. We confirmed whether geometric shapes could be perceived by changing friction during touch movement as described in the Introduction.

As an example of geometric shapes, we aimed to present the shapes of sloped edges of bumps. It appears that the shape of the slope is perceived as an increasing virtual lateral force as the friction sensation gradually increases during touch movement. It also appears that a higher slope is perceived when either the rate or the span of the increase in friction sensation is larger. The reason is that the lateral force increases faster when the slope is sharper. Therefore, we examined whether different heights were perceived depending on the rate or span of increasing friction sensation.

B. Task and Procedure

To control the friction sensation, the normal force was increased artificially. The method we have suggested for synthesizing a friction sensation is based on Coulomb friction model. Therefore, as the normal force increases, a lateral force (fixing strength) increases. Moreover the period of the stick-slip transition is influenced. The virtual normal force was increased from N_1 to N_2 at a rate of increase k over a span L when a user stroked a virtual object on a computer screen as shown in Fig. 11. The normal force was $N_1 = 0.5$ on the left side of the virtual object, and was changed to N_2 depending on L and k in the middle of the virtual object. The normal force $N(x)$ at the position x was expressed as

$$N(x) = \begin{cases} N_1 & (L_0 \leq x < L_1) \\ k(x - L_1) + N_1 & (L_1 \leq x < L_2) \\ N_2 & (L_2 \leq x < L_3). \end{cases} \quad (4)$$

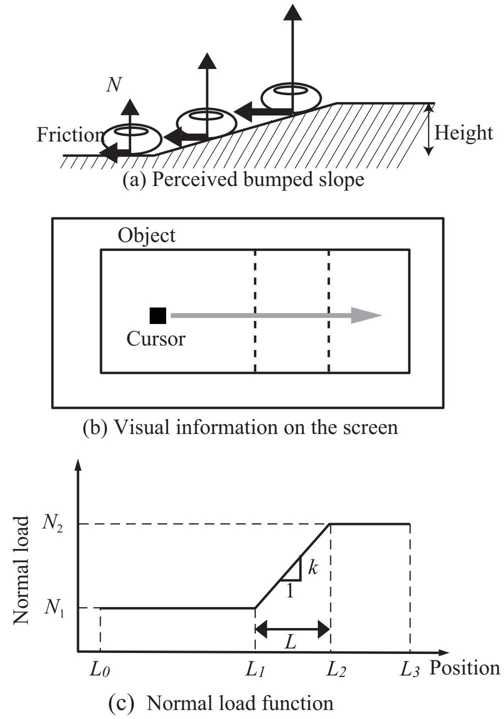

Fig. 11. Tactile height illusion via virtually controlling normal finger-force

The perceived height of a slope was influenced by the changing normal force. In this experiment, after the normal force reached N_2, the normal force did not change.

Six values of the increasing span $L = 5, 10, 15, 20, 25, 30$ [mm] and three values of the rate of increase $k = 0.05, 0.1, 0.15$ [N/mm] were used. Thus, one set of conditions contained 6×3 combinations.

A magnitude estimation method was used to evaluate the perceived height of the slope. Participants were asked to subjectively assign an arbitrary number to quantify the perceived height within 30 seconds after the moment of reaching the largest normal force N_2 at the end of the span. Each participant evaluated one set (18 trials). The order of the stimulation combinations was random. Participants experienced maximum L and minimum L for each k before the experiments. They wore headphones through which pink noise was played to cover the sounds generated by the vibrator. Five men and one woman aged from 20 to 40 performed the tasks.

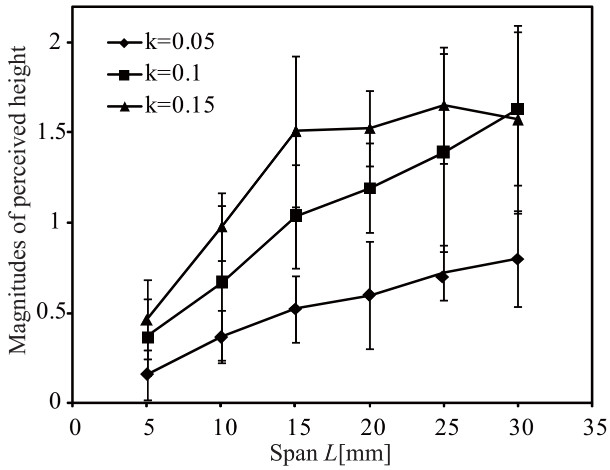

Fig. 12. Magnitude of perceived height

C. Experimental Result

The magnitudes of perceived height were calculated as the geometric average of the normalized results from all participants. Fig. 12 shows that the perceived height increased as L increased and as k increased. However, the perceived height only increased slightly above $L = 15$ with $k = 0.15$; apparently the perception of shape by friction sensation was limited by a ceiling.

D. Discussion

These results indicated that the heights of slopes could be perceived from an increase in friction sensation. Higher perceived slopes when the rate or span of the increase in friction sensation was higher corresponded to the anticipated result. Therefore, it would appear that the friction sensation presented in this experiment operated similarly to the lateral force in the method of presenting geometric shapes proposed by Robles-De-La-Torre et al.

From interviews with participants, we confirmed that they perceived both a bump when their hand moved from left to right and also a dent when their hand moved from right to left in Fig. 11. It appeared that the heights perceived depended on both the bump and the dent, because participants moved their hands from side to side in experiments.

The reason that perceived height only increased slightly above $L = 15$ with $k = 0.15$ was a problem in the method of synthesizing the friction sensation. A continuous sense of stroke was not perceived, because the period of the stick-to-slip transition of the friction model became too long when the normal force was too high. More continuous slopes might be presented by restricting increase of the period of the stick-to-slip transition when the normal force is too high.

In this study, participants needed to image the shapes by themselves, because the visual stimulus was constant and the slope was not represented visually. We expect that it would be easy to present geometric shapes by tactile sensation combined with visual representations of the shapes in practical systems. Virtual Active Touch has an advantage to add visual effects on the screen because the virtual finger does not hide the screen. In addition, Virtual Active Touch would be easier to image the shapes represented by the tactile stimulation than tactile interfaces including actual hand movement because no movement of the finger affect the kinesthetic perception.

VI. CONCLUSION

Our target was the reproduction of the kinesthetic sensation induced by the tactile sensation. In particular, we aimed to reproduce human perception of geometric surface shape induced by the cutaneous sensation of friction. This approach will drastically expand the range of tactile applications, compared with conventional quality-oriented tactile displays. To use the friction display through Virtual Active Touch, we confirmed that the proposed friction method can be applied in Virtual Active Touch, which is the concept that implements virtual exploration through a pointing-stick-type tactile interface.

First, we compared the perceived friction sensation from the pointing-stick-type tactile interface with the linear-slider-type tactile interface, which allows actual hand movement. Psychophysical experiments showed that the proposed friction display method could deliver perceived friction corresponding to the friction coefficient as well as the linear-slider-type with slight differences in sensitivity to changes in friction coefficient.

Second, we evaluated the perception of surface height in the context of bumped shape perception induced by the friction display. The experimental results agreed with our expectation that larger rates and longer spans of increasing friction sensation were perceived as higher bumped shape. These results strongly suggest that the friction sensation presented here has the same effect as lateral force in the shape perception reported by Robles-De-La-Torre et al [1].

VII. ACKNOWLEDGMENTS

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B) #18760179, Grant-in-Aid for Young Scientists (A) #21686024, and by the Ministry of Internal Affairs and Communications, Grant for the Strategic Information and Communications R&D Promotion Program #082102006.

REFERENCES

[1] G. Robles-De-La-Torre and V. Hayward, Force Can Overcome Object Geometry In The Perception Of Shape Through Active Touch. Nature, Vol. 412, pp. 445-448, 2001.
[2] http://www.immersion.com/
[3] J. Luk, J. Pasquero, S. Little, K.E. MacLean, V. Levesque, and V. Hayward, A Role for Haptics in Mobile Interaction: Initial Design Using a Handheld Tactile Display Prototype. Proc. of the ACM 2006 Conf. on Human Factors in Computing Systems (CHI2006), pp.171-180, 2006.
[4] Q. Wang and V. Hayward. Compact, portable, modular, high-performance, distributed tactile display device based on lateral skin deformation. In Proc. IEEE HAPTICS' 06, pp.67-72, 2006.
[5] T. Yamauchi, M. Konyo, S. Okamoto, and S. Tadokoro, Virtual Active Touch: Perceived Roughness Through a Pointing-Stick-Type Tactile Interface, The Third Joint Eurohaptics Conference and Symposium on Haptic Interface for Virtual Environment and Teleoperator Systems (WorldHaptics 2009), May, 2009 (in printing).
[6] L.A. Jones and S. J. Lederman, Human Hand Function, New York: Oxford University Press, 2006.
[7] M. Konyo, H. Yamada, S. Okamoto and S. Tadokoro, Alternative Display of Friction Represented by Tactile Stimulation without Tangential Force, Proc. of EUROHAPTICS 2008, pp.619-629, 2008.