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Basic Characteristics of Shear Tactile Stimulus Generated by Rotating Contactors

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Abstract

This paper describes the characteristics of haptic sensation that is evoked at the finger skin by a shearing stimulus presented using rotational contactors. First, the relation among the contact area, the contact force and the diameter of contactors was investigated. The tactile sensation scaling of the tangential force was performed regarding the speed, the direction of rotation and the size of the contactor. In addition, the sensitivity difference was investigated in terms of the sites on a fingertip where the contact-shaft stimulation was added. Moreover, the interference between two tangential force stimulations provided by a pair of contactors with a 3-mm interval was investigated.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information interfaces and Presentation]: Multimedia Information Systems—Evaluation/methodology

1. Introduction

Recently the haptic feedback in the VR technology has increased its importance for the virtualization of the real space. A medical trainer and a remote control are those which need haptic feedback from the 3D work space. The feedback is also necessary in operating an object in a VR space.

In the physical manipulation of objects, it is well-known that we use the information of shear force at the fingertip [JW84]. The shear stimulus distribution at the finger surface is crucial when the friction forces of textured surfaces are presented, although it is hard to measure precisely the forces added to the fingerpad or slip condition of the finger surface since they are fluctuated intricately by body movement. It is important to produce the distribution of shear stimulus that occurs in holding an object against the gravity and rubbing against the surface of an object in the VR space when its precisely presented and controlled. By incorporating this tangential tactile stimulus in addition to the normal force that deforms skin normally to the surface, it is considered that the various tactile sensation might be reproduced.

We propose a tactile display that imparts shearing stimulus distribution on the skin of a fingertip using a row of rotating contactors. In the present paper, we describe a prototype design of the display and a part of basic characteristics based on a psychophysical experiment performed under constant rotation of the contactors.

2. Related work

A design of shear force display is presented in [MFK08] where a shear force is generated by a contact belt driven bidirectionally by two motors. The display is able to present a static shear force as well as variation of force that are expected to be caused when the user holds and manipulates a real object in the real 3D space. A tactile display using rotation of the plural contactors is shown in [BBH04]. Although psychophysical characteristics of the device are not presented in the paper, it looks that this device would produce shearing stimulus at the finger surface. Researchers [HC00, WH06, LPH07] proposed the device that generated a stimulus on the contact region of a finger surface by a small vibrating comb-like actuator moving to tangential direction to the finger surface. These designs do not discuss chiefly the distribution or variation of shearing stimulus profile in the contact area.

The perception of slip is investigated [WBF07] in the case of rotational disk contact which is not the same condition as the present study. They found that the JND for rotational disk speed was rather large that indicated the perception accuracy

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of sliding contact was not very high. The paper [SCV04] also discusses the perception of slip and its direction at the higher rotational speed range than the present paper. The JNDs were highly dependent on surface texture. A slip display with a force feedback is presented in [WMV05] that used ball rotation. The direction and speed perception was investigated for the design, and the effect of the slip display in paper manipulation task is discussed. These studies have unique structures and original procedures to present the sensation of slip, however they did not achieve presentation of distributed shear stimuli nor exploration about the created sensation by the displays. In the present study, we propose the display design in which the distribution of shear stimulus is presented.

3. Tangential force distribution display

Figure 1 shows the whole view of the prototype display. The display presents at the fingertip the tangential force distribution that occurs when rubbing against an object, by independently controlled six rotating contactors. The device presents forces that are virtually equivalent to those the finger receives when it is moved on an object. In the real space, a larger force would be applied at the point on the skin near the base phalanx than the fingertip when the finger is moved to the user's body. The distribution of the forces is created by the different rotational velocities among the rollers. In addition, it is expected that a couple of rotating contactors with different rotational directions and velocities are able to create particular sensation as if the finger surface received a force normal to the surface. Although we have not explored the fact in detail by an experiment if the device creates the sensation of normal force, some users reported that finger surface was clearly pulled downward between shafts when the contactors were rotated at a specific condition.

The device consists of six DC motors (Maxon Motor, EC6 1.2W with a 57:1 reduction gear) arranged with 3-mm interspacing. The contactors are made of brass with diameter 1 mm, 1.2 mm, and 2 mm. In addition, a contactor with hexagonal cross section of 2-mm diameter can be attached to the motor. A rotational encoder is implemented in each motor that provides the rotational speed to the counter board of a control PC. The encoder outputs 5,700 pulses a rotation of the roller. The control signal from the PC's DA board is input to the amplifier to control the rotational velocity at the rate of 1000 Hz. The specifications of the motor and the control are shown in Table 1.

4. Basic characteristics of tangential force sensation

We assumed that the sensation of shearing contact is related to three factors, (1) contact area, (2) normal contact force, and (3) rotational velocity of the contactor. In the limited measurement below, we discuss these factors to develop appropriate tactile stimulation.

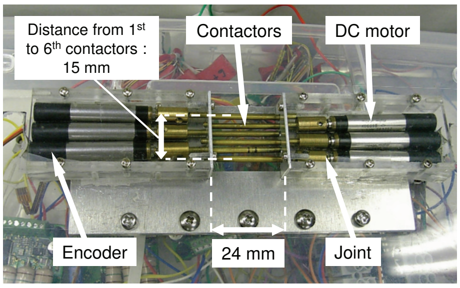

Figure 1: *Prototype display consisting of six rotation-shaft contactors.*

Table 1: *Motor control specification*

Control mode	Implemented control/motor	Voltage input	Velocity servo
Peak velocity [rpm]	550	∼633	∼600
Control mode	closed loop	open lp	closed lp
Rise time (10–90%) of 500 [rpm]	0.108 s	0.111 s	0.317 s
Peak torque [mNm]	0.241 (motor)	←	←
Reduction ratio	57 : 1 (gear)	←	←

4.1. Contact condition between finger and contactors

4.1.1. Procedure of measurement

We measured the relationship between the contact area and the contact force of the finger to the contactor. The contact area is measured by counting the amount of ink transferred to the contactor from the finger surface. The normal force was measured by a weigh scale. The location of measurement was the tip of an index finger, more specifically the point a forth of the length of the first phalanx from the very tip of the finger. Seven subjects, male students of mean age 23.3 from the university, participated in the experiment. They all reported to have normal tactile sensation.

4.1.2. Result

Figure 2 and Table 2 show the result. The shape of curves of the two thinner contactors (1-mm and 1.2-mm dia.) is almost the same and saturating as the contact force increases. The contact area is about 13 mm^2 when the contact force is about 20 g that is around the real magnitude at which it is usually used. With the 2-mm dia. contactor, the contact area is about 22 mm^2, which is about 1.7 times as large as that of the 1-mm dia. contactor. The contact area increased as the load (normal force) increase at the same rate between two directions of parallel and vertical to the axis of the finger bone. The contact area increased fast at a small normal load from 5 g to about 20 g for three diameters. In this range of the normal force loadings, the finger surface might be easily deformed elastically.

Although the contact area increased as the normal force increased, the contact stresses are almost the same with 10 g loading and 20 g loading with 2.0-mm diameter contactor. The contact stress with 2.0-mm dia. contactor is about twice as large as two thinner contactors. Therefore, with 20 g normal force loading, the finger surface deformed easily and the contact area increased to the sufficient amount. From this observation we adopted to use 20 g as a standard normal force loading.

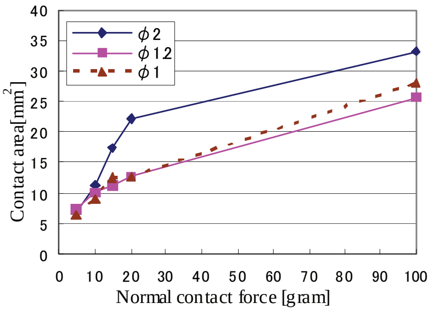

Figure 2: *Contact area as a function of normal contact force.*

Table 2: *Normal contact force, area, and stress.*

Diameter [mm]	Normal force [g]	Contact area [mm²]	Stress [g/mm²]
Φ1.0	20	12.65	1.583
Φ1.2	20	12.63	1.581
Φ2.0	10	11.41	0.876
Φ2.0	20	22.23	0.900

4.2. Sensation scaling

We carried out a fundamental experiment to construct a scale of the sensation intensity of shear stimulus that can be presented with a rotating contactor.

Figure 3 shows the experimental setting in operation of psychophysical measurement. We measured the differential limen between 100 and 550-rpm rotation velocities where stable rotation is obtained. The tangential speed of this interval is 10.47 to 57.7 mm/s in the case of 2-mm dia. contactor. We named the rotational direction that rotates the contactor from near to far the normal (forward) direction, and the opposite rotational direction the reverse (backward) direction. The stimulating location was the same as the previous measurement of the contact area. We provided the weight scale reading of the normal contact force to the subjects so that the subject could regulate it by himself throughout the measurement session.

We adopted the method of adjustment from 100 rpm in an ascendant series. A single trial for each condition was performed in the experiment. All the information except for haptic channel was eliminated by providing the band-limited noise via the headphones and the sheet to prevent direct visual observation of the motors. The subjects were the same seven male students as previous measurement who had the normal finger skin sensation and they had not used this type tactile display that created shearing tactile stimulus.

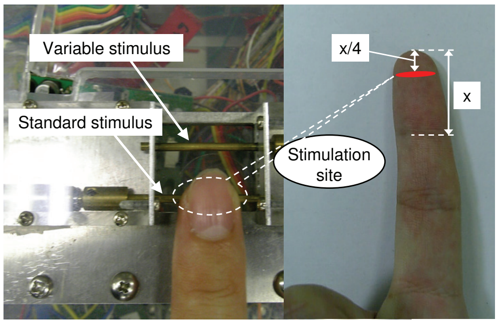

Figure 3: *Tangential force display in operation of psychophysical measurement*

4.2.1. Measurement procedure of the differential limen of angular velocity

The subject touched two contactors alternately that presented different shear stimuli, then discriminated the difference of them. The near contactor defined the standard stimulus and the other far contactor presented a variable stimulus. The subject increased(decreased) the variable stimulus by ±1 rpm or ±10 rpm by himself using designated keys on a keyboard. When the subject felt the minimum difference perceivable between the standard and the variable stimulus, the subject pushed the record key to store the rotation velocity. Then the stored velocity was set to the standard stimulus contactor.

This procedure was repeated to make a series of minimum differences as a psychophysical scale. The diameters of circular profile contactors used in the measurement were 1.0, 1.2, and 2-mm. A 2-mm hexagonal contactor was also used for presentation. The normal force to put the finger on the contactor was set to 20 g which was adopted in the previous section as it seemed appropriate to feel the tangential force. As for the 2-mm dia. contactor, the 10 g normal force loading was also used since the contact area is almost the same as that of 1-mm dia. contactor with 20 g loading. The relation of the normal force, the contact area and the stress of the experiment was shown in Table 2.

4.2.2. Result and discussion

Figure 4 shows the typical sensation scale of the intensity of tangential force that was measured in the experiment. It indicates the series of differential limen of seven subjects

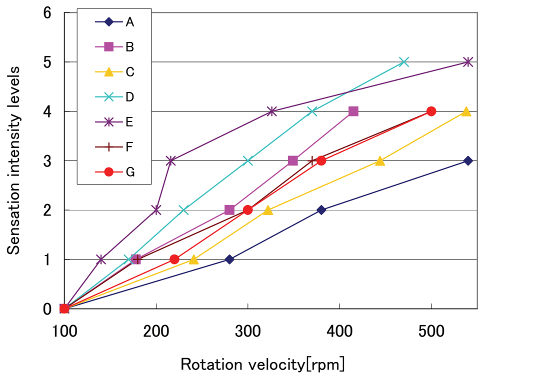

Figure 4: *Sensation scale of the shaft contactor 1.0-mm diameter with normal rotation*

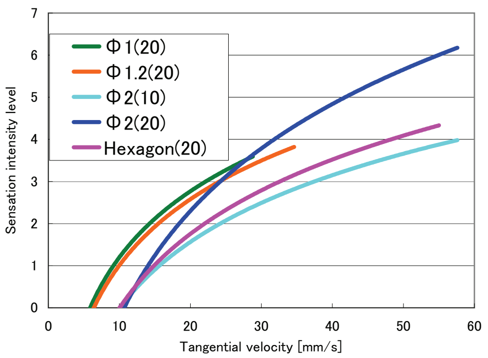

Figure 5: *Sensation intensity as a function of tangential velocity*

in the case of the contactor 1.0-mm diameter with normal rotation direction.

Figure 5 shows the logarithmic approximation lines of sensation intensity for each stimulus condition as a function of rotation speed. The sensitivity of 2-mm dia. at 20 g loading was the largest among the conditions. The sensitivity of other conditions (2-mm dia. at 10 g, 2-mm dia. with hexagonal profile, 1.2-mm dia. and 1.0 mm dia.) were all about a half of 2-mm dia. at 20 g. Since the normal stress is almost the same between 10 g and 20 g loading with 2.0 mm dia. contactors and the contact area is doubled, it looks that the contact area might be closely related to the sensitivity. The area increase implies that the number of receptors involved might affected the result.

The number of sensation intensity levels of 2-mm dia. with hexagonal profile was lower than the same diameter contactor of circular profile. This indicates that the hexagonal contactor was inappropriate since the stimulation was too strong. Some subjects reported that the change in the rotation

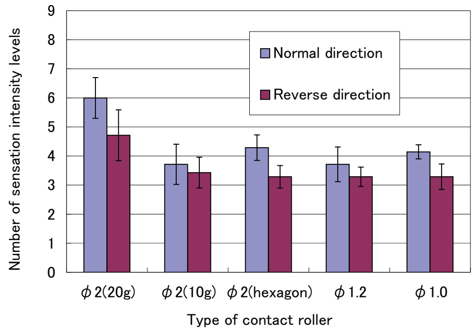

Figure 6: *Sensation intensity levels discriminated.*

velocity of the hexagonal contactor was considerably hard to perceive since the vibration stimulus caused by the six edges masked the tangential force. The other subject reported that the changes in rotation was not easily perceived due to the numbness from the vibration generated by hexagonal edges at about 50 Hz that corresponds to the characteristic band of the Meissner corpuscle.

Figure 6 shows the number of rotation speeds that can be discriminated between 100 and 550 rpm. In other words, it shows the maximum sensation intensity level for each condition. The error bar indicates 1.96 SEM. The 2-mm dia. contactor produced the largest number of levels. Six levels for the normal-direction rotation, 4.7 levels for the reverse rotation and 5.4 levels in the mean were observed at the condition. The number of levels was higher for the normal rotation than the reverse rotation. In the two thirds of whole trials, the number of levels was larger in the case of the normal rotation.

The suggested design alternative from the limited experimental result discussed here is that the 2-mm dia. contactor with circular profile will produce better performance than the others including a hexagonal contactor with excessive vibration stimulus. Then we obtained a display of a tangential force with 5.4 levels on average, of intensity change of the force in addition to a directional control (normal and reverse) of rotational velocity. Moreover, it is considered that it is possible to present shear stimulus over the both directions by equating the intensity. Slightly reducing the rotation velocity for the normal rotation as compared to the reverse direction is possible based on the difference observed in Figure 6.

5. Sensitivity distribution and interference effect

5.1. Device

We used the stimulation device shown in Figure 7 to investigate the dependence of tangential force perception upon the stimulation site of the fingertip more closely than the proto-

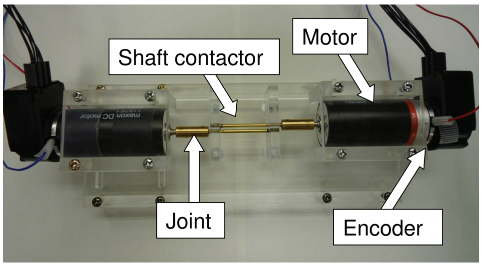

Figure 7: *Tangential force stimulator device 2*

type display. Two shaft contactors were used in the device. They were arranged with 3, 6, 9, 12, and 15 mm inter-shaft distance. The range of rotational speed was 100 to 1500 rpm.

5.2. Sensation intensity dependency on simulation sites

We performed sensation scaling of the tangential force at six stimulation sites on the finger surface.

5.2.1. Experimental procedure

The first stimulation site is about a forth of the length of the first phalanx from the very tip of an index finger. The second-to-sixth stimulation sites were placed with a 3-mm interspacing toward the first joint as shown in Figure 8. The subject put their index finger on the contactor with 20 g loading. Then we measured the differential limen between 100 and 1500 rpm of contactor rotation velocity which the stable rotation was obtained. We provided the weigh scale reading of the normal contact force to the subjects so that the subject could regulate it by himself throughout the measurement session. We adopted the method of adjustment from 100 rpm in an ascendant series. The subject increased the variable stimulus by ±10 rpm, ±50 or ±100 rpm by himself. When the subject felt the minimum difference of the force, between the standard and the variable stimulus, he pushed the record key to store the rotation velocity. A single trial for each condition was performed in the experiment. To avoid the vibration of the device by abrupt changes of rotation velocities, rotation velocities were changed along with sine wave with 2 seconds. The subjects were 5 male students who had the normal skin sensation.

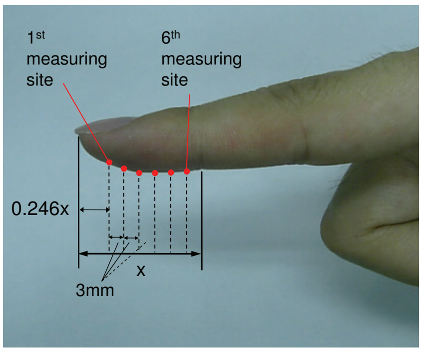

Figure 8: *Stimulation sites*

5.2.2. Result and discussion

Figure 9 shows the relation between the rotation velocity and the sensation intensity of the second stimulation site as a typical result. Figure 10 shows the logarithmic approximation lines of each stimulation site. The sensation intensity for tangential force depended on the measurement site. The first stimulation site at the most distal point in the six sites tested on the fingerpad, showed the highest sensitivity. The sensitivity decreased as the site of measurement approached the middle phalanx and that of fourth-to-sixth stimulation site was almost the same. The weber ratio is shown in Figure 11. In the case of normal rotation, the weber ratio of the fifth stimulation site, which has the lowest sensitivity, is about twice as large as that of the first stimulation site.

Figure 12 shows the number of sensation intensity levels discriminated in the range of 100-to-1500 rpm of rotation velocity. The error bar indicates the 95 % confidential interval. The number of levels at the first stimulation site was 7.2

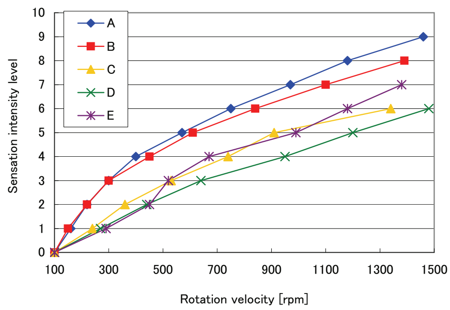

Figure 9: *A typical result of rotational-threshold series.*

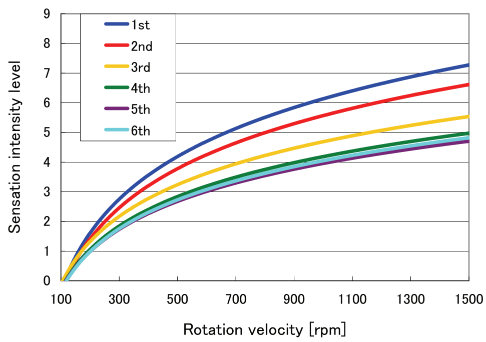

Figure 10: *Sensation intensity curve for six sites.*

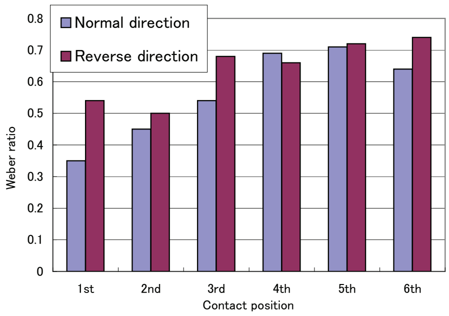

Figure 11: *Weber ratios at six stimulation sites.*

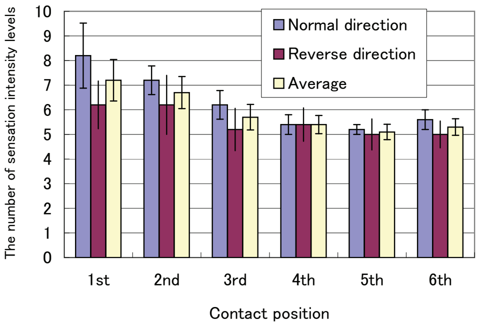

Figure 12: *Maximum sensation intensity.*

in the mean. At the range from the middle part of fingerpad to the middle phalanx, about five to six levels of tangential force was discriminated. The number of levels was higher for the normal rotation than the reverse rotation, which was statistically significant at 5% level.

5.3. Interference effect between two stimuli

We investigated the interference between two shear stimuli provided by a pair of shaft contactors with a 3-mm interspacing.

5.3.1. Experimental procedure

We performed sensation scaling of tangential force under the existence of another tangential force using two contactors. The two contactors were put in 3-mm interspacing. The rotational direction of two contactors were the same (normal-normal and reverse-reverse). The contactor on the second site rotated at a constant velocity. We measured the differential limen for the tangential force at the first site. The constant stimulus at the second site was 1-to-7 levels of the force which had been observed in the previous experiment. The subject put an index finger on the two contactors with 40 g loading. The other procedures of measurement including the subjects were the same as the previous experiment.

5.3.2. Result and discussion

Figure 13 shows the logarithmic approximation lines of sensation intensity at the first site. Table 3 shows the contribution ratios. The maximum sensation intensity levels are shown in Figure 14.

The number of sensation intensity levels that can be discriminated in the range of 100-to-1500 rpm of rotation velocity at the first site decreased as the stimulus intensity at the second site increased. The maximum sensation intensity level with normal rotation direction decreased from eight to six by adding the level one stimulus force at the second site. The maximum sensation intensity levels also decreased almost linearly with the increase of stimulus intensity at the second site from the level one to four.

It is expected that two tangential forces presented to the finger deformed the skin surface at the first site. It is considered that the tangential force generated by the second site contactor added to the tangential force generated by the first site contactor because the deformation volume was large since the middle part of finger surface easily deformed in the normal rotation direction. On the other hand, the fingerpad might be hard to be deformed in the reverse rotation direction because the very restrictive part of fingerpad pulled by the contactor.

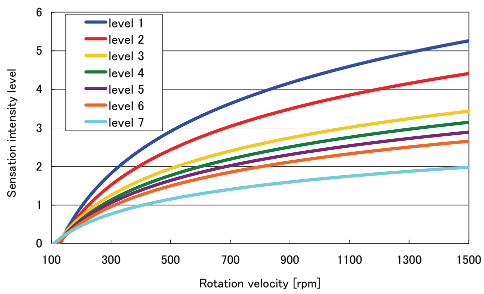

Figure 13: *Sensation intensity under additional shear stimulus at adjacent contactor.*

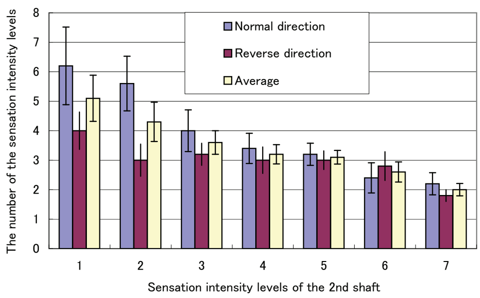

Figure 14: *Maximum sensation intensity vs. adjacent shear stimulus level.*

Table 3: *Approximation contribution ratio*

Shear force level	Normal direction	Reverse direction	Average
1	0.589	0.767	0.558
2	0.631	0.685	0.591
3	0.693	0.779	0.688
4	0.762	0.789	0.772
5	0.815	0.802	0.802
6	0.785	0.784	0.783
7	0.797	0.876	0.805

6. Conclusion

In this paper, we developed the prototype of the haptic display which produced the tangential force distribution to the fingerpad by rotating contactors and investigated its basic characteristics experimentally. In the range of 100-to-550 rpm of rotation velocity of contactor, tangential force was discriminated easily by using 2-mm dia. with 20 g loading compare to the other contactors(1.0-mm dia. 1.2-mm dia.). Using the contactors, six levels of sensation intensity for tangential force was presented. The sensation intensity increased as logarithmic function to the rotation velocity increase. The hexagonal shaft contactor was not appropriate for presenting shearing stimulus since the vibration caused by its edges masked the stimulus and the levels of sensation intensity that can be discriminated by the subjects were lower than other cylindrical contactors.

The sensation intensity depended on the measurement site on the fingaerpad. The highest number of levels was observed at the most distal site among six sites tested on the fingerpad. The device produced about six to eight levels of the tangential force at the first site. The sensitivity decreased as the site of measurement moved to the middle phalanx. The number of levels was higher for the normal rotation direction than the reverse rotation direction. It is considered that the sensitivity difference depended on the asymmetry of the deformation volume of the fingerpad.

The interference by the second site, which had a 3-mm interspacing to the first site contactor, decreased the sensation intensity level at the first site almost linearly as the tangential force of the second site increased. The interference effect was more definite in the normal direction than the reverse direction. The maximum sensation intensity level decreased from seven to five by the interference of the second site. These data provided the basic design parameters of the haptic display for shearing stimulus presentation.

The future work includes the investigation of the sensation scaling under broader conditions specifically with multiple active contactors. Also we have to explore if the device creates a tactile sensation in the direction normal to the finger surface. Application of these results to the presentation of real objects is the final objective of the research.

References

[BBH04] Benali-Khoudja, M., Beny, A.-L., Hafez, M. and Kheddar, A. VT vector-touch: a new slip/stretch tactile display. Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004), Vol. 4, pp. 3583-3588, (2004).

[HC00] Hayward, V., Cruz-Hernandez, M., Tactile display device using distributed lateral skin STretch. Proc. Symposium on Haptic Interfaces for Virtual Environments and Teleoperator System (IMECE2000), Orlando, Florida, USA. Proc. ASME Vol. DSC-69-2, pp. 1309-1314, (2000).

[JW84] R. S. Johansson, G. Westling : Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects, Experimental Brain Research, Vol. 56, pp. 550-564, (1984).

[LPH07] Levesque, V., Pasquero, J., Hayward, V., Braille Display by Lateral Skin Deformation with the STReSS2 Tactile Transducer, pp. 115-120, World Haptic Conference 2007, (2007).

[MFK08] Minamizawa, K., Fukamachi, S., Kajimoto, H., Kawakami, N., Tachi, S., Wearable haptic display to present mass and internal dynamics of virtual objects, TVRSJ, Vol. 13, No. 1, (2008).

[MI07] Makino, R., Ikei, Y., Development of shearing force tactile display consisting of shaft contactors, Proc. the 13th VRSJAC CDROM, pp. 624-625, (2007).

[SCV04] Salada, M., Colgate, J.E., Vishton, P., Frankel, E., Two experiments on the perception of slip at the fingertip, HAPTICS'04, pp. 146-153, (2004).

[WBF07] William R. Provancher , Brandt D. Erickson , Federico Barbagli, Hong Z. Tan : Tactile Perception of Rotational Sliding, Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07), pp. 127-132, (2007).

[WH06] Wang, Q., Hayward, V,. Compact, portable, modular,high-performance, distributed tactile transducer device based on lateral skin deformation, HAPTICS'06, pp. 67-72, (2006).

[WMV05] R. J. Webster, T. E. Murphy, L. N. Verner, A. M. Okamura: A Novel Two-Dimensional Tactile Slip Display : Design, Kinematics and Perceptual Experiments, ACM Trans. on Applied Perception, 2(2), pp. 150-165, (2005).