Friction Sensation Produced by Laterally Asymmetric Vibrotactile Stimulus

Akihiro Imaizumi, Shogo Okamoto(✉), and Yoji Yamada

Department of Mechanical Science and Engineering,
Nagoya University, Nagoya, Japan
okamoto-shogo@mech.nagoya-u.ac.jp

Abstract. Vibrotactile texture stimuli have commonly been used to produce sensations of roughness. The extension of such stimuli to other textural modalities enhances their applicability. We found that laterally asymmetric vibrotactile stimuli cause a sensation of friction rather than vibration. When a vibrotactile contactor moves in one direction, it sticks to the finger pad and induces lateral skin stretch. In contrast, when the contactor moves in the other direction, it slips because of its quick motion and induces little skin stretch. As a result, humans experience frictional sensations in scanning vibrating contactors with their fingertips. We examined participants' subjective responses and measured interactive forces between the finger pad and the contactor. Both perceptual and physical experiments corroborated the hypothesis of the production of a sensation of friction. Laterally asymmetric vibrotactile stimuli increased stretching of the finger pad skin and increased the sensation of friction.

Keywords: Texture display · Skin stretch · Friction · Vibrotactile

1 Introduction

Tactile texture displays have been extensively studied as a user interface technology that complements visual and auditory displays. Texture sensations consist of multiple modalities, including roughness, softness, friction, and thermal sensations. A texture display that addresses more modalities is considered to be more valuable. In the field of vibrotactile texture displays, which have been studied extensively because of their ease of use and commercial availability, many research groups have developed display techniques for roughness sensations. In addition, researchers have studied that the accurate representation of vibratory signals that are generated by rubbing materials impart their textures (e.g., [1]). If friction sensations can be conveyed in addition to these sensations, broader types of textures can be represented by vibrotactile stimuli.

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The objective of this study was to examine how to increase friction sensations using vibrotactile stimuli. Although many studies on frictional vibration between fingers and textures have been conducted [2–4], there has been little research on the production of the sensation of friction using vibrotactile stimuli. This is partly because a mechanism with an unlimited motion range is necessary to present friction sensations when the contactor of a tactile display is traced by a finger in one direction and a friction force works continuously in the opposite direction. Hence, spherical contactors that rotate infinitely in one direction [5] and skin stretchers that do not cause slippage between a finger pad and a stimulator [6,7] have been adopted in practice. In addition, the squeeze effect [8,9] and static electric friction [10] have been used to increase or decrease friction. A unique vibrotactile method was developed by Konyo et al., to convey friction sensations using vibratory stimuli normal to a finger pad and hence simulate high-frequency stick-slip vibration [11]. However, vibrotactile approaches to induce lateral skin stretching for conveying friction sensations have yet to be reported (see also the last paragraph in Sect. 2).

As described in Sect. 2, we asymmetrically vibrated a tactile contactor or stimulator in a direction tangential to a finger pad to induce the sensation of friction between the finger pad and the contactor. The effectiveness of this type of asymmetric vibrotactile stimulus in producing the sensation of friction was evaluated using a psychological test and friction force measurement.

2 Assumed Principle: Friction Sensations Produced by Laterally Asymmetric Vibrotactile Stimuli

Humans perceive friction from the shear deformation of the finger pad [6]: a larger shear deformation evokes a sensation of greater friction. We separated the frictional conditions of a finger pad moving across a contactor into two phases: sticking and slipping phases. Static and kinetic friction forces act during the sticking and slipping phases, respectively. Naturally, the finger pad stretches more in the sticking phase. We can also induce friction sensations by manipulating the finger pad stretch. In this section, we describe how laterally asymmetric vibration may preferentially cause stick or slippage.

As Fig. 1 shows, we assume that the contactor vibrates asymmetrically, moving more quickly to the right, and more slowly to the left, whereas the maximum displacements are the same in both directions. When the fingertip moves rightward across the contactor, and the contactor moves quickly, the relative velocity between the fingertip and the contactor is sufficiently large for them to slip and hardly stick (Fig. 2, Case A). In contrast, when the contactor moves slowly leftward, sticking frequently occurs because the relative velocity between the fingertip and the contactor is sufficiently small to cause sticking (Case B). Hence, humans feel more friction in Case B and less friction in Case A. As a result, a sensation of friction is induced rather than a sensation of vibration. We call these combinations of fingertip movements and asymmetric contactor motions "sticking conditions."

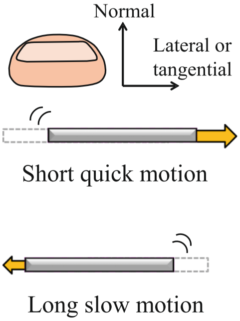

Fig. 1. Laterally asymmetric vibration

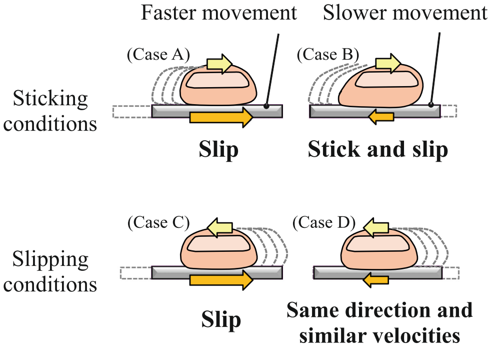

Fig. 2. Friction produced by rubbing asymmetrically vibrating contactor with fingertip

When the fingertip moves leftward, the shear deformation is moderate. When the contactor moves quickly, the finger pad deformation is small because the slipping phases is dominant owing to the largely relative velocity between the two bodies (Case C). When the contactor and the fingertip move in the same direction at similar velocities, the skin stretch is minimal because of the small relative displacement between the fingertip and the contactor (Case D). As a result, in these two cases, humans perceive weak friction sensations. We call these conditions “slipping condition.”

Also, in cases A and D, the direction of finger deformation may become the same as the finger motion, which never happens in scanning still surfaces. Under such cases, the sense of friction is weakened [12]. Hence, we assume that the phenomenon reported in this article cannot be fully explained by physics but also by perceptual effects.

The overall idea is somewhat similar to the method developed by Chubb et al. [9]. They combined a tangential vibration and ultrasonic vibration to selectively produce shear forces in one direction. Although they used ultrasonic vibrations to reduce frictions when the contactor moves in one direction, we use fast lateral displacement of the contactor to reduce frictions. As a result, our method takes advantage of asymmetric lateral vibrations whereas the earlier study used symmetric ones. Asymmetric vibratory cues were also used for a different purpose in the field of haptics. They provide directional force sensations to a hand in which a vibratory source is grabbed [13,14].

3 Experimental Setup

3.1 Tangential Vibrotactile Display

We used a vibrotactile display based on a DC motor (RE-40, Maxon) with an encoder (Type L, Maxon), as shown in Fig. 3. The contactor was made of finely

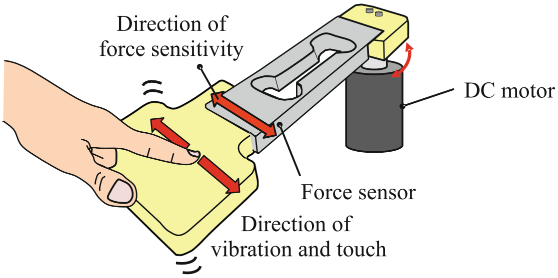

Fig. 3. Lateral vibrotactile display

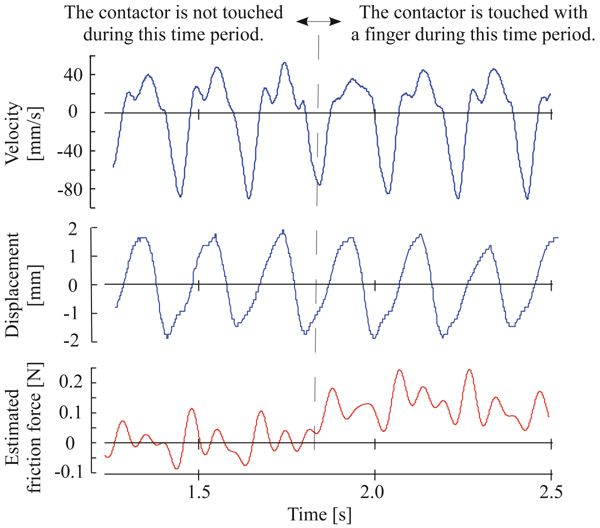

Fig. 4. Saw-toothed vibrotactile stimulus and estimated frictional forces between finger pad and contactor

polished ABS plastic that was fastened to the motor through a strain-gauge load cell (Model 1004, Tedea Huntleigh). This load cell measured the inertial force of the contactor and the frictional force between the contactor and a finger pad. We estimated the friction force by subtracting the inertial force, which is the product of the inertia of the contactor and its acceleration, from the measured force values.

3.2 Laterally Asymmetric Vibrotactile Stimuli

Figure 4 shows an example of the displacement and velocity of the asymmetric vibrotactile stimuli and the estimated friction force between the finger pad and the contactor. The displacement of the contactor was similar to a saw-tooth profile with the contactor moving in one direction with a peak speed of

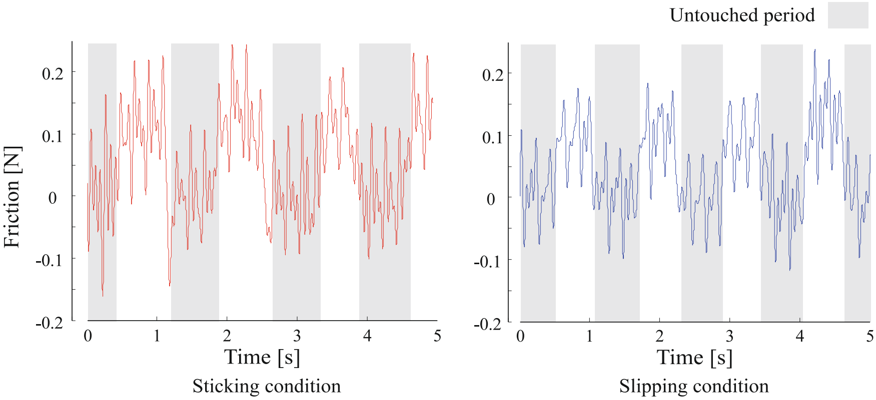

Fig. 5. Sample of friction forces

approximately 90 mm/s and in the other direction with a peak speed of 40 mm/s. The peak-to-peak displacement of the contactor was approximately 3.5 mm, and its frequency was set at 5 Hz. The motion of the contactor was feedback-controlled to maintain asymmetric motion even during contact with the finger pad. We determined the feedback gains using the linear quadratic integral design method. It should be noted that asymmetric motions are not necessarily ensured with large disturbance forces.

4 Experiment: Perceptual and Physical Measurement of Friction Under Laterally Asymmetric Vibrations

4.1 Methods

We tested the differences in the friction and frictional sensations between the *sticking* and *slipping* conditions in two types of experiments.

Five blindfolded and auditory-masked volunteers participated in paired comparison tasks. They were unaware of the objectives of the experiment. They scanned the contactor leftward and rightward for 10 s and identified the direction that corresponded to a stronger sensation of friction in a forced-choice manner. Ten trials were conducted for each volunteer, with the direction of asymmetric vibration randomly changed between trials.

After these tests were completed, we measured the frictional forces between the participants' finger pads and the contactor as each of the participants touched the contactor, using the load cell installed on the contactor. The participants slid their fingertips across the contactor in each of the two directions for 10 s.

Table 1. Answer ratios in forced-choice task of friction between *sticking* and *slipping* conditions.

Participant No.	Answer ratio (*stick* > *slip*)
1	0.6
2	0.8
3	1.0
4	0.9
5	1.0
Ave. ± S.D.	0.86 ± 0.17

Table 2. Impulse of friction. Averages and standard deviations were calculated for participants 2–5.

Participant No.	Impulse [N·s]	
	Stick	*Slip*
1	2.14	2.41
2	0.44	0.31
3	0.40	0.23
4	0.30	0.20
5	0.98	0.83
Ave. ± S.D.	0.53 ± 0.31	0.39 ± 0.30

4.2 Result: Differences in Perceived Friction Between the Two Conditions

Table 1 shows the ratios at which the participants felt that the *sticking* condition produced more friction than the *slipping* condition. Overall, the *sticking* condition was judged to produce more friction than the *slipping* condition ($t_0(4) = 4.81$, $p = 0.0085$, two-tailed paired t-test), except for participant 1. As described later, this participant experienced exceptionally substantial frictional forces for both conditions, potentially due to the large forces in the normal direction with which he pressed the contactor.

4.3 Result: Frictional Force

Figure 5 shows the estimated frictional forces measured during two trials for participant 2. The left and right figures correspond to the *sticking* and *slipping* conditions, respectively. During the masked periods, the frictional forces were small for a sustained period of time, which means that the participant's finger was not in contact with the contactor. The data for these periods were not used in the calculation of the statistics reported later.

Both the magnitude and duration of friction that the participants experienced may affect the participants' perception of friction; therefore, we calculated the impulse of friction forces (integral of friction over time) as a point of reference. Table 2 shows the impulses calculated for a single trial, typically eight strokes for 10 s, under the two conditions. These impulses were larger under the *sticking* condition than under the *slipping* condition, except for participant 1, for whom unusually large frictional forces were measured. We excluded the data for participant 1 from the statistics because of their inconsistency with the results for the other participants. Although conclusions drawn from the results should be viewed with caution because of the small number of participants, the trend observed was statistically valid ($t_0(3) = 7.98$, $p = 0.0021$, two-tailed paired t-test).

5 Conclusions

In this study, we examined the friction sensation caused by vibrotactile stimuli. We assumed that asymmetric vibrotactile stimuli cause anisotropic shear deformation of the finger pad and influence the perception of friction, although such mechanism should be discussed further. We controlled the motion of the contactor to ensure a saw-toothed-like displacement profile that produced an asymmetric vibrotactile stimulus. The participants felt stronger friction when scanning the contactor in one direction than in the other direction. In addition, the impulses of the friction forces between the participants' finger pads and the contactor were different between these two directions. This approach to producing the sensation of friction using vibrotactile stimuli broadens the applicability of vibrotactile texture displays.

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