# On the Effect of Vibration on Slip Perception During Bare Finger Contact

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**Abstract.** This study investigated the influence of the presence and timing of cutaneous vibration cues supplied to the finger pad on the perception of slip of a contact surface slid beneath it. We designed an apparatus that made it possible to supply precisely controlled shear force, sliding displacement and vibration cues to the finger pad via a moving surface. We conducted an experiment to assess the effect, if any, of the presence and timing of vibrotactile feedback presentation relative to slip onset on the perceived duration of slipping between the finger and the sliding surface. We found that vibrotactile stimuli that are presented at slip onset or during the slip phase both increased the perceived duration of slipping. In contrast, if the same cues are presented during the stick phase, they tended to decrease perceived slip duration. These results support a perceptual role for cutaneous vibrations felt in slip estimation, and indicate an opposite perceptual interpretation depending on their timing relative to slip onset.

**Keywords:** Slip sensation, Stick-to-slip transition, Slip onset, Vibrotactile stimuli, Skin vibration

## 1 Introduction

Humans can readily perceive whether an object in contact with the finger is slipping or not, and slip detection in this form is assumed to be instrumental to a variety of manipulation tasks. However, the mechanism through which slip is perceived is not fully understood. During shear interaction between the finger and a contacting surface, slip generally proceeds through three contact phases [1, 2]. First, in the stuck phase, the tangential (shear) force grows without macroscopic relative displacement of the contacting surfaces. Second, at slip onset, a stick-to-slip transition occurs, in which relative displacements begin propagate locally in the contact area. Finally, in the full slip phase, the stuck contacting area disappears entirely, and the contacting surfaces undergo macroscopic relative sliding. In each of these phases, transient local deformations of the finger pad are generated, exciting concurrent activity in multiple types of mechanoreceptive afferents [3, 4]. The activation of these receptors is understood to contribute to

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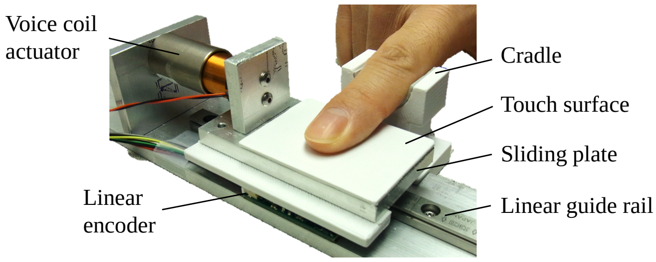


**Fig. 1.** Apparatus used to apply force profiles

the unconscious regulation of grip forces in ways that arrest slipping [5, 6], but the precise way in which vibrotactile stimuli affect slip perception has yet to be revealed. To this end, we designed a novel apparatus to stimulate the skin with shear sliding and vibration cues and undertook an experiment to investigate the influence of the presence and timing of cutaneous vibration stimuli on slip perception.

We specifically sought to investigate the role of vibrotactile stimuli that are presented in each of the three phases described above, i.e.: sticking, slip onset, and full slipping. As noted, we refer to the stuck phase as the period of time during which a shear strain is applied to the fingerpad without slipping. We hypothesized that the combination of tangential (shear) force and imposed cutaneous vibration cues would lead to a perceptual interpretation that slip had occurred. Although we refer to the second phase in our experiment as slip onset, the precise timing of slip is difficult to detect, since it accompanies a very rapid collapse of the stuck area of contact [2]. We could identify the occurrence of this transient phenomenon only immediately afterward, when the sliding speed reached a threshold value (see methods, below). Nonetheless, we regard this phase as the transient initiation of slipping. We hypothesized that an imposed vibrotactile stimulus presented in this phase would enhance the detection of slip onset. Finally, we hypothesized that during the full slipping phase, which temporally follows slip onset, imposed vibration feedback could enhance participants' sense that the contact surface was slipping beneath the finger.

In summary, if the sense that a surface is slipping under the finger is associated with the activity of mechanoreceptors in the fingerpad, then imposed skin vibrations that activate these receptors may influence the perceived slip duration. However, the extent and nature of influence could depend on the relative timing of presentation.

Motivated by the foregoing considerations, we designed an apparatus that makes it possible to supply precisely controlled force, sliding displacement and vibration cues to the finger pad. We conducted an experiment to assess the influence of the presence and timing of vibrotactile feedback on the perceived duration of slipping between the finger and a sliding surface.

## 2 Methods

The experiment investigated the discrimination of slip duration. It was based on the method of paired comparison.

### 2.1 Apparatus

The device we designed for this investigation is shown in Fig. 1. The moving part consists of a plate with a contacting surface mounted on a low noise linear guide. To ensure consistent friction conditions, during the experiment, a rectangle of cardstock paper was affixed to the plate, and the fingerpad of the participant was allowed to rest on this plate. A voice coil actuator (GVCM-019-032-02, Moticont, CA, USA) drove the linear guide as commanded by a microcontroller (mbed NXP LPC1768, NXP semiconductors, Netherlands) and a voltage-controlled current amplifier (4-Q-DC LSC 30/2, Maxon Motor, Switzerland). The displacement of the sliding plate was captured by a linear encoder (OEM-030U-01, Moticont, CA, USA). The sampling rate of the control and measurement were set to 2.5 kHz and due to the controlled mechanical design, the usable frequency bandwidth of the device extended to more than 1 kHz, ensuring that shear force, sliding displacement, and vibration cues could be precisely delivered to the fingerpad. A cradle was used to restrict kinematic movement of the finger; consequently, the displacement of the linear guide virtually corresponded to the skin deformation until slip onset.

### 2.2 Procedure and task

Six participants, all of them are students in the authors' department, volunteered for the study. Participants were naive with respect to the purpose of the investigation. They sat on a chair and placed the index finger of their dominant hand on the sliding plate while maintaining an approximately constant normal force of 1.5 N in order to avoid variations in friction forces. They were trained to produce the specified normal force through feedback from a digital scale, and were re-trained at maintaining this force level at breaks and wore sound insulating headphones playing a pink noise sufficient to mask any sounds produced by the apparatus during experiments.

In each trial, participants felt the plate strain the fingerpad, then slide beneath it while their finger remained passive. This occurred for two different configurations of the slip stimulus. Participants then responded indicating whether the duration of the first or second slip was greater. They were instructed that "duration of slipping" referred to the length of the time period during which they felt slipping to occur. A slippage is difficult to be subjectively scored, therefore we employed the perceived slip duration as the evaluation index.

### 2.3 Stimuli and procedure

The experiment employed four different configurations of vibratory stimuli applied to the finger pad, that consisted of commanded shear force trajectories

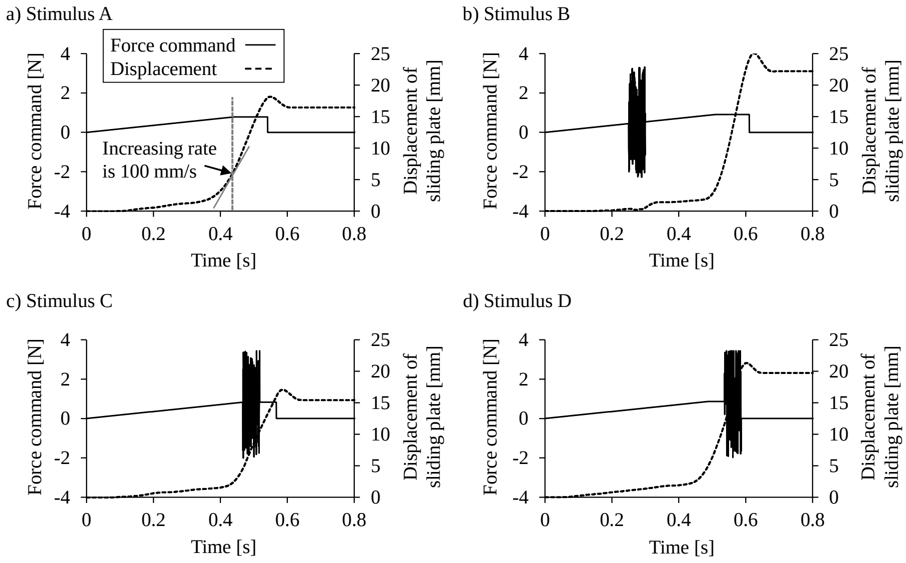


**Fig. 2.** Examples of force command and displacement of sliding plate in four types of stimuli

with or without imposed vibrations. They were presented via the apparatus described above. The four types of stimuli used in the experiment (A, B, C, and D; see Fig. 2) differed according to the presence and timing of vibrotactile cues. The timing of the latter cues was specified relative to one of two events: the onset time $t_0$ of shear stimulation of the finger or the subsequent time $t_s$ of onset of slip between the plate and the finger. Slip onset was determined to be detected reliably as first the time $t_s > t_0$ at which the rate of displacement reached 100 mm/s. This time varied outside the experimenters' control from trial to trial due to variations in frictional parameters. The stimuli are described in detail in the following paragraphs.

*Stimulus A: No vibrotactile stimulus* For stimulus A, as shown in Fig. 2a), the force command was increased at a rate of 1.78 N/s after a random time delay of 0–1 s. After slip onset, the force stopped increasing and was held constant for a further 100 ms before it was reduced to 0 N.

*Stimulus B: Vibrotactile stimulation during stuck phase* An example of the force command and the slider displacement for stimulus B are shown in Fig. 2b). The difference from stimulus A is in the presence of vibrotactile stimulus. We adopted a white noise as the vibrotactile stimulus for stimulating multiple mechanoreceptors in the fingerpad skin, because these receptors react to the dynamic deformation of fingerpad [3, 4]. This vibrotactile noise cue was initiated at a time 250 ms after $t_0$ and lasted for 50 ms.

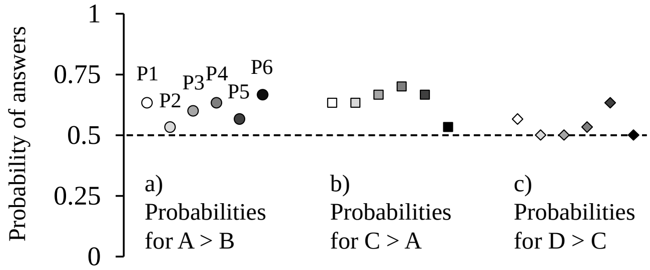


**Fig. 3.** The frequencies with which the estimated slip duration in each stimulus condition is perceived longer than those in its paired conditions

*Stimulus C: Vibrotactile stimulation at slip onset* Fig. 2c) shows an example of the force command and the displacement for stimulus C. The vibrotactile stimulus was applied coincident with the slip onset time, $t_s$, and lasted for 50 ms.

*Stimulus D: Vibrotactile stimulus presented during slip phase* An example of the force command and plate displacement for stimulus D are shown in Fig. 2d). The vibrotactile stimulus was supplied at 50 ms after the time of slip detection and lasted for 50 ms.

*Pairwise comparisons* Participants were presented with five different paired comparisons (A-A, A-B, A-C, B-C, and C-D) in a two-alternative forced choice task in which they judged which stimulus had a longer slip duration. The paired stimuli and five combinations were presented to each participant in randomized order. The purpose of comparisons (A-B, A-C, C-D) was to assess the influence of vibrotactile stimulation and timing on the perceptual estimation of slipping duration. The remaining comparisons (A-A, B-C) were included in order to assess the extent to which participants' slip duration judgements may have been biased by the presence of vibration stimuli independent for reasons unrelated to slip duration perception. These were, in short, used as control trials.

For each participant, 250 comparisons were conducted, so that each stimulus pair was presented 50 times per participant. Participants were required to pause and rest after each 50 trials. The experiment lasted approximately two hours per participant.

## 3 Results

In analyzing the results, we removed trials in which slip occurred later or earlier than expected due to changes in contact or frictional conditions, or variations in normal force because these differences may affect the perceived slip duration. In each of five comparisons, 10 trials in each condition with the largest value of difference of $t_s$ between a stimulus pair and 10 trials that exhibited the largest difference of maximum slip displacement were excluded. We analyzed the remaining data, which consisted of 30 trials for each participant in each experimental condition.

Figure 3 shows the probabilities at which the slip duration in each condition was perceived longer than those other conditions with which it was paired. We used hypothesis testing to assess whether the participants' answer ratios were significantly greater than chance level (0.5).

*Comparison between stimuli A and B* As shown in Fig. 3a), the perceived slip duration for stimulus A was significantly longer than that for stimulus B (two-tailed $t$-test, $t(5) = 5.27$, $p < 0.01$). This result indicates that the vibrotactile stimulus presented at the sticking phase reduced the perceived slipping duration.

*Comparison between stimuli A and C* As shown in Fig. 3b), the perceived slip duration for stimulus C was significantly longer than that for stimulus A (two-tailed $t$-test, $t(5) = 5.93$, $p < 0.01$). The participants tended to perceive the slip duration longer when the vibrotactile stimulus was presented at slip onset. We should note that the influence of stimulus B was opposite to that of stimulus A.

*Comparison between stimuli C and D* Fig. 3c) shows that there is no significant difference between the perceived slip durations between stimuli C and D (two-tailed $t$-test, $t(5) = 1.78$, $p > 0.05$). This result implied that the vibrotactile stimulus presented during the slipping phase has a similar effect on the perceived duration of slip to one presented at slip onset (stimulus C).

*Comparison between stimuli B and C* The perceived slip duration for stimulus C was significantly longer than that for stimulus B (two-tailed $t$-test, $t(5) = 5.56$, $p < 0.01$). This result is consistent with the above comparisons in which A $>$ B and A $<$ C, which indicates that the participants' answers were not merely affected or biased by the presence of vibration.

## 4 Discussions

From the results of comparisons (A-B), it can be inferred that imposing vibration at a time preceding slip onset tends to reduce perceived slip duration. This might be explainable in terms of vibrotactile masking, which could reduce sensitivity to slip onset cues. For example, when humans experience high and low-frequency vibrations in succession, they perceive the latter vibration to be weaker than the former one [7]. Thus, the pre-slip vibration stimuli used in our experiment could have contributed to obscuring the detection of cutaneous vibrations caused by the transition from sticking to slipping phases.

From the comparisons (A-C, C-D), it could be inferred that vibration cues presented at slip onset or during the slip phase can influence the perception of slip duration. Stimulus C, which presented vibration at slip onset, might have been perceptually fused with transient skin vibrations occurring at the transition from stick to slip. If so, this could explain why stimulus C tended to increase estimates of slip duration. Alternatively, stimulus D, in which vibration occurred during mid-slip, could have been perceptually fused with skin vibrations elicited by sliding. The latter occur due to transient contacts between epidermal ridges and asperities constituting fine surface texture. If this were the case, stimulus D may have elicited a sensation similar to that experienced during continuous slipping.

In summary, we can conclude from these results that humans make perceptual use of vibration information felt through the skin in estimating slip duration, and that the timing at which a vibration cue is felt also has an effect on the perception of slip duration, to the extent that vibration presented during an appropriate phase can either increase or decrease the perception of slip duration. These discussions are based on the results from six participants, therefore more participants are preferable for precise discussions.

## 5 Conclusion

We investigated the perceptual influence of imposed vibrotactile cues during shear interactions between a surface and the fingerpad, by designing a novel apparatus for presenting precise vibration and shear displacement cues, and by conducting an experiment in which shear stimuli were presented with and without vibrotactile cues, and with variable timing of vibration presentation. The results of these experiments indicate that slip duration can be affected by vibrotactile stimuli in ways that depend on the timing of vibration. These support the idea that similar vibrations may play a role in the perception and regulation of slip during bare finger contact with an object, and may have further implications for understanding the mechanisms underlying perceptual exploration and manipulation of palpated objects.

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