Ultrasonic Friction Modulation While Pressing Induces a Tactile Feedback

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Abstract. Current touchscreen technology makes for intuitive human-computer interactions but often lacks haptic feedback offered by conventional input methods. Typing text on a virtual keyboard is arguably the task in which the absence of tactile cues imparts performance and comfort the most. Here we investigated the feasibility of modulating friction via ultrasonic vibration as a function of the pressing force to simulate a tactile feedback similar to a keystroke. Ultrasonic vibration is generally used to modulate the sliding friction which occurs when a finger moves laterally on a surface. We found that this method is also effective when the exploratory motion is normal to the surface. Psychophysical experiments show that a mechanical detent is unambiguously perceived in the case of signals starting with a high level of friction and ending to a low friction level. A weaker effect is experienced when friction is increasing with the pressure exerted by the finger, which suggests that the mechanism involved is a release of the skin stretch accumulated during the high-friction state.

Keywords: Surface-haptics, finger friction, keyclick, virtual keyboard

1 Introduction

Typing text on flat glass panel is a much more difficult task than using a conventional keyboard. The absence of tactile cues in virtual keyboard decreases the users efficiency and increases the cognitive load [1, 2], making the interaction uncomfortable and slow. In addition, when no haptic cues are available, the user has to rely on visual cues, which might interfere with other tasks. Providing tactile feedback resembling a mechanical keyclick on flat glass, would allow for programmable and tangible touch-screen interfaces.

Mechanical switches, such as those found in computer keyboards are based on various mechanisms that provide haptic cues which notify the user that the pressure exerted is sufficiently strong and the action has been successfully performed. One possible embodiment, which is illustrated in Fig. 1**a**, involves a spring and a linear cam to create a region in the trajectory of the keys where the apparent stiffness becomes negative. Because of the negative stiffness, the key is accelerated downward, and the reaction force applied the pulp of the finger is momentarily reduced, leading to a distinct feeling of keyclick [3, 4]. Other technical implementation such as those that use buckling of a coiled spring [5], a flexible dome [6] or a scissor linkage [7] have increased reliability, reduced noise and minimized the size.

The mechanical displacement of the surface contacted by the finger is often not compatible with touchscreen technology, and vibrotactile stimulation can therefore be used to simulate the feeling of a keyclick. The method mainly used for this purpose is based on a short vibratory signal, which is triggered when force reaches a programmed threshold. The signal is usually a short sine-wave burst, which emulates the finger contact with a rigid material [8]. The vibration can be transmitted to the user using piezoelectric actuators [9], voice-coils [1] or electromagnets [10]. Adding vibrotactile feedback to this kind of virtual keyboard has been shown to increase the typing speed and user's comfort [11]. In addition, vibrotactile feedback can be used in a interactive way to influence the perceived compliance of an object. Visell et al. have reported that if the amplitude of a vibration is modulated according to the rate of change in the force while a user steps onto a actuated tile, the assembly appears to be more compliant [12]. While very effective, touchscreen interaction mediated by vibrotactile feedback generaly needs a flexible mounting for the screen, because of the large amplitude of the vibrations, which is often an engineering challenge.

The user's interactions with a glass plate can be altered when it is subjected to ultrasonic transverse vibrations. The vibration induces a non-linear compression of the film of air trapped between the skin and the glass surface, called squeeze-film, which reduces the friction. Increasing the amplitude of the ultrasonic wave results in a monotonic decrease of the friction force [13]. This effect has been exploited to create interfaces that produce virtual bumps and textures while the finger is laterally sliding on the surface [14–16].

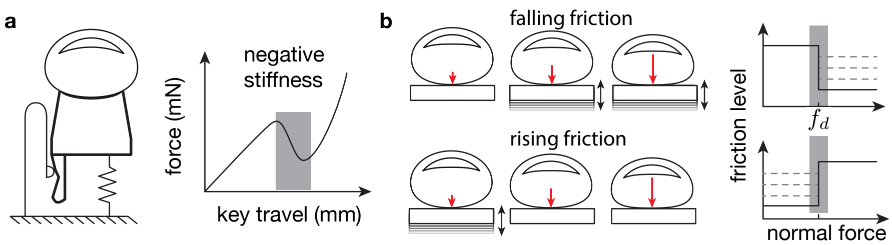

Fig. 1. **a**. Schematic of a mechanical switch. The detent of the switch is triggered by a reversal of the stiffness at a pre-defined travel threshold. The negative stiffness region relieves some of the interface stretch built up while pressing the key. **b**. Similar skin-stretch relief is achieved by decreasing or increasing friction once the normal force reaches a threshold f_d. Dashed lines show the various friction levels used in this experiment.

The working hypothesis adopted in this study, hinges on the observation that at the first contact between the one's finger and a surface, enough information is acquired to be able to estimate the frictional properties and the compliance of the object [17]. Although the compliance is likely to be extracted from the contact area spread rate and the relation between the force and the deformation of the finger pulp [18, 19], the mechanism used by the central nervous system to estimate frictional properties of the surface seems to be based on the distribution of tangential stress created in the contact area by the friction between the surface and the skin [20]. We focus here on the skin-stretch induced by the friction at the interface between the subjects' skin and a glass plate. As illustrated in Fig. 1**b**, a sudden change in the friction coefficient induced ultrasonic transverse waves evokes a sensation corresponding to the detent of a switch, such as that typically experienced when using mechanical buttons.

2 Experimental procedures

2.1 Apparatus

The friction reduction device used in the present experiment based on a similar rectangular glass plate to that presented in [16], vibrating in the 1×0 mode. The frame is mounted on a strain-gauge force sensor that measures the normal force exerted by the finger. The sensor is able to resolve 10 mN of force in a 3.5 N range. The normal force is acquired with a 12 bits resolution by the onboard analog-to-digital converter of the micro-controller and processed via a lookup table containing the profile of excitation. The value is then converted back to analog, smoothed by means of a 1 kHz reconstruction filter and multiplied to the carrier to produce the amplitude-modulated signal. The reconstruction filter ensures that the signal is smooth and devoid from vibrotactile artifacts. The analog signal is then amplified 20 times with a maximum voltage of 160 V and fed to the piezoelectric actuators bonded to the plate. The whole assembly is able to reach peak-to-peak amplitudes up to 4μm at the 35 kHz resonant frequency. A picture of the apparatus and the functional scheme involved is presented in Fig. 2.

2.2 Participants

Fourteen right-handed volunteers (5 females and 8 males), ranging from 21 to 43 years of age, participated in the study. They were naive to the aim of the study and had no experience with surface-haptic devices. None of them reported having any skin conditions or perceptual deficits. The study was conducted in line with the recommendations of Aix-Marseille University's ethics committee and the participants gave their informed consent to the procedure.

2.3 Protocol

Participants sat in a chair in darkness and wore noise-canceling headphones to prevent any visual or auditory cues. They were asked to press on the device

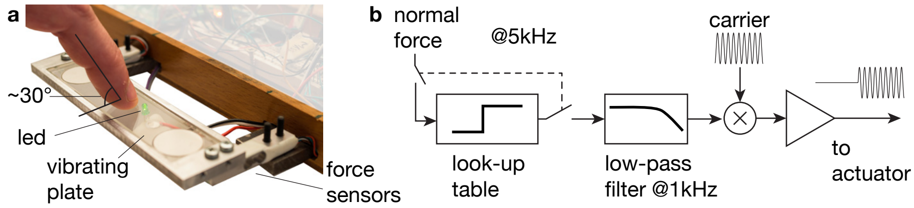

Fig. 2. a. Picture of the apparatus showing the glass plate used for friction modulation, mounted on normal force sensors. **b**. Rendering scheme. The force is fed into a lookup table controlling the envelope of the ultrasonic vibration.

with their index finger, using their dominant hand. The location on the device where the participants had to press was indicated by a LED placed below the glass plate. Subjects first found a comfortable position, which amount roughly to placing their finger at a 30° angle to the surface. They were instructed to press with a similar force "to that exerted when using a tablet, or typing on a keyboard" and to restrict their motion in the vertical direction. When the measured force reached the threshold f_d, the led turned off to indicate they could answer. A constant stimuli single interval paradigm protocol was used. Participants are asked if "they felt a mechanical detent", i.e. a key click sensation. They answered pressing on YES or NO buttons, with other hand.

Preliminary trials showed that fast transient from one level of friction to another resembled the perceptual substance of a mechanical switch most closely. Signals of two kinds were delivered in the this study. In the first case, friction varied from high-to-low values (falling edge condition) and in the second case increased from low-to-high values (rising edge condition), see Fig. 1b. The force threshold used to trigger the transition from one state to the other was set at 0.3 N, based on previous informal experiments. Each signal is derived with 10 different levels of reduced friction, the higher friction being set by the glass plate at rest. Each condition was repeated 10 times, for a total of $2 \times 10 \times 10 = 200$ trials. Each of them was presented randomly and the session lasted 15 to 20 minutes.

3 Results

The effects of the frictional keyclick on both the participants responses and the behavioral changes in the force production levels were analyzed.

3.1 Detection thresholds

The participants' responses to the single interval paradigm procedure were aggregated. The proportion of "keyclick detected" answers were compared with the intensity of the stimulus presented using non-parametric Spearman's coefficients r_s. Fig 3 presents the value of the coefficient obtained by each participant

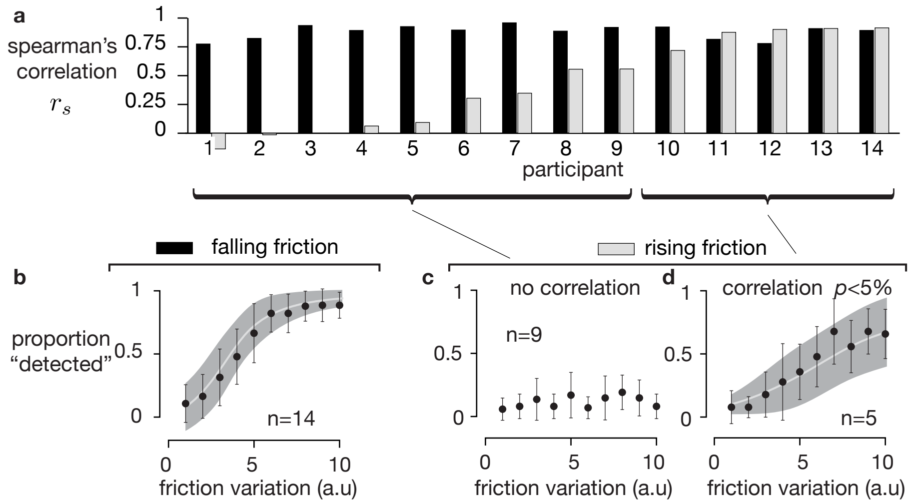

Fig. 3. a. Spearman's rank correlations calculated from each participant's psychometric data. **b**. In the case of rapidly decreasing friction, every single participant response follows a psychometric curve, showing that the keyclick has been unambiguously detected. **c,d**. In the condition starting with low friction, two groups emerged. The one group obtained a low detection rate and no correlation was observed between the responses and the friction level (**c**, n=9). The other group detected the largest difference of friction and followed a psychometric curve (**c**, n=5). Light gray line shows the averaged results of the fitting procedure with a logistic function. The dark gray are show the one standard deviation of the logistic regression. Error bars represent one standard deviation of the data

in each condition test. In the condition where the friction levels switched from high-to-low, the correlation is always greater than 0.75, with a p-value $p < 0.05$, indicating that the data are statistically correlated. On the other hand, in the condition in which the friction increased from low to high level, the correlation depended strongly on the participant. The response of five participants out of the fourteen were significantly correlated with the level of friction ($p < 0.05$).

In each case where significant correlation was found to exist between friction variation and the detection rate, a logistic function $f(x) = 1/(1 + \exp(\frac{-x+\mu}{\sigma}))$ was fitted using non-linear least-square methods, where μ is the absolute threshold and σ is the standard deviation. The values of the detection threshold are presented in Fig. 4. It can be noted here that the detection threshold when the friction increases is greater (average $\langle \mu_{rising} \rangle = 8$ a.u.) than for the decreasing friction condition (average $\langle \mu_{falling} \rangle = 3$ a.u.). Two-sample t-test rejected the null hypothesis of a correlation between the distribution across participant of absolute threshold in both cases ($p = 0.03$).

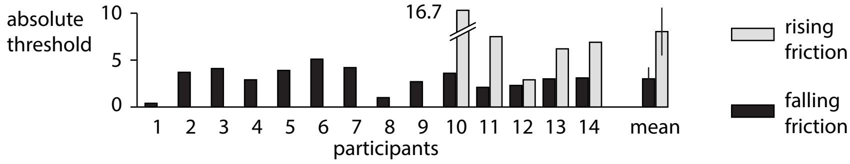

Fig. 4. Each participant's absolute detection threshold in both conditions. Only the trials in which responses are statistically correlated to the amplitude of friction variation are shown.

3.2 Behavioral changes

The time-related evolution of the normal force suggests how the haptic feedback provided via ultrasonic vibration influences the exploratory behavior of the participants. We selected only the trials in which the responses were unambiguous, i.e., those in which friction values of less than 1 were used in the "undetected" cases and more than 9 in for the "detected" cases, regardless of the condition. Two datasets were excluded because participants 1 and 6 repeatedly saturated the force sensor.

The typical force profile follows a bell shaped curve, as can be seen from Fig 5a. The duration and level of the peak force delivered varied from one trial to another, see Fig 5b. The largest forces took longer time to develop. In order to find a unique descriptor, we used principal component analysis (PCA) was performed to obtain the average and standard deviation of the locus of the maximum force delivered of in each trial in the force/time space, along the first eigenvector. The relative change is computed on the basis of $(\sigma_{detected} - \sigma_{undetected})/\sigma_{detected}$ where σ is either the average value or the standard deviation along the first eigenvector. Fig 5c indicates that the relative change in the locus between the detected and the undetected response is positive for a majority of the participant and trial. In other words, the presence of a tactile feedback significantly reduced the peak force and the time taken to produce the keyclick by 14% on average. In addition, the variability of the force delivered from one trial to another also decreased by 36% in the cases where the keyclick was detected.

4 Discussion and possible mechanisms involved

Friction modulation devices operate on the basis that the finger explores the surface laterally and the relative movement of the two surfaces in contact gives rise to friction forces. However, fast changes in the frictional force occurring during a normal pressing movement suffice to produce haptic feedback, even without any lateral motion. The results of the psychophysical and behavioral experiments performed here indicate that this effect is stronger when the friction is initially high and then decreases, which provides clues to the mechanism underlying the perception of changes in friction occurring during normal finger motion.

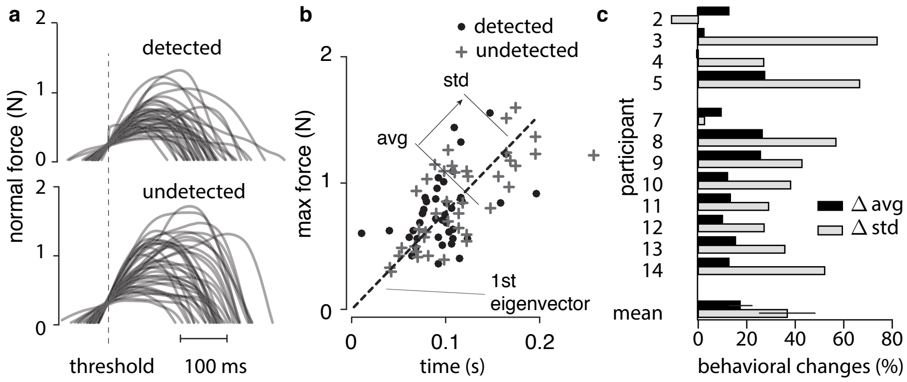

Fig. 5. a. Typical force traces obtained with participant 8 when he detected or did not detect the keyclick. **b**. Locus of the maximum force exerted in each trial by participant 8. The average and standard deviation were measured along the first eigenvector.**c**. Average and standard deviation of the maximum force locus along the principal axis for each participant. When the keyclick was not detected the maximum force was greater and the variability across trial increased.

The results support the idea that the feeling of a keyclick is achieved by suddenly releasing stretching of the skin, built up during the initial contact with an adherent surface. The skin is a membrane that progressively sticks to the surface as the finger is pressing down. The edge of the contact area pulls on the rest of the skin that is already in contact, creating an interfacial shear stress that is radially distributed around the initial point of contact. Evidence of this lateral stress field has been presented in [17] and used in a robotic finger in [20].

In the opposite case, where the friction level changes from low to high, the skin will not undergo any stretching, because the surface is almost frictionless. The transition was therefore not so clearly perceived by the subjects. Some of the participants did feel a detent, but the absolute threshold was higher in this case and the effect was not as strong. The perception was probably due here to an acute sensitivity to frictional changes. It could also be due to undesirable lateral movement, leading to slight gross slippage of the participant's finger. Future investigation will control the deployment of lateral forces .

During the contact with a real mechanical keyboard, however, the depression of the keys temporarily reduces the normal force and thus releases some of the accumulated stretch in the contact area. With the present device, the tangential stretching of the skin was relieved when the ultrasonic vibration was turned on, breaking the contact between the plate and the skin. The sudden release of the stress accumulated as the result of the friction between the finger and the plate gave rise to a perceptible tactile transient.

5 Conclusion

We developed an apparatus for accurately measuring the normal force applied by a user onto a glass plate. We used it to control in real-time the frictional properties of a glass plate, via the application of ultrasonic vibrations, while the user is pressing down. The results of the psychophysical experiment shows that a robust perceptual experience, resembling the effect of a keyclick, is felt by the user.

Ultrasonic vibration has been proven to be an effective method to render tactile texture and shape by modulating the friction of the user's finger while it slides onto a surface. In this study, it was established that even in the absence of lateral motion, a tactile stimulus can be vividly perceived. This study extends the range of potential application of friction modulation, by showing that it is possible to leverage changes in friction in cases where no relative lateral movements have occurred between the finger and the plate. Moreover, this method can create virtual switches on flat surface-haptic devices without requiring any additional vibratory actuators.

The frictional signals delivered in this study were transient and therefore relatively easy to detect. Future studies will look into the effect of more complex signals such as ramp, noise and periodic wave, in order to investigate the full rendering capabilities of this approach. In addition, the results of the psychophysics experiment suggest the existence of a mechanism based on the release of residual skin stretch. High-speed imaging will help quantify the temporal evolution of the tangential stress field under various ultrasonic vibration patterns, and the results obtained will predictably shed light on the exact mechanisms at work.

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