Optimal Skin Impedance Promotes Perception of Ultrasonic Switches

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Abstract— **Ultrasonic friction reduction is one potential technology for bringing tangibility to flat touchscreens. We previously established that this approach can be used to create an artificial sensation of pressing a mechanical switch by varying the coefficient of friction, which depends on the force applied by the user. This sensation proves effective majority of , but a non-negligible fraction reported feeling only weak sensations or none at all. In the present study, we examined the factors possibly involved in producing a vivid perception of a stimulus by measuring the mechanical impedance of the fingertip as an index to the frictional behavior, and performing psychophysical experiments. Subjects who experienced weaker sensations were found to have a weaker susceptibility to friction modulation, which may in turn be attributable to either a larger or a smaller than average impedance; whereas those with a mechanical impedance of around 33 N.s/m clearly perceived the ultrasonic switch. Measuring and factoring the users impedance in real time could therefore provide a useful means of improving the rendering of ultrasonic surface haptic devices.**

I. INTRODUCTION

Touching a plate that is vibrating at ultrasonic frequencies produces a sensation of smoothness, which is attributed to the decrease in the frictional resistance to sliding motion. Harnessing this phenomenon offers the possibility of creating artificial tactile stimuli on otherwise featureless touchscreen displays, by means of modulating the friction between the finger and the plate in real time. In order to produce relief and textural patterns, previous authors have shown that the friction forces can be updated depending on the position of the users finger , thus creating the illusion of out of plane shapes [1], [2]. It has been recently established that even in the absence of lateral motion, modulating the friction as a function of the normal pressure force induces the sensation of pressing a mechanical button [3], [4]. Despite its potential, methods of ultrasonic friction modulation still show relatively large variability in terms of the control of the friction force. This variability taints the realism of these interfaces. The relationship between the friction force and the amplitude can differ by as much as 40% from the average value. A wide range of parameters seem to contribute to this variability [5]–[7].

The exact mechanism underlying ultrasonic friction reduction is still a matter of continuing research. Watanabe and Fukui [8] have postulated that squeeze-film lubrication is the main mechanism at work in this process: the vibration creates a pressurized film of air which reduces the contact forces [9]. An alternative hypothesis is that friction reduction may result from an intermittent contact with the skin rather than involving a squeeze film mechanism. Evidence of intermittent contact was obtained using Laser Doppler vibrometry, which showed the occurrence of fast transients in the vertical velocity of the skin, which were compatible with the timing of the impact between the finger and the glass screen. However, since optical measurements alone do not give any information about the time-average gap between the glass and the skin, no definite answer to the question about the possible presence of a squeeze-film mechanism was obtained [10].

Frustrated total internal reflection imaging of the contact between a vibrating plate and the fingertip provides a useful means of probing both the dynamics of the contact and the time-averaged evolution of the interfacial gap [7]. This method unequivocally showed the levitation of the skin over the vibrating plate, which confirmed that a squeeze film levitation process is involved in the reduction of friction. In addition to the simple levitation of the skin, micro-second imaging also showed that the skin undergoes oscillations, in line with findings made in previous studies. These results suggested the hypothesis that the skin is bouncing not on the plate, but on a film of air. An ultrasonic click sensation is created when some of the elastic energy stored is latched by friction during compression of the pulp of the fingertip. When the vibration is turned on, the friction is reduced and the energy released, see Fig. 1a. A change in the effectiveness of the ultrasonic friction modulation affects the amount of elastic energy released and hence, the perception of the ultrasonic switch.

Ultrasonic friction reduction is a complex process involving acoustic, biomechanical and tribological components. It is therefore not surprising that a large number of parameters affect the end result. The biomechanical responses of the finger tissues are a crucial factor contributing to the perception of ultrasonic levitation. In a study on three artificial fingers and that of a human subject, Fenton Friesen et al. established that the damping ratio measured around the oscillation frequency of the device was correlated with the subjects sensitivity to ultrasonic friction modulation [11], [12]. Higher damping ratios —i.e. damping normalized to the inertia—resulted in a greater decrease in the friction at a given vibration amplitude. Damping effects introduce a lag between the excitation and the motion of the skin which makes the two bodies in contact oscillate out of phase. When elastic conditions predominate, the skin and the plate remain constantly in contact, which means that there can be no acoustic levitation or friction modulation. The physico-chemical properties of the skin also play a decisive role in the variability and the strength of the effect produced. Even

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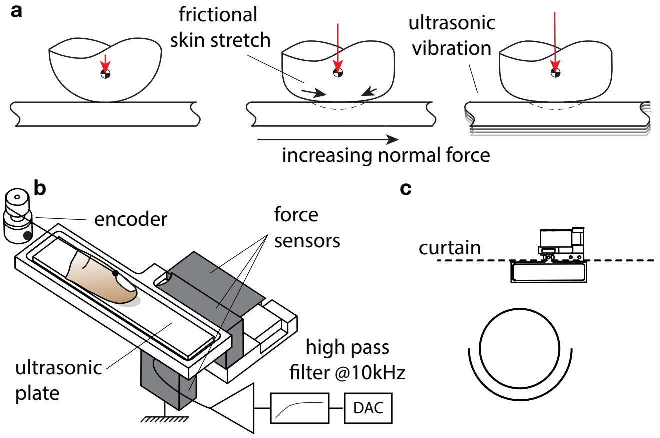

Fig. 1. **a**. Pressing on the glass plate induces a local stretching of the skin due to the loss of lateral mobility created by friction. Triggering ultrasonic vibration releases the elastic energy stored, which produces the feeling if pressing a switch. **b**. In these experiments, participants were first allowed to freely explore the surface of the glass plate. The interaction forces and the position of the finger were recorded by three orthogonal force sensors and an incremental encoder connected magnetically to the fingernail. **c**. The entire setup was hidden from the subjects view, except for the ultrasonic plate.

in the absence of ultrasonic vibration, fingertip friction is notoriously difficult to predict, since the friction coefficient varies by more than one order of magnitude between dry and moist skin conditions [13], [14], as well as depending on the size of the finger, the oil content of the skin and the exploration/friction velocity [6].

The modulation of friction while sliding is well perceived with Webers fraction in the order of 20%, which is roughly the same level of precision as that recorded in the case of viscosity and weight perception [15]. Patterning spatial distribution of friction levels highlighted how this technology can improve human computer interaction [16], [17]. Among the factors on which the subjects perception depends, Ben Messaoud et al. [18] noted that participants subjected to a small change in the frictional force had greater difficulty in perceiving frictional stimuli than those subjected to large variations.

In a previous study on the frictional switch, the majority of users described a striking unambiguous perceptual experience [4], whereas a small fraction of the subjects experienced only a weak stimulus or none at all. The aim of this study was to rigorously quantify the proportion of participants who perceived a weaker effect and more importantly, to investigate the factors possibly responsible for these perceptual differences . Based on previous studies in the literature, biomechanical data on the pulp of the fingertip were combined with tribological measurements and a psychophysical assessment of the minimum ultrasonic vibration amplitude required to generate a click sensation. In line with [18], the tribological properties of the skin were found to be good predictors of the subjects ability to detect the stimulus. In addition, the tribological parameters were found to be closely linked to the impedance of the skin: these findings will help develop more effective ultrasonic friction modulation devices.

II. MATERIALS AND METHODS

A. Setup description

The friction reduction device used in the present experiments, which was similar to that previously used in [4], was based on a rectangular ultrasonic glass plate vibrating at a frequency of 34,590 Hz.A piezoelectric sensor glued to the center of the plate was used to measure the plate deformation in real time. The sensor, which was calibrated with an interferometer, (IDS3010, Attocube, Munchen, Germany) gave a linear response in the ±2.5 µm amplitude range. The plate was mounted onto an aluminum frame carrying a set of three strain-gauge force sensors (LCEB-5, Omega, Norwalk, CT, USA) measuring three orthogonal components of the force exerted by the finger, see Fig. 1b. The load cells were calibrated to eliminate cross-talk. The position of the finger was recorded using a incremental encoder (BTIV 24S 16.24K, Baumer AG, Frauenfeld, Switzerland) equipped with a capstan fixed to the fingernail. Forces and positions were transmitted to a data acquisition board (USB-6229, National Instrument, Austin, TX, USA) at a sampling rate of 200 kHz, corresponding to about 8 samples in one oscillation cycle.

The driving signal produced by the data acquisition board was fed to a 10 kHz analog high-pass filter in order to attenuate vibrotactile artifacts. The signal was then amplified 20-fold before being sent to the piezoelectric actuators. Envelope of the vibration was computed offline using Hilbert transform.

B. Participants

Fifteen right-handed volunteers (6 females and 9 males), ranging from 19 to 63 years of age, participated in the study. They were naive as to the purpose of the experiments and had no previous experience of haptic devices. None of them reported having any skin conditions or perceptual deficits. The study was conducted with the approval of the *Comité de Protection des Personnes Sud Meditéranée* ethics committee and the participants gave their prior informed consent to the procedure.

C. Experiment sequencing

In order to record the participants mechanical, tribological and perceptual responses, three separate experiments were performed. The first experiment was designed to measure the impedance of the participants right index fingertip placed on the plate on the plate. The aim of the second experiment was to assess the range of forces produced by friction modulation when the subjects finger was scanning the vibrating plate to which amplitude modulated ultrasonic signals were delivered. Lastly, the threshold vibration amplitude required for the subjects to be able to reliably detect a click was determined by performing psychophysical experiments. The moisture of the skin was measured with a capacitive skin moisture analyzer delivering values ranging between 0 and

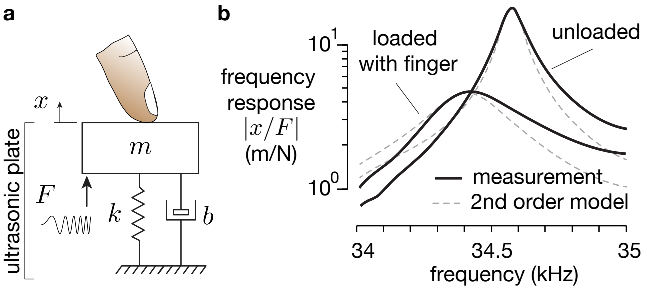

Fig. 2. **a**. Diagram of the impedance measurement device. The resonant system and the finger are approximated as second-order systems. **b** Representative responses of the plate around the resonance frequency of the plate, with and without the fingertip. The mass of the finger and the damping induced were calculated based on these data, along with the phase data.

100 on an arbitrary scale. Contact area of the finger was determined by asking the participants to ink their finger and press on a paper sheet. The fingerprints were scanned and processed as described in [19]. The entire session lasted roughly 30min. Participants were sitting comfortably in a chair, and the entire setup was hidden from their view apart from the glass plate, as illustrated in fig. 1c.

D. Finger impedance measurements

1) Protocol/Procedure: Skin impedance was determined from the effect of the finger pressure on the resonance of the vibrating plate. Given the low mechanical impedance of the resonating plate around its nominal resonance frequency, this set-up can be used as a measuring device by simply analyzing how the finger affects the resonance amplitude and frequency [12], [19].

Participants pressed on the glass plate with a constant normal force of 0.5 N. A 0.2s swept-sine signal increasing linearly from a frequency of 34 kHz to 35 kHz was fed to the piezoelectric actuators. The amplitude was kept to 30% of the maximum amplitude to prevent the occurrence of any non-linear phenomena, such as saturation of the actuator and acoustic levitation of the skin. Data were stored only as long as the finger pressure remained stable within a 10% margin.

2) Data analysis: In the first run, the natural impedance of the plate was fitted to a second-order linear model (mass-spring-damper), the parameters of which were determined by taking some of the key features of the frequency response. Since the plate undergoes a flexural deformation, the vibration inertia of the plate was found to be half the weight, $m =$ 8.5 g. Given the value of the inertia, the frequency at which the real part of the frequency response $\mathrm{Re}(F/x) = k - m\omega^2 = 0$ occurred gave the stiffness of the plate $k = m\omega_0^2$, which in this case amounted to $k =$ 401 N/µm. The unloaded damping was determined via the imaginary part of the frequency response $\mathrm{Im}(F/x) = b\omega_0$, or $b = 4.3$ N.s/m.

A similar procedure was applied to the signal when a finger was applied to the screen, which made it possible to assess the combined inertia, stiffness and damping of the fingertip in contact with the plate. Assuming that at these frequencies, the contribution of stiffness to the impedance was small, the mass of the skin was obtained by subtracting the unloaded mass m from the loaded mass and the unloaded damping b_p from the loaded damping. Fig 2 shows typical responses of the loaded and unloaded systems. A detailed description of the computation can be found in [12].

E. Friction modulation measurements

1) Protocol: Participants were asked to explore the plate while a full amplitude 2 Hz modulation of the ultrasonic carrier was applied to the ultrasonic plate, inducing a slow, steady change in the friction coefficient. Interaction forces were measured by the load cells, and the position of the finger was determined by the encoder fixed to the fingernail via a magnetic contact. The task was timed via a metronome beating at a frequency of 0.5 Hz. Participants were instructed to keep their normal force as steady as possible.

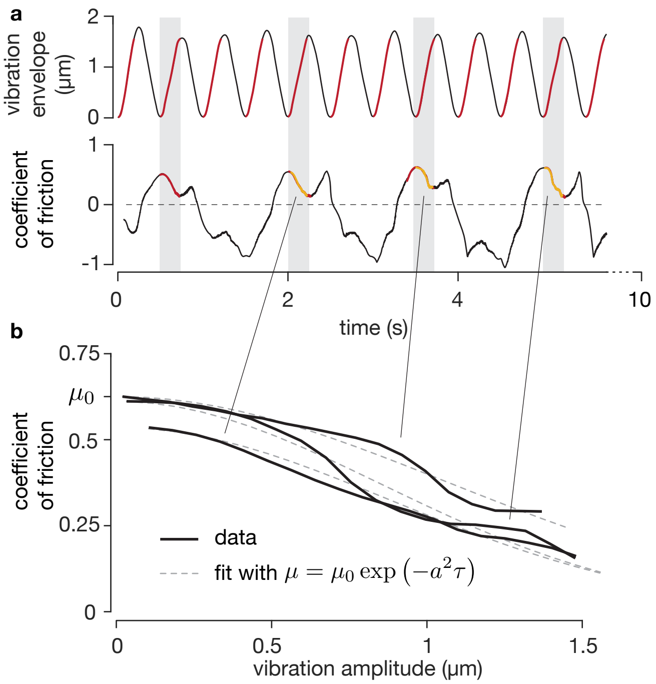

Fig. 3. **a**. Typical data recorded and the selection process. Subsets of time series were selected when the finger was moving from left to right and the envelope of the vibration was decreasing. **b**. Friction modulation plots and the corresponding fitted Gaussian functions.

2) Data analysis: Preliminary data were recorded for 10s and the 3 most successful runs were saved. The first 2s of the recording were removed because of the great variability of the data at the start of the trials. The phases in which the finger was moving from left to right and the vibration envelope was increasing were then selected and analyzed separately. A typical set of data is presented in Fig 3.

In each segment/phase, a Gaussian function $\mu = \mu_0 \exp\left(-a^2\tau\right)$ was fitted to the relationship between the friction coefficient and the vibration amplitude, giving the nominal friction μ_0 —i.e., that which occurred when the vibration was turned off— and the subject susceptibility to ultrasonic friction modulation τ. The latter value, which reflected the amplitude required to obtain a specific decrease in the friction, can be related to the "frictional contrast" described in [6] using a first-order approximation. The choice of a Gaussian function to fit the data was based on the model for ultrasonic levitation phenomena developed in [7]. Only segments in which the fitting procedure showed a good fit $R^2 > 0.9$ were kept for further analysis.

F. Perceptual experiments

Participants were asked to press on the device with their index finger using their dominant hand. They were instructed to press on the surface "as if they were using a tablet or typing on a keyboard" and to avoid to move in the vertical direction. A red led indicated whether the participant was applying too much shear force. If the participant was pressing in the lateral or distal instead of the vertical direction, a red led was turned on, and the participant had to start pressing again. Any auditory cues emitted by the actuator were blocked using headphones emitting a pink noise. Participants were instructed to use the pulp of the fingertip, corresponding to the last phalanx, forming an angle of 30° with the glass plate.

Subjects were asked whether they perceived a click. The method used here consisted of a three-down, one-up staircase procedure [20]. The experimenter sat nearby in order to ensure that the participants posture remained stable during the test and to record their Yes or No verbal answers. The detection threshold was determined after 5 reversals of direction, which usually took about 40 trials. Figure 4 shows a typical example of a trial using the psychophysical procedure.

III. RESULTS

A. Mechanical properties and frictional behavior

Fig. 5 gives scatterplots and the corresponding histograms of the individual data collected during the mechanical and tribological experiments. In the mechanical tests, every measurement led to a decrease in resonance frequency of the plate when the finger was pressed down, which confirmed that, in this frequency range, the mass of the finger contributes more than the stiffness of the tissues to the impedance. The moving mass was found to be 0.11 ± 0.04 g and the damping, to be 22 ± 10 N.s.m^{-1}, in line with previous experiments. No correlations were found to exist between the damping and the mass.

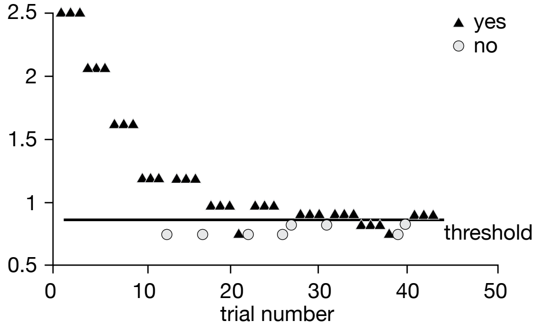

Fig. 4. The staircase method made it possible to quickly determine the participants detection threshold. The initial value of the amplitude was set to a peak-to-peak amplitude of 2.5 µm. The threshold corresponds to an 80 % click detection accuracy.

The friction plot also shows the great variability of the nominal friction coefficient $\mu_0 = 1.2 \pm 0.67$. Considerable intra-personal variability was observed: some participants had standard deviations from the mean of up to 1. The effectiveness of the friction modulation was also highly variable $\tau = 0.39 \pm 0.27$ μm^{-2}, showing an intra-subject variability of up to 1.4 μm^{-2}.

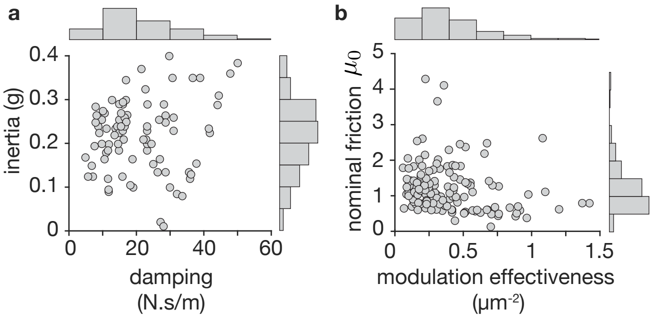

Fig. 5. **a**. Scatterplot of all (n = 14) skin inertia and damping measurements based on changes in the resonance frequency of the plate. **b**. Scatterplot of the nominal initial friction and the effectiveness of the decrease in the fingers interactions with the ultrasonic device at increasing friction amplitudes

B. Perceptual differences

The distribution of the subjects detection thresholds is presented in Fig. 6. The data clearly show a bimodal pattern of distribution, since a subset of participants did not reliably perceive the stimulus. The maximum separation between the two groups was found to occur at 1.6 µm using Fisher's linear discriminant test, which maximizes the interclass variance. A post-hoc unpaired two-sample Wilcoxon rank sum test showed that the detection thresholds of the two groups differed significantly ($p < 0.01$).

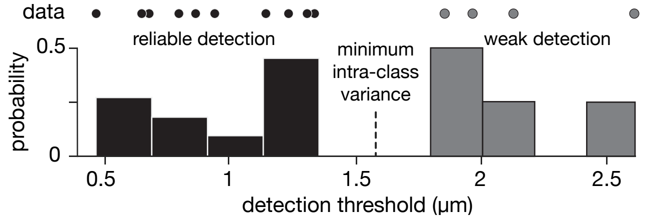

Fig. 6. Raw data and histogram of the participants' detection thresholds in response to a click. The central line gives the value dividing the histogram into two classes with a maximum inter-class variance: these results show that the subjects in the one group clearly perceived the stimuli, whereas the others perceived only weak stimuli or none at all.

C. Influence of mechanical and tribological factors on subjects perception of the click

The click detection threshold and the friction modulation amplitude were found to be negatively correlated (Spearman's coefficient $r = -0.71$, $p = 0.002$). Larger changes in the frictional force facilitated the perception of the click, as shown in Fig. 7a. The difference in perceptual sensitivity between the two groups was also significant (Wilcoxons rank sum test, $p = 0.003$), see Fig. 7b.

Mass and damping were both weakly correlated with the other parameters tested, especially the detection threshold and the friction modulation. To determine the effects of these two parameters, we investigated the effects of the magnitude of the mechanical impedance, defined as $|Z| = \sqrt{b^2 + m^2\omega^2}$.

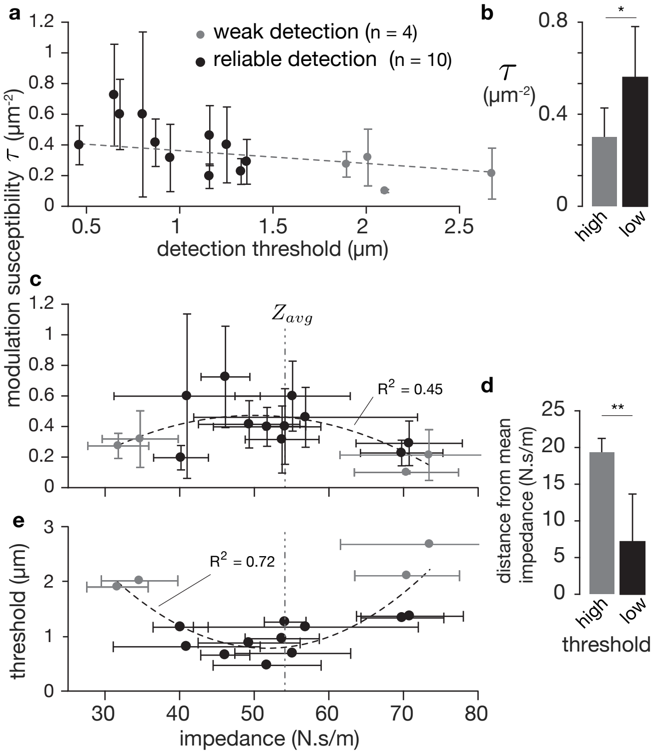

Fig. 7. Correlations. Error bars stand for the standard deviations. **a**. The detection threshold was negatively correlated with the effectiveness of the modulation. **b**. The friction modulation amplitude differed significantly between the two perceptual groups. **c**. Modulation of the friction showed a U-shaped relationship with the impedance. **d**. The two groups differed significantly in terms of the distance from the average impedance, $|Z|_{avg}$: the values obtained by the group which clearly perceived the click were closely concentrated around the average impedance. **e**. Impedance significantly affects the perceptual detection threshold.

The impedance and the subjects sensitivity to ultrasonic friction modulation were not straightforwardly correlated. It can be seen from the graph in Fig 7c that this relationship followed an inverted U-shaped curve, giving a maximum sensitivity at the average impedance $|Z|_{avg} = 33$ N.s.m^{-1}. Quadratic regression fitted the data loosely with a coefficient of determination $R^2 = 0.34$, and the L^1 distance to $|Z|_{avg}$ showed a negative correlation with detection threshold (Spearman's coefficient $r = -0.51,\ p < 0.05$). Surprisingly, contrary to the results obtained in [12], no direct correlations were found to exist between the any variable and the damping ratio. The impedance of participants who perceived the stimulation only weakly was far from the average value. Wilcoxon rank sum tests on the distance from the average impedance ruled out the null hypothesis that the two groups have the same average value ($p < 0.01$), see Fig 7d.

The U-shaped correlation was even more pronounced in the case of the relationship between the skin impedance and the perceptual detection threshold. A quadratic fit corresponding to a good fit of $R^2 = 0.60$ was obtained. The distance from $|Z|_{avg}$ was positively correlated with the subjects perceptual threshold (Spearman's coefficient $r = 0.72,\ p = 0.003$): subjects whose impedances were around $|Z|_{avg}$ perceived smaller changes in the frictional properties.

D. Influence of skin moisture and age

Other noteworthy correlations were also observed upon analyzing the data. In particular, moisture was found to have a significant effect on the skin damping (Spearman's coefficient $r = 0.58,\ p < 0.05$) and a weakly significant effect on the subjects sensitivity to friction modulation (Spearman's coefficient $r = 0.58,\ p < 0.05$). More importantly, skin moisture was found to be significantly correlated with the subjects perceptual performances: participants with moist fingers obtained better scores than those with dry fingers (Spearman's coefficient $r = 0.55,\ p < 0.05$).

Friction behavior is affected by fingertip characteristics; in particular, the nominal friction μ_0 is weakly negatively correlated with the area of contact (Spearman's coefficient $r = -0.50,\ p < 0.1$) and age (Spearman's coefficient $r = -0.45,\ p < 0.1$).

TABLE I
CORRELATIONS OF RELEVANT VARIABLES

	1	2	3	4	5	6	7
1. b	1						
2. m	0.05	1					
3. $\lvert Z\rvert$	0.07	0.05	1				
4. μ_0	0.1	0.17	0.07	1			
5. τ	-0.05	-0.4	-0.67**	-0.39	1		
6. moist.	0.58*	-0.11	0.33	0.39	-0.46†	1	
7. age	0.21	-0.08	0.12	-0.46†	0.29	-0.32	1
8. thresh.	0.47†	0.29	0.54*	0.52*	-0.75**	0.56*	-0.3

*Note †p<0.1, *p<0.05, **p<0.01

IV. DISCUSSION

The absence of any straightforward correlations between the mechanical parameters studied here seems to indicate that each participant had a unique set of mechanical properties. The frictional data showed even larger variations, even during the same trial run. Moisture build-up and the subsequent softening of the *stratum corneum* may be responsible for the fast changes observed in the mechanical parameters and in both the nominal friction on glass and the susceptibility to ultrasonic vibration.

Perceiving the ultrasonic switch can be a challenging task at times. Although some subjects could perceive differences in the ultrasonic amplitude as small as 0.5μm, the psychophysical experiments clearly showed the existence of a difference between two groups of participants. Some participants could unambiguously perceive the stimulus, whereas others required amplitude variations which were twice as large on average to be able to detect the stimulus. In line with previous findings, [6], [18], the net average susceptibility to friction modulation differed significantly between the two groups studied here. This difference confirms that users with a measurably lower susceptibility to ultrasonic friction modulation tended to perform the perceptual task less successfully.

The main contribution of this study is that it establishes that this variability in susceptibility to ultrasonic friction reduction, on which the perception of switch stimuli depends, involves an impedance that is far removed from the average impedance value. Because of the intrinsic limitations of the methods of measurement available, it is worth remembering that the skin impedance was modeled here in the form of a parallel combination of a damper and a mass. The elastic behavior of the skin in this frequency range has never been established so far. In addition, participants who did not clearly perceive the stimulus had either a larger or a smaller impedance than the average impedance of the group of participants who perceived the click correctly. In the case of the larger impedance, it is possible that, since the finger has less mobility at a given frictional change, less deformation of the skin occurs, resulting in an impaired perceptual experience. Conversely, the fingertips of participants with a low mechanical skin impedance might behave more elastically, resulting in the behavior described in [12]. Elastic skin would tend to move in phase with the ultrasonic plate, preventing the formation of a gap, which would result in impaired acoustic levitation [7].

Individual differences also existed between the perceptual performances of participants having similar impedances. It is worth mentioning that a subject with one of the lowest perception thresholds also happened to be a flute player, and was therefore accustomed to relying regularly on the perception of subtle skin deformations.

V. CONCLUSION

This study focused on the effects of mechanical and tribological parameters on the detection of an ultrasonic switch. About one quarter of the participants tested here did not clearly perceive the click stimulus. The results show that the users impedance was a significant factor, which supports the hypothesis that mechanical parameters contribute importantly to the squeeze film levitation process. Online impedance measurements could help tune the stimulation to provide users with a consistent stimulus.

Alternatively, the latter finding begs the question as to whether the impedance of the plate may also affect the squeeze film levitation process. In fact, thicker plates, which have a higher acoustic impedance, tend to deliver stronger signals. Studies involving the imaging of the skin stretching which occurs during ultrasonic stimulation are now under way The results should shed useful light on the exact role played by the skin impedance in the modulation of friction.

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