Perception of ultrasonic switches involves large discontinuity of the mechanical impedance

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Abstract—The distinct tactile feedback provided by mechanical keyboards notifies users that their actions have been successfully recorded. The presence of these subtle yet informative tactile cues is one of the reasons why mechanical keyboards are still preferred to their virtual counterparts. An artificial sensation of pressing a mechanical switch can be produced by varying the coefficient of friction as the user is pressing down on a glass surface using ultrasonic vibration. We examined the factors involved in producing a vivid sensation of a stimulus by measuring the mechanical impedance, the frictional behavior of the fingertip and the perceptual thresholds. Subjects who experienced weaker sensations also showed a weaker sensitivity to friction modulation, which may in turn be attributable to the presence of a larger or a smaller than average impedance. In the second experiment, the user's finger impedance was measured during the click, and it was observed that the successful detection of the stimulus was correlated with the presence of considerable discontinuity in the mechanical impedance added to the plate by the finger. This discontinuity in the evolution of the impedance supports the idea that the skin is being reconfigured towards a new equilibrium state after the change in friction.

Index Terms—H.5.2 User Interfaces, H.5.2.g Haptic I/O, L.1.0.b Biomechanics, L.2.0.c Tactile display, L.1.0.g Perception and psychophysics

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1 INTRODUCTION

TOUCHING a plate vibrating at an ultrasonic frequency produces a sensation of smoothness owing to the decrease in the frictional resistance of a finger to sliding motion [1]. Harnessing this phenomenon by modulating the friction between the finger and the glass plate in real time makes it possible to create artificial tactile stimuli on otherwise featureless touchscreen displays. The friction forces can be updated as a function of the position of the users finger to create the illusion of out-of-plane shapes [2], [3] or textures [4]. It has been recently established that even in the absence of lateral motion, modulating the frictional properties as a function of the normal force can induce the feeling of pressing a mechanical button [5], [6], [7], [8].

One likely explanation for this illusion is that when pressing a finger onto a high-friction surface, the skin in contact with the surface is unable to move laterally and cannot relax back to an equilibrium state. Potential elastic energy is therefore stored in a radially-distributed lateral stretching of the skin [9]. When the ultrasonic levitation is triggered, the skin is subjected to a new force balance and suddenly relaxes into a new equilibrium position. The motion of the skin is perceived by nearby mechanoreceptors and the message they deliver is interpreted as resulting from a mechanical detent, see Fig. 1.

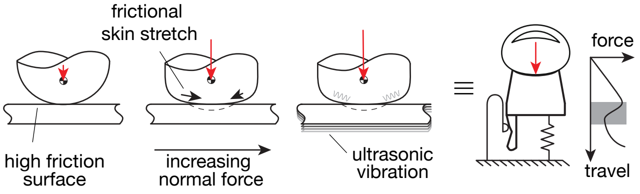

Fig. 1. Inferred mechanical behavior that leads to the perception of a detent. During compression of the pulp of the fingertip, friction holds the skin in contact with the glass. Residual lateral skin stretch can be suddenly released by reducing friction which creates a transient stimulation resembling the effect of striking a key.

The keys with which mechanical keyboards are equipped are usually fitted with a component which creates a region of negative stiffness, via either the buckling of a spring or a cam. This negative stiffness component momentarily reduces the reaction force applied to the pulp of the finger, generating a distinct feeling of keyclicking [10], [11]. The similarity in the fast change of force might be what causes the illusion. One of the advantages of mechanical keyboards over virtual keyboards is that a tactile feedback is received by the user upon pressing the keys, which signals that the action has been successfully performed. When there is no such feedback, we rely on visual cues to position our fingers. The visual attention required distracts the user up to the point that we can even forget the content of the message we are about to write. In addition, because of the increase in the visual load necessary to ensure that the appropriate key is hit, the user's typing performances become less efficient, more uncomfortable and slower [12], [13]. Emulating mechanical keyclicks on flat glass screens such as programmable touch-screen interfaces would increase the usability by providing tactile feedback validating particular actions.

Previous experiments have shown that the perception of ultrasonic keyclicks is user dependent [6]. Although most

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of the subjects reported that a clear-cut perception of the stimuli occurred at vibration amplitudes of less than 0.5 μm, and a few of them needed three times larger amplitudes to be able to perceive these sensations. The aim of this study is to investigate in depth the biomechanical, tribological and perceptual factors possibly responsible for the perception of weaker sensations. In the first part of the study we combined a biomechanical characterization of the pulp of the fingertip with tribological measurements and a psychophysical assessment of the minimum amplitude of the ultrasonic vibration required to generate conspicuous click sensations. In the second part of this paper, we present a method for measuring the evolution of the mechanical impedance while users were pressing on the glass surface. The online impedance measurements were then compared with the participants' perception of a transient signal.

2 BACKGROUND

2.1 Physics of ultrasonic friction modulation

The exact mechanism underlying ultrasonic friction reduction is still a matter of debate. Watanabe and Fukui [1] have suggested 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 [14].

An alternative hypothesis is that friction reduction may result from an intermittent contact with the skin rather than involving a squeeze-film levitation process. Evidence of intermittent contact was obtained using Laser Doppler vibrometry, which showed the occurrence of fast transients in the vertical velocity of the skin. These transients are 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 [15], [16].

Frustrated total internal reflection imaging of the contact between the vibrating plate and the fingertip provides a useful means of investigating both the dynamics of the contact and the time-averaged evolution of the interfacial gap [17]. This method unequivocally showed the occurence of levitation of the skin over the vibrating plate, which confirmed the involvement of squeeze-film levitation processes in the reduction of friction. In addition to the time-averaged levitation of the skin, micro-second imaging methods showed that the skin undergoes oscillations, which suggests that the skin is bouncing not on the plate, but on a film of air.

2.2 Causes of variability in friction modulation

Prescribing a precise friction force using ultrasonic friction modulation is not easily done. At a given vibration amplitude, the value of the friction force can deviate by as much as 40% from the average [18], [17]. The interaction between the ultrasonic wave and the skin is a complex process, which involves acoustical, biomechanical and tribological factors, all of which influence the outcome of the force modulation and hence, the perception of the stimulus.

The biomechanical responses of the finger tissues are a crucial factor contributing to the perception of ultrasonic levitation. In particular, the damping greatly affects the subjects susceptibility to ultrasonic friction modulation. Artificial fingers with elastic properties and very little dissipation were found to be insensitive to ultrasonic vibration and did not respond to friction reduction [19]. On the other hand, fingers with large damping with respect to their inertia showed a significant decrease in friction at the same vibration amplitude. Damping introduces a time lag between the excitation and the motion of the skin, which creates out-of-phase oscillations of the two contacting bodies. When the dynamics are dominated by elastic forces, the skin and the plate remain constantly in contact, which limits the acoustic levitation and the modulation of friction [20].

The physico-chemical properties of the skin also play a decisive role in the variability and the strength of the effects produced. Even 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 [21], [22]. Friction also depends on the size of the finger, the oil content of the skin and the exploration velocity [23].

2.3 Mechanical impedance of the fingerpad

The dynamics of the skin and those of the fingerpad can be gauged via the notion of mechanical impedance $\mathbf{Z}$, which represents the amount of force $\mathbf{F} = F_0\, e^{i\omega t}$ required to prescribe a harmonic velocity $\mathbf{u} = u_0\, e^{i(\omega t - \phi)}$ at a given angular frequency ω so that:

$$\mathbf{Z} = \frac{\mathbf{F}}{\mathbf{u}} = \frac{F_0}{u_0} e^{i\phi} \qquad (1)$$

where ϕ is the phase lag of the motion and $i = \sqrt{-1}$. The impedance is a complex number, which encapsulates the amplitude ratio and the phase difference between the force and the velocity. The impedance reflects the dynamic properties of a system and in most cases, it can be described by a linear combination of three elements: a spring $\mathbf{Z} \propto 1/i\omega$, a damper $\mathbf{Z} = \mathrm{cst}$ and a mass $\mathbf{Z} \propto i\omega$. The spring and the mass are responsible for the imaginary part of the impedance, which consists of the energy stored by the system and reflected back to the actuator. The damper contributes to the real part of the impedance, which consists of the energy dissipated by the system. Below a frequency of 1 kHz, the impedance of the skin can be accurately described by a spring and a damper working in parallel [24], [25]. Above 1 kHz, the impedance can be approximately described as a combination of inertia and damping [26]. The dissipation included in the real part of the impedance can be attributed to heat generation as well as wave propagation in the tissues [27], [28].

The impedance is usually measured using an impedance head, which is typically composed of a force sensor and an accelerometer. But because of their size and their mass, impedance heads are not accurate enough for measuring frequencies in the ultrasonic range. Alternatively, the impedance can be determined by studying the impact on the vibration of a resonating actuator when adding a test sample, either by measuring the change of amplitude and phase that the test sample imposes on the actuator or by tracking the shift of the resonant frequency required in order to remain at resonance. These methods, which are widely used in the field of nanotechnology [29], [30], have also proved to be useful for determining the impedance of the skin in the vibrotactile and ultrasonic frequency range [25], [20].

2.4 Perception of ultrasonic friction modulation

A difference of 20% in the friction force can be perceived by users, which is of the same order of magnitude as the difference between the viscosity or weight perception thresholds [31]. Virtual textures can be created by patterning the friction force as a function of the position of the finger. The difference in magnitude between these virtual textures can be perceived with a 25% Weber fraction, which is of the same order as physical texture [32]. Humans perception is generally acutely sensitive to transients, and the perception of fast changes in the friction force while the users finger is sliding are perceived with an average Weber fraction of 11% [33]. The creation of patterns and targets helps to guide the users motion, and has been found to significantly improve human-computer interactions [34]

Although the precision of humans' perception of frictional patterns is on a par with that of the perception of physical surfaces, frictional stimuli are not perceived equally clearly by all individuals. In particular, participants who experienced small variations of the frictional force had greater difficulty in perceiving the frictional stimuli than those subjected to large variations [35]. This finding confirms that the sensitivity to friction modulation, i.e., the amplitude of the ultrasonic wave required to reach a certain relative decrease in the friction, is a good predictor of individuals subjective assessment of a frictional pattern.

3 INFLUENCE OF FINGER BIOMECHANICS ON THE PERCEPTION OF ULTRASONIC SWITCHES

In the first experiment, the three main factors involved in the perception of keyclicks via a fast change in the frictional conditions were investigated. First, the dynamic parameters of the skin were measured by assessing the impact of the subjects finger on the ultrasonic plate. Each participants perception of friction was then measured. In particular, the susceptibility of the dynamic coefficient of friction to ultrasonic friction modulation was recorded. Lastly, the physical measurements were compared with each subjects detection threshold of the ultrasonic clicks, using an adaptive psychophysical procedure.

3.1 Material and Methods

3.1.1 *Description of the setup*

The friction reduction device used in the present experiments, which was similar to that previously used in [6], 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 deformation of the plate 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. 2. The load cells were calibrated to eliminate cross-talk. The position of the finger was recorded using an incremental encoder (BTIV 24S 16.24K, Baumer AG, Frauenfeld, Switzerland) equipped with a capstan fixed to the subject's 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 per oscillation cycle.

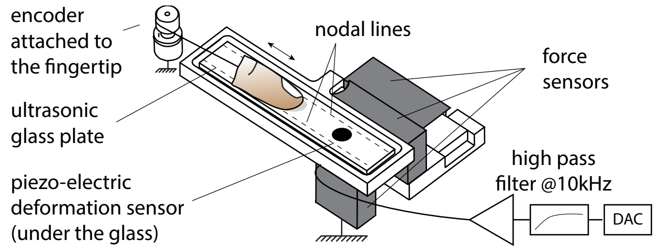

Fig. 2. In these experiments, participants were first allowed to freely explore the surface of the glass plate. The interaction forces and the position of the finger were recorded by three orthogonal force sensors and an incremental encoder connected magnetically to the subjects index fingernail.

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

3.1.2 *Participants and protocol*

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.

Three separate experiments were performed to record the participants mechanical, tribological and perceptual responses. The first experiment was designed to measure the impedance of the participants right index fingertip placed on the plate. The aim of the second experiment was to assess the range of forces produced by the changes in the friction which occurred 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 psychophysical methods. Skin moisture and the size of the contact area were also monitored but no noteworthy correlations between were found to exist. The entire session lasted for approximately 30min. Participants were sitting comfortably in a chair, and the entire setup was hidden from their view apart from the glass plate.

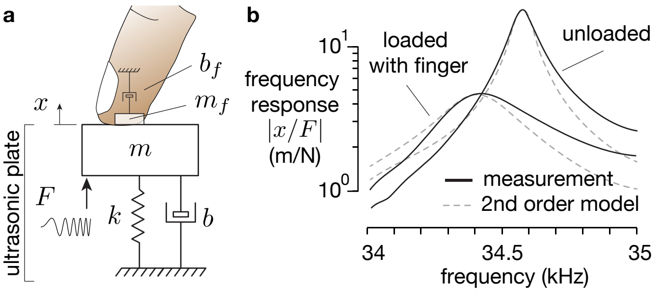

Fig. 3. **a**. Diagram of the impedance measurement device. The resonant system and the finger are approximated as second-order systems. **b** Representative responses of the plate around its resonance frequency, with and without the fingertip from which the mass and the damping are computed.

3.1.3 Finger impedance measurements

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 analyzing how the finger affects the resonance amplitude and frequency [25], [20].

Participants pressed on the glass plate with a constant normal force of 0.5 N. A 0.2 s swept-sine signal increasing linearly from a frequency of 34 kHz to 35 kHz was fed to the piezoelectric actuators. The amplitude was kept are 30% of the maximum value 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.

During a calibration trial, the natural impedance of the plate was fitted to a second-order linear model (mass-spring-damper), see Fig. 3a, the parameters of which were determined by taking some of the key features of the frequency response. Since the plate underwent a flexural deformation, the vibration inertia of the plate corresponds to half the weight, $m = 8.5$ g [36]. Given the value of the inertia, the angular frequency ω_0 at which the real part of the frequency response $\mathrm{Re}(F/x) = k - m\omega_0^2 = 0$ occurred gave the stiffness of the plate $k = m\,\omega_0^2$, which amounted to $k = 401$ N/µm. The unloaded damping was determined via the imaginary part of the frequency response $\mathrm{Im}(F/x) = b\,\omega_0$, where $b = 4.3$ N.s/m. Once the mechanical impedance had been determined, the force factor of the piezoelectric actuator $\gamma = b\omega_0|x|/V$, where V is the voltage applied to the actuator, could be obtained from the unloaded amplitude at the resonant frequency.

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 the contribution of the stiffness to the impedance to be small at these frequencies, the mass of the skin was obtained by subtracting the unloaded mass m from the loaded mass and the unloaded damping b from the loaded damping. Fig. 3b shows typical responses of the loaded and unloaded systems. A detailed description of the calculations can be found in [20].

3.1.4 Friction modulation measurements

The frictional behavior of the skin subjected to ultrasonic vibration was assessed by tracking the evolution of the dynamic friction coefficient during steady-state sliding of the finger when the amplitude of the vibration was being slowly modulated. This measurement was based on the assumption that the static and dynamic friction processes show similar behavior in the presence of ultrasonic vibration. This assumption is compatible with the adhesive theory of friction and was partly proved to be true in [17]. In comparison with static friction methods of measurement, using steady-sliding methods to measure the friction coefficient yields a large, precise dataset in a short amount of time, which limits the presence of biases due to the participants skin biomechanics and hygrometry.

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 via the load cells, and the position of the finger was determined by the encoder fixed to the index fingernail via a pair of magnets. The task was timed using a metronome beating at a frequency of 0.5 Hz. Participants were instructed to keep their normal force steady.

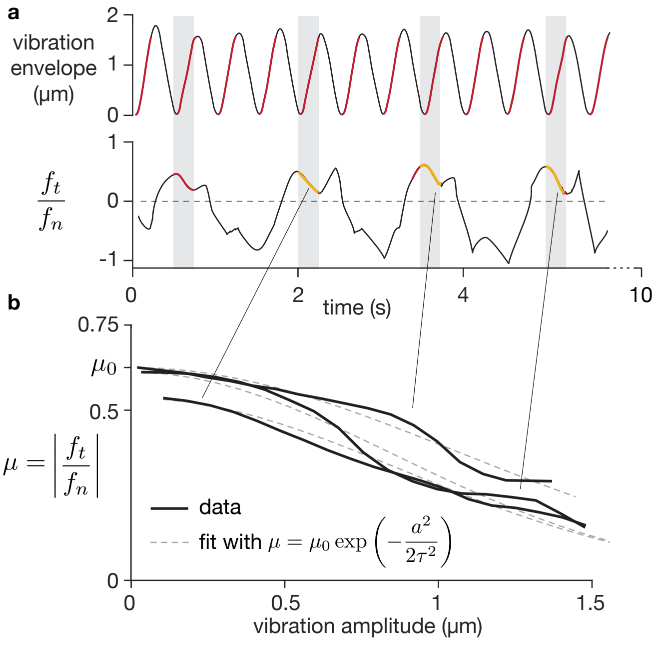

Fig. 4. **a**. Typical data recorded. Subsets of time series were selected when the finger was moving from left to right and the envelope of the vibration was increasing. **b**. Friction modulation plots and the corresponding fitted Gaussian functions.

Preliminary data were recorded for 10 s and the 3 most successful runs were saved. The first 2s of the recording were removed because of the large 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 processed separately. A typical time series is presented in Fig. 4a and the corresponding relationship between the amplitude and the friction coefficient is shown in Fig. 4b.

In each segment, a Gaussian function $\mu = \mu_0 \exp\left(-a^2/2\tau^2\right)$ was fitted to the relationship between the friction coefficient and the vibration amplitude, based on the model for ultrasonic levitation processes developed in [17]. The fitting procedure provided values for the nominal friction μ_0 —i.e., which occurred when the vibration was turned off— and for the subjects susceptibility to ultrasonic friction modulation τ. The latter value, which reflected the amplitude required to obtain a 64% decrease in the friction, can be related to the so-called frictional contrast described in [23] using a first-order approximation. Only segments in which the fitting procedure resulted in a satisfactory fit $R^2 > 0.9$ were kept.

3.1.5 Detection threshold of the ultrasonic switch

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 moving horizontally. A red light indicated whether the participant was applying a shear force greater than 0.2 N. If the participant was pressing in the lateral or distal instead of the vertical direction, the red light was turned on, and the participant had to start pressing again. Any auditory cues emitted by the actuator were blocked using noise isolating headphones playing pink noise. Participants were instructed to use the pulp of the fingertip and to press down, keeping an angle of 30° between the distal phalanx and the glass plate.

Subjects were asked whether they perceived a click. The method used here consisted of a three-down, one-up staircase procedure [37]. The experimenter sat nearby to make sure that the participants posture remained stable during the test and to record their verbal yes/no answers to the question "did you perceive a mechanical detent?". The staircase method is based on the hypothesis that the detection rates follow a psychometric curve, which was confirmed during previous experiments using of a constant stimuli method [6]. The detection threshold was determined after 5 reversals of direction, which usually took about 40 trials. Figure 5 shows a typical example of a trial of the psychophysical procedure.

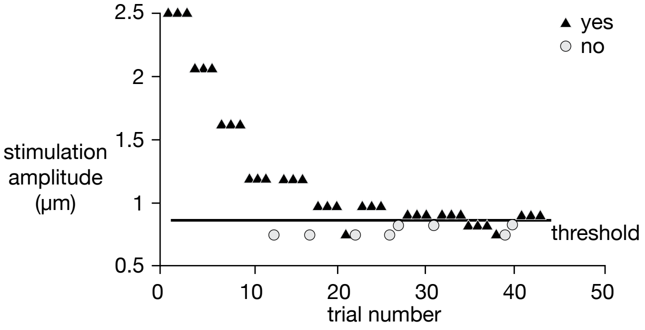

Fig. 5. Using the staircase method, the participants detection thresholds were quickly determined. The initial value of the amplitude was set to a peak-to-peak amplitude of $2.5\ \mu\text{m}$.

3.2 Results

3.2.1 Mechanical properties and frictional behavior

Scatterplots and the corresponding histograms of the individual data collected during the mechanical and tribological experiments are shown in Fig. 6a and b respectively. In the mechanical tests, every measurement revealed a decrease of the resonance frequency of the plate when the finger was pressed down, which confirmed that the inertia of the finger contributes more than the stiffness of the tissues to the impedance in this frequency range. The moving mass m_f and the damping b_f were found to be 0.11 ± 0.04 g and $22 \pm 10\ \text{N.s.m}^{-1}$ respectively, in line with previous experiments [25]. No correlations were found to exist between damping and mass.

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 susceptibility to ultrasonic friction modulation was also highly variable $\tau = 1.32 \pm 0.45\ \mu\text{m}$, since an intra-subject variability of up to $1.4\ \mu\text{m}$ was observed.

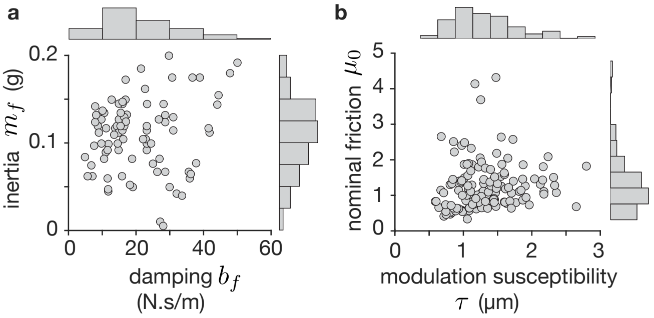

Fig. 6. **a**. Scatterplot of all ($\text{n} = 14$) the skin inertia and damping measurements based on changes in the resonance frequency of the plate. **b**. Scatterplot of the nominal initial friction and the effectiveness of the decrease in the fingers interactions with the ultrasonic device at increasing friction amplitudes

3.2.2 Perceptual differences

The distribution of the detection thresholds was bimodal, since a subset of participants ($\text{n} = 4$) needed larger amplitudes to be able to perceive the stimulus. The maximum difference between the two groups was found to occur at $1.6\ \mu\text{m}$ using Fisher's linear discriminant test, which maximizes the interclass variance. A post-hoc unpaired two-sample Wilcoxon rank sum test showed that the median detection thresholds of the two groups differed significantly ($\text{p} < 0.01$). These results are in line with the detection threshold of $1.605\ \mu\text{m}$ detected with constant stimuli methods in [6]

3.2.3 Influence of mechanical and tribological factors on subjects perception of the clicks

The click detection threshold and the friction modulation susceptibility were found to be positively correlated (Spearman's coefficient $\text{r} = 0.8,\ \text{p} = 5 \times 10^{-4}$). 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 (Wilcoxon's rank sum test, $\mathrm{p} = 0.003$), 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 $|\mathbf{Z}| = \sqrt{b_f^2 + m_f^2\,\omega_0^2}$.

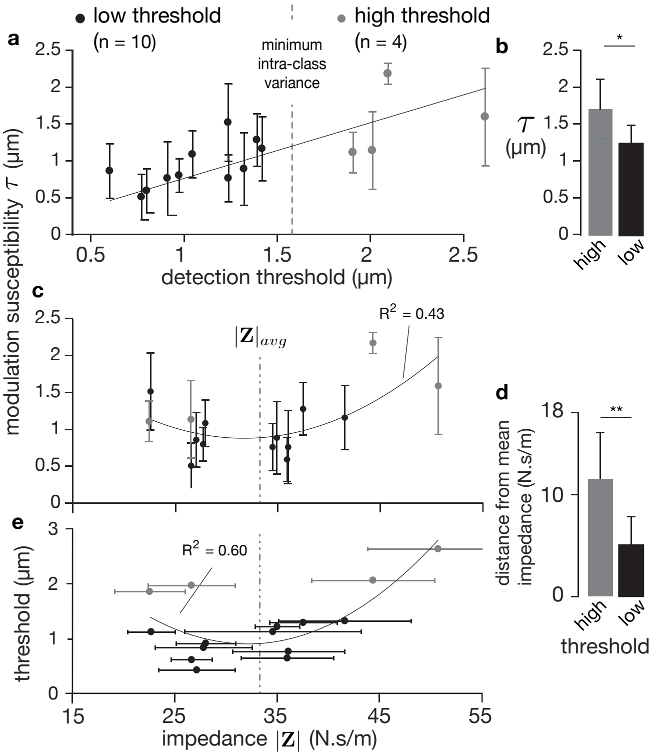

Fig. 7. **a**. The detection threshold was negatively correlated with the effectiveness of the modulation. The central line divides the data into two groups by minimizing the intra-class variance. **b**. The friction modulation amplitude differed significantly between the two perceptual groups. **c**. 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, $|\mathbf{Z}|_{avg}$. **e**. The detection thresholds were therefore affected by the fingertip impedance.

The impedance and the subjects susceptibility 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, with a minimum of the amplitude required to reduce the friction at the average impedance value $|\mathbf{Z}|_{avg} = 33\ \mathrm{N.s.m^{-1}}$. Quadratic regression fitted the data loosely with a coefficient of determination $R^2 = 0.43$, and the L^1 distance to $|\mathbf{Z}|_{avg}$ showed a positive correlation with the detection threshold (Spearman's coefficient $\mathrm{r} = -0.67,\ \mathrm{p} < 0.007$). Surprisingly, contrary to the results obtained in [20], no direct correlations were found to exist between any of the variables studied and the damping ratio. The impedance of participants who perceived the stimulation with a high detection threshold was far removed from the average value. Wilcoxon rank sum tests on the difference between these value and the average impedance ruled out the null hypothesis that the two groups might have the same mean value ($\mathrm{p} < 0.01$), 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 difference between individual impedance values and the $|\mathbf{Z}|_{avg}$ was positively correlated with the subjects perceptual thresholds (Spearman's coefficient $\mathrm{r} = 0.67,\ \mathrm{p} = 0.007$): subjects whose impedances were around $|\mathbf{Z}|_{avg}$ perceived smaller changes in the frictional properties, see Fig. 7e.

3.3 Intermediary conclusion

This first set of experiments show that the mechanical parameters, especially the impedance of the skin, seem to play a crucial role in the development of squeeze-film levitation processes and the subsequent reduction of friction. Participants who perceived the stimulus reliably also happened to have an average skin impedance of approximately 33 N.s/m when pressing down on the vibrating plate with a force of 0.5 N.

4 EVOLUTION OF THE INSTANTANEOUS IMPEDANCE DURING FINGERTIP COMPRESSION

In this section, it was proposed to evolution of the impedance while users were pressing down on the ultrasonic switch, which was measured by inspecting the instantaneous phase lag and the instantaneous amplitude of deformation of the ultrasonic plate, on similar lines to the first experiment. The only difference was that the amplitude was not kept at a low level, and the impedance therefore reflected not only the dynamic behavior of the skin but also the effects of the contact conditions such as the presence of a squeeze-film levitation process. In this respect, the impedance is a metric which reflects the transfer of acoustic energy between the plate and the skin. The real and imaginary parts of the complex impedance can be used as proxies for the dissipation and the reflection of the acoustic energy by the finger, respectively. Successful perception of the click coincided with the occurrence of a large drop in the mechanical impedance when the ultrasonic vibrations were triggered. The force threshold value, which was previously set at 0.5 N, was varied in this experiment in order to influence the value of the impedance before the ultrasonic vibrations were triggered.

The first experiment showed that the participants sensitivity to friction-modulation was correlated with their skin impedance, which in turn was linked to the participants detection threshold. Here we adopted the working hypothesis that the impedance measured by the system depends on the quality of the contact, as larger areas of skin in intimate contact with the plate will favor propagation of the acoustic energy into the tissues. The instantaneous impedance is therefore a relevant mesure for gauging the ability of the skin to receive acoustic energy.

4.1 Material and Methods

4.1.1 Description of the procedure

Seven right-handed volunteers (2 females and 5 males) ranging from 23 to 37 years of age participated in the study after giving their informed consent. They had not taken part in any previous experiments and were naive as to the purpose of the experiments. Each participant experienced 6 normal triggering forces of 0.1, 0.4, 0.5, 0.8, 1.2 and 1.8 N as well as 2 kinds of actuation profile consisting of increasing and decreasing friction. They were instructed to press with a "light", "medium" or "strong" force and since they were given visual feedback about the force applied, they could correct it if necessary. They were given a 30-second learning period, during which 3 typical click-triggering forces were presented. Under all 12 randomly mixed conditions, the minimum amplitude of the vibration change that led to a conscious perception of the click was determined using a Modified Binary Search [38], [39]. The method finds the threshold by testing the detection of the value which is the average a lower and an upper bounds. Depending if the average stimulus is detected or not, the upper or the lower bound is updated and the procedure repeats. After 4 reversals, the procedure was stopped. Although the procedure is less accurate than a constant stimuli or staircase method, it converges rapidly to the perceptual threshold. It has been proved to be effective when exploring a large set of conditions [40]. In the present experiment, the duration was reduced from 2 h in the case of a staircase method to 35 min per participant, and thus reduced the subjects' fatigue.

4.1.2 Description of the Setup

The ultrasonic plate was replaced by a more powerful version measuring $51 \times 67 \times 5\ \text{mm}^3$ and vibrating at a resonant frequency of 28.85 kHz. A dynamic identification procedure showed that the plate had a moving mass of 19 g, a stiffness of 625 N/μm, an unloaded damping rate of 9.5 N.s/m and a force factor of $\gamma = 0.1$ N/V. The value of the force factor was determined by scaling the impedance of the unloaded plate measured with the mass-spring-damper model, on similar lines to what was done in section 3.1.3. The signal was produced by a signal generator (Tektronix, AFB3022B, Beaverton, OR, USA), which was combined with the command signal using an analog multiplier. Lastly, the amplitude-modulated signal was amplified within a range of ±200 V using a linear amplifier (A.A. Labs Systems, A-303, Hayetzira, Israel).

4.1.3 Measuring the impedance using the Hilbert transform

In the first experiment, the impedance of the fingertip was recorded using a swept-sine signal requiring a separate procedure. The impedance was therefore known only in the form of an overall parameter, and its evolution during each trial was not specified. To overcome this limitation, the instantaneous impedance was measured from the phase and amplitude shifts in the deformation of the plate measured by the piezoelectric sensor in the form $x(t) = x_0 \sin(\omega t - \phi)$ while the actuator received a harmonic voltage signal $v(t) = v_0 \sin(\omega t)$ with a frequency of $\omega/2\pi$. The changes in the instantaneous complex-valued impedance were tracked using an offline IQ demodulation scheme of the vibration and force time series, as illustrated in Fig. 8a. The demodulation transformed the real valued time series of the displacement and the voltage applied into a complex valued time series, which also gave the quadrature component of the signal at any point in time. A typical time series is shown in Fig. 8b, from which it can be seen that the force and the input signals both influenced the amplitude of the vibration.

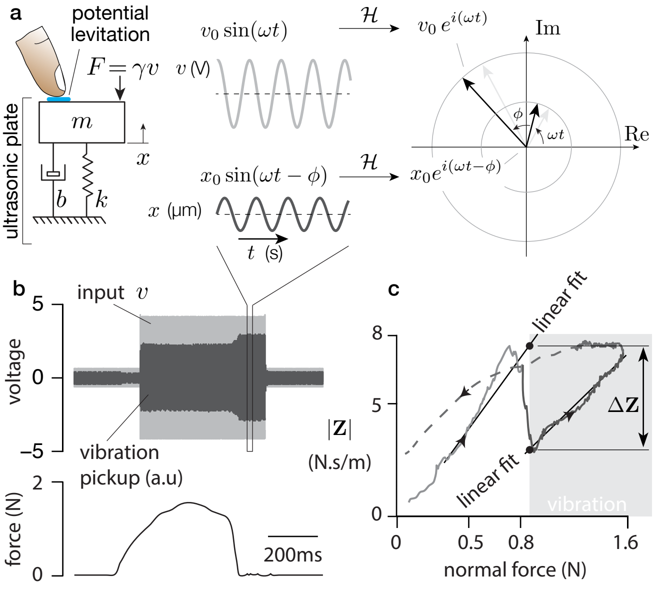

Fig. 8. **a**. Illustration of the process used to measure the impedance during the participant's action. The Hilbert transform of the sinusoidal signal delivered to the amplifier and that measured by the deformation sensors yielded a pair of complex valued time-series, the ratio between which was the impedance **Z**. **b**. Typical time-series of the force, input and deformation signals as a participant was pressing on the device. **c**. Evolution of the impedance calculated from the ratio between the input voltage and the deformation signal. The sudden change in the impedance $\Delta\mathbf{Z}$ was expressed by the difference between the linear fits before and after the vibrations were triggered.

The imaginary component of each signal was reconstructed from the signal recorded using the Hilbert transform to recover the complex valued impedance as follows:

$$\mathbf{v}(t) = \quad v(t) + i\,\mathcal{H}(v(t)) \quad = v_0\, e^{i\omega t} \tag{2}$$

$$\mathbf{x}(t) = \quad x(t) + i\,\mathcal{H}(x(t)) \quad = x_0\, e^{i(\omega t - \phi)} \tag{3}$$

and the total impedance of the plate loaded with the finger was determined using

$$\mathbf{Z}(t) = \frac{\gamma\, \mathbf{v}(t)}{\dot{\mathbf{x}}(t)} \tag{4}$$

In practice, the Hilbert transform, which was run offline, was obtained by multiplying the Fourier transformed time series $u(t)$ by the imaginary number i and then applying the inverse Fourier transform, or:

$$\mathcal{H}(u) = \mathcal{F}^{-1}\left(-i\ \text{sng}(\omega) \cdot \mathcal{F}(u)\right) \tag{5}$$

where $\mathcal{F}$ is the Fourier transform operator.

The Hilbert transform leaves the amplitude of the spectral components unchanged but shifts the phase by $\pi/2$. The unloaded impedance of the plate was extracted before and after applying the normal force based on the continuous measurement of the vibration amplitude and the signal input. We took special care to ensure that the piezo-electric actuators glued to the plate remained at a constant temperature throughout the trial. The temperature was stabilized by applying ultrasonic vibration for 5 min prior to each experiment. Saturation of the actuator was also a concern, since it creates static non-linearity of the ratio between the voltage and the displacement, which in turn might bias the impedance measurements towards lower values. To avoid any bias in the measurements, the system was kept in the linear regime with the entire panel of waveforms used.

Once the impedance of the plate $\mathbf{Z_p}$ had been determined, the instantaneous impedance of the finger was calculated as follows:

$$\mathbf{Z_f}(t) = \mathbf{Z}(t) - \mathbf{Z_p} \tag{6}$$

The complex valued impedance showed a distinctive pattern of evolution, whereas the rest of the study focused on the norm of the impedance, especially during the activation of the ultrasonic vibration. A typical plot of the evolution of the impedance during one press on the screen is shown in Fig. 8c. In some trials, the impedance dropped significantly immediately after the vibration had been triggered. After the drop, the impedance resumed its monotonic increase with an increasing normal force, showing a similar slope to that observed previously but a lower zero-intercept. With a view to quantifying the change of impedance, the portions of the curve before and after the threshold value were both fitted with a linear model, and the drop was computed from the difference in value between the fitted lines at the force level that triggered the vibration. Performing linear regressions on the relationship between impedance and normal force in order to compute the change of impedance, reduced the reliance on the data located around the transient, which was more likely to be tainted by measurement errors due to the dynamics of the system.

4.2 Results

4.2.1 *Influence of the normal triggering-force value on the detection thresholds*

The detection threshold is shown in Fig. 9 under each of the conditions studied. In line with the results of [6], the detection thresholds were consistently significantly lower in the case of decreasing friction (Student's t-test, $p < 10^{-4}$) than with increasing friction. In both cases (decreasing and increasing friction), the triggering level at a normal force of 0.5 N resulted in the lowest detection threshold.

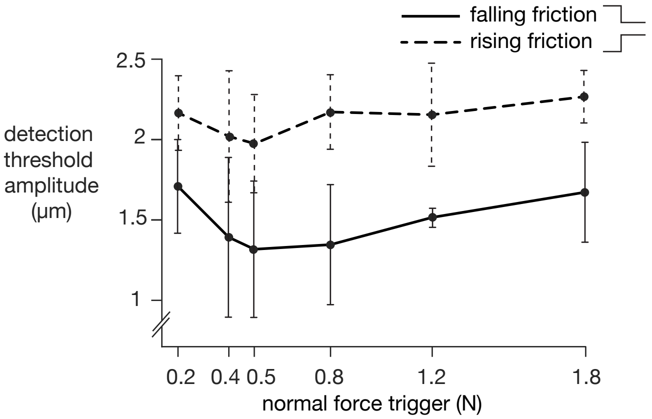

Fig. 9. Vibration amplitude at which the stimulus was unambiguously perceived by participants versus the normal triggering force trigger. Means and standard deviations recorded in each condition are given. The lowest detection threshold occurred when the normal triggering force was equal to 0.5 N.

4.2.2 *Evolution of the mechanical impedance*

The mechanical impedance is presented as a function of the force applied in the insets in Fig. 10. Even when the vibration was not turned on, the impedance load applied by the finger to the ultrasonic plate increased with increasing force levels during the loading phase, and continued to show the same trend when the finger was removed. In the majority of the trials, hysteresis of the impedance occurred during the loading cycle, which is consistent with the previously reported finding that the effects of the mechanical properties of the fingerpad are time-dependent [41], [25].

The impedance can be said to correspond to the amount of skin in contact with the plate. Assuming the damping of the skin to be homogenous, the closer the contact, the more acoustic energy will be absorbed by the skin, and the higher the value of the impedance will therefore be.

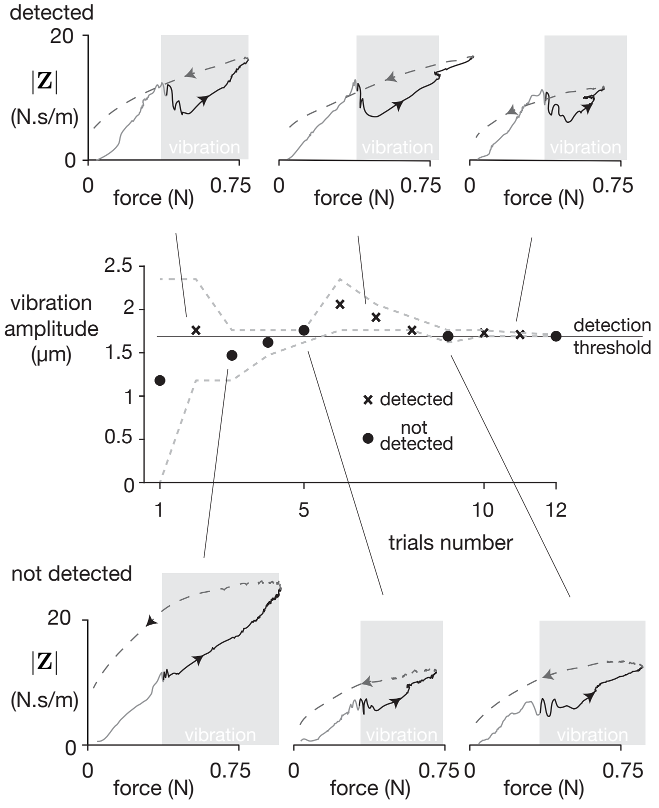

Fig. 10. Typical Modified Binary Search procedure used to determine the perceptual threshold. The insets show the evolution of the impedance as a function of the normal force applied in the case of three positive and three negative responses. The gray area shows the point where the ultrasonic vibration was activated, and hence the low friction state was reached.

One particularly striking observation that can be made when looking at Fig. 10 is that trials where the participant detected a stimulus were often associated with a large decrease in the impedance measurements. However, the drop was less pronounced in trials where the participant did not perceive the change in the friction.

4.2.3 *Fast changes in the mechanical impedance*

The distributions of the size of the decrease in the impedance, $\Delta\mathbf{Z}$, depending on the friction condition (increasing or decreasing friction) and the cases in which the

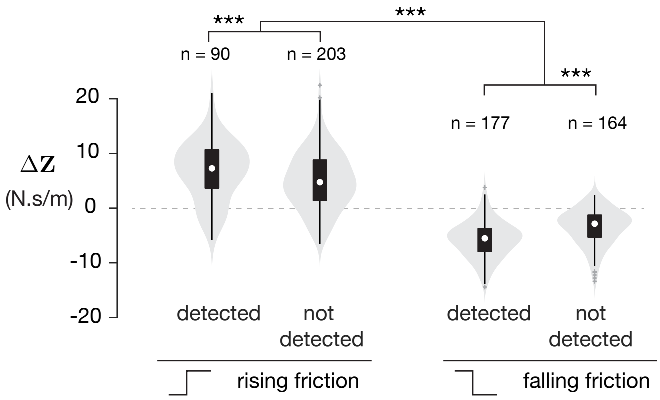

Fig. 11. Distribution of the changes in the impedance $\Delta \mathbf{Z}$ during a trial, depending on the condition (increasing or decreasing friction) and the participants' responses. The white dots indicate the medians, and black boxes the quartiles, and the black lines give the 10th and 90th percentiles of the distribution. The shaded area is the probability density function, where the horizontal width corresponds to the rate of occurrence of a particular value of $\Delta \mathbf{Z}$.

stimulation was detected or not are presented in Fig. 11. In both conditions, the average change in the impedance differed significantly between the detected and undetected trials (two-tailed Student's t-test, $\mathrm{p} < 10^{-4}$ in both conditions). The results obtained combining all the measurements obtained in each condition separately also showed that the change in the impedance was greater with the increasing friction condition than with decreasing friction condition (one-tailed Student's t-test, $\mathrm{p} < 10^{-4}$). Contrary to what occurred in the decreasing friction condition, where the impedance decreased, most of the changes in the impedance occurring in the rising friction condition were in the positive direction, which indicates that the skin increased its coupling with the plate when friction was increased.

In the case of decreasing friction, larger ultrasonic vibration amplitudes were easier for participants to perceive. In addition, the amplitude of the vibration was negatively correlated (Spearman's coefficient $\mathrm{r} = -0.54,\ \mathrm{p} < 10^{-10}$) with the changes in the impedance, which were all negative, and therefore increased in magnitude.

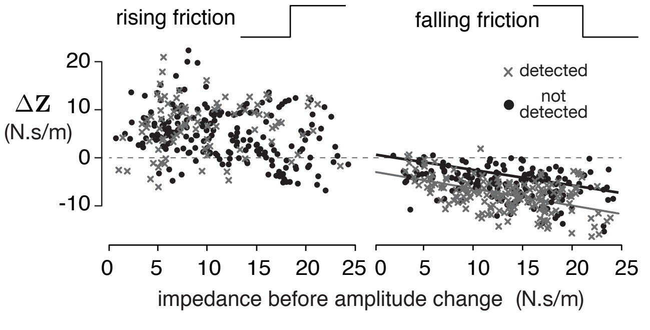

Fig. 12. Changes in the mechanical impedance after a fast change in the friction, depending on the value of the impedance prior to the change.

It can be seen from Figure 12 that the pattern of the impedance variations caused by the changes in friction, differed considerably between the increasing and decreasing friction conditions. In the case of increasing friction, the variation of impedance value were not correlated with the value of the impedance before the trigger (Spearman's coefficient $\mathrm{r} = -0.04,\ \mathrm{p} = 0.45$). The changes were mostly positive, which means that the coupling between the skin and the glass plate increased in most cases. In some rare instances, a drop in the value of the mechanical impedance was also observed, although it was of a relatively small magnitude. On the other hand, in the decreasing friction condition, where the elastic energy of the skin was released, the drop in the impedance was greater when the impedance had reached a fairly high level before the vibration was triggered (Spearman's coefficient $\mathrm{r} = -0.45,\ \mathrm{p} < 10^{-4}$). When the impedance was initially high, it could plunge quite sharply, making easier for the subjects to perceive the ultrasonic switch.

The linear regression of the data recorded in the falling friction condition presented in Fig. 12 showed that the proportionality between the initial impedance and the size of the variations in the impedance was similar between the undetected and detected responses (slopes of -0.27 and -0.26, respectively). The difference lies in the offset of the linear trend, which was close to null in the case of the undetected stimuli, but amounted to -2.25 N.s/m when the stimuli were detected. This findings means that the absolute magnitude of the changes in the impedance was distinctly greater in the case of the detected stimuli, whereas the linear relationship with the initial impedance remained unchanged.

5 DISCUSSION

5.1 Mechanical impedance as a proxy to measure the contact between the finger and the glass plate

By demodulating the force and the displacement of the plate, we obtained a unique picture of the coupling between the plate and the subjects finger. The impedance, as given by from the shift in amplitude and phase of the vibration, reflects the quality of the mechanical coupling between the plate and the subjects skin. A high interfacial impedance indicates that the acoustic energy generated by the actuator has been absorbed by the fingertip. At low vibration amplitudes, the skin is probably stuck to the plate and the interfacial impedance reflects the mechanical impedance of the tissues moving along with the plate. However, when the vibration amplitude is larger than a few tenths of micrometers, the interaction is likely to involve more complex behavior. At large amplitude, the ultrasonic levitation process is fully developed and the contact between the finger and the skin is therefore reduced, which in turn decreases the absorption of the acoustic energy produced by the plate [17]. The real time decoding of the mechanical impedance can be used to indirectly determine the real contact area, which is linked to the frictional behavior of the skin.

The fingertip subjected to transverse waves has typically been modelled as a compressive transmission line in which only the interaction normal to the ultrasonic surface has an effect on the contact [36], [16]. However, the results presented in this study suggest that the lateral motion of the skin, or the lack thereof, also contributes to the overall impedance seen by the vibrating plate. In fact, the lower the vibration, the higher the friction and the larger the impedance will be.

5.2 Implications for creating robust virtual switches

The absence of any straightforward correlations between the mechanical parameters (mass and damping) measured suggests that each participant has unique skin dynamics. In addition, the frictional data showed large variations, even during a given trial run. Moisture build-up and the subsequent softening of the *stratum corneum* may also be responsible for the fast changes observed in the mechanical parameters and in both the nominal friction on glass and the participants susceptibility to ultrasonic vibration.

The continuous changes in the mechanical properties involved, might explain why perceiving the ultrasonic switch can be a challenging task at times. Although some subjects could perceive differences in the ultrasonic amplitude as small as 0.5 µm, the psychophysical experiments showed the existence of a difference between two groups of participants. Some of them 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, [23], [35], the net average susceptibility to friction modulation differed significantly between the two groups studied here. This difference confirms that users with a measurably higher susceptibility to ultrasonic friction modulation tended to perceive the stimulus more successfully than the others.

The online impedance measurements showed that sudden changes in the impedance of more than 5 N.s/m while the user is pressing on the plate can be used to predict a robust perception. One particularly interesting guideline that emerged from this study is that in order to produce an ultrasonic switch stimulus that is robustly perceived by the majority of users, it is best to use a decreasing friction profile after starting with a high friction coefficient and ending with a low friction state, and triggering the transition when the finger-pressing force reaches 0.5 N. The changes in the vibration amplitude of 1.6 µm used on the ultrasonic plate were clearly perceived by most of the participants and also produced the largest absolute changes in the impedance.

5.3 Implications for ultrasonic friction modulation

The results presented here show that a low sensitivity to drops in the ultrasonic friction, on which the perception of switch stimuli depends, occurred in participants with skin impedances which were 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 stimuli had either a larger or a smaller impedance than the average impedance of the sub-group of participants who perceived the clicks correctly. In the case of larger impedances, it is possible that since the finger has less mobility when a given frictional change occurs, less deformation of the skin will occur, resulting in an impaired perceptual experience. Conversely, the fingertips of participants with a low mechanical skin impedances might behave more elastically, resulting in the behavior described in [20]. 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 processes [17].

Individual differences also existed between the perceptual performances of participants having similar skin impedances. In particular, one of the subjects who showed 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.

6 CONCLUSION

Individual differences in the mechanical and tribological processes of each of the participants correlated with their ability to detect small changes in the friction when they were presented with an ultrasonic switch waveform. In the first experiment, about one quarter of the participants tested here did not reliably perceive the click stimulus and required larger than average changes of friction. They also showed a different average mechanical impedance from the mean impedance of the group. This supports the hypothesis that mechanical parameters contribute greatly to the squeeze film levitation process and that soft skin and harder skin are both less susceptible to friction modulation than skin which has an average impedance. In the second experiment, we introduced a means of monitoring the mechanical impedance of the skin as it was touching the surface. The data thus obtained showed that successful perceptions of the ultrasonic switch were accompanied by a sudden large decrease in the impedance of the tissues.

One of the potential applications of the findings made in this study would be to use the impedance as a monitoring tool to tune the stimulation and provide users with a consistent stimulus. A simple inspection of the impedance jump might also provide a basis for ensuring that the clicks have been correctly presented and adjusting the signals if need be. Studies involving the imaging of the skin stretch which occurs during ultrasonic stimulation are now under way. The results should shed useful light on the exact role played by the skin friction which occurs when subjects are working on screens equipped with ultrasonic switches.

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